



RESEARCH ARTICLE

Effect of microbial consortia and moisture regimes on mustard yield and productivity in Northwestern India

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Abstract

Across the globe, microbial consortia for plant nutrition have been explored widely, but systematic knowledge on their effects on moisture stress mitigation is meagre. To investigate microbial consortia, influence on addressing moisture stress and improving Indian mustard productivity under diverse moisture regimes a field experiment was conducted during rabi seasons of 2021–2022 and 2022–2023 at the Research Farm, Chatha, Jammu, India. Conventional and 50 % deficit irrigation and unirrigated (rainfed) treatments were evaluated with five microbial consortia namely, MRD 17, MKS 6, Biophos+Biophos⁺, CRIDA MI-I and CRIDA MI-II. Conventional irrigation, though at par with 50 % deficit irrigation along with application of microbial consortia CRIDA MI-II followed by application of CRIDA MI-I and Biophos+Biophos⁺ resulted in significant increase in seed yield, oil yield, yield attributes, net returns, benefit cost ratio, soil microbial population of Indian mustard than unirrigated plots and use of MRD 17 and MKS 6 microbial consortia in comparison, respectively. The bacterial population (48 %) dominated the soils followed by fungi (31 %) and actinomycetes (21 %) populations and were significantly affected by the use of microbial inoculation like CRIDA MI-II, CRIDA MI-I and Biophos+Biophos⁺ formulations thereby significantly influencing the microbial population in the soils. A significant positive correlation (0.87) was observed between the seed yield and relative water content in view of effective moisture stress mitigation through use of microbes like CRIDA MI-II and CRIDA MI-I. Based on the study, CRIDA MI-II microbial consortia with 50 % deficit irrigation can be recommended in water limited agro-ecologies.

Keywords: deficit irrigation; microbes; microbial population; mustard; relative water content

Introduction

Among all agricultural commodities, vegetable oil accounts for more than 40 % of the world's total production. India surpasses both China and USA as the largest global purchaser of edible oils, with \$16.65 billion in imports. After the USA, China and Argentina, India has the fourth largest vegetable oil economy in the world, with 39.60 million tonnes of oilseed produced in 2023–24 (1). Total area, production and productivity of rapeseed–mustard in world during 2022–23 was 42.49 million hectares with total production of 91.0 million tonnes and productivity of 2.0 tonnes per hectare. India's rank first in area (9.8 million hectare) and third in

production (12.05 million tonnes) of Indian mustard, accounting for about 12 % of the world's total rapeseed–mustard production and about 8.5 % of the world's total rapeseed–mustard "oil" after European Union (20.05 million tonnes), Canada (18.8 million tonnes) and China (15.4 million tonnes), respectively (2). Among all the oilseed crops grown in the country, rapeseed –mustard stand first in term of production with 35 % share in total oilseed production of the country followed by soyabean and ground nut with a share of 34 % and 24 % respectively. In Jammu and Kashmir, the Rapeseed–mustard crops occupy an area 56000 ha with an annual production of 42.34 thousand quintals and productivity of 7.56 kg ha⁻¹ during 2022–2023 (3).

Indian mustard requires timely irrigation at flowering and seed filling stages to maintain its internal water balance in the crop and due to erratic rainfall sometimes the crop undergoes moisture stress during the critical stages thereby necessitating the need of irrigation at flowering and seed filling stage for achieving higher crop yields and productivity. The decline in crop yield due to absence of adequate irrigation is one of the reasons that crop becomes susceptible to moisture stress, which can cause a significant reduction in crop yields (4). Further, Indian mustard does not have high water requirement during the crop season as most of its requirements are met through receipt of winter rains caused due to western disturbances created in Central Asian region thus causing rains during the winter months of November–December or end of January–February. Also, it is important to maintain a proper soil moisture content during the crop's critical crop growth stages so as to decrease the effect of moisture stress and minimising the crop yield loss (5). Therefore, maintaining the internal water balance during the moisture stress periods at critical stages is imperative for higher crop growth and productivity (6).

The soil microbes play a major role in enhancing soil fertility and soil health, including the physical, chemical and biological characteristics of the soil. Microorganisms are key players in nutrient cycling and hence form important components of a soil ecosystem. Besides, improving nutrient availability, certain microorganisms also provide growth and health benefits to plants through direct and indirect mechanisms (7). Dryland soils are poorly developed with low organic matter content and hence have poor water retention capacity. Besides, dryland soils face various abiotic stresses like nutrient imbalance, drought, heat etc. Increased abundance of microorganisms in dryland soil can help in improving soil aggregation and soil organic matter carbon content, thus increasing the water retention capacity of the soil. Recent studies suggest that microbial inoculants offer a cost efficient and eco-friendly solution to addressing moisture stress. In last two decades, numerous pots and a few field studies have highlighted the potential of these microbes to induces tolerance against abiotic stress (8). The microbes encourage the plant growth by synthesising siderophores exopolysaccharides polymeric substances (EPS) and Indole acetic acid production (IAA) production thus playing a key role in increasing root growth, nitrogen fixation and water intake by the crop (9). This could ultimately increase yield and yield attributes of Indian Mustard.

The high-altitude terrain and diverse microclimatic conditions of the North-Western Himalayan region pose significant challenges for sustainable crop production. Small and marginal farmers in this region often struggle with water scarcity arising from erratic rainfall patterns and soil heterogeneity, which collectively reduce the yield potential of major crops such as Indian mustard. Considering these challenges, the present study was undertaken to identify the most suitable microbial inoculants capable of mitigating moisture stress during early crop growth and terminal heat stress at later growth stages. The study hypothesises that specific microbial inoculants can enhance biochemical resilience in Indian mustard by promoting hormonal secretions that stimulate proline synthesis, thereby improving plant tolerance to water deficit and temperature stress. Such physiological improvements are expected to contribute to better crop establishment and enhanced yield stability under the fluctuating

climatic conditions of the North-Western Himalayas.

Materials and Methods

A field experiment was conducted during winter (rabi) season of 2021–22 and 2022–23 at Research Farm, SKUAST-Jammu located in the Jammu & Kashmir (UT). The experimental field is located at 32°39' 33'' N latitude and 74°48' 45'' E longitude and 293 m above mean sea level (mean sea level), in the subtropical foothills of the Shivalik Himalayas of India. The average rainfall of about 371 and 157 mm was received from October to March during 2021–22 and 2022–23, respectively. The mean monthly minimum and maximum temperature varied between 6.7 to 14.3 °C and 16.2 to 28.6 °C, respectively, in 2021–22, whereas in 2022–23 they were 5.1 to 12.9 °C and 16.6 to 30.6 °C, respectively, during growing season (October to March) (Fig. 1). The soil of experimental site was sandy clay loam in texture, slightly alkaline pH (7.4), low in organic carbon (4.09 g kg⁻¹) and available nitrogen (171.8 kg ha⁻¹), but medium available phosphorus (15.3 kg ha⁻¹) and available potassium (121 kg ha⁻¹). The experiment was conducted in split-plot design with three irrigation levels in main plots i.e., I₁: Unirrigated (rainfed); I₂: 50 % deficit irrigation and I₃: Conventional irrigation and 6 treatments of microbial consortia i.e., M₁: MRD-17; M₂: MKS-6; M₃: Biophos + Biophos⁺; M₄: CRIDA MI-I; M₅: CRIDA MI-II and M₆: control were arranged in sub plots with 3 replications. The conventional irrigation composed of two irrigations which were applied at flowering and seed development stage, whereas, under 50 % deficit irrigation level, the irrigation was applied depletion of 50 % of the total moisture held by the soil at field capacity (21–21.4 %). Irrigation was given when the soil moisture reading from conventional irrigation treatments reached Management allowable depletion (MAD). Irrigation amounts for conventional irrigation treatment were estimated by multiplying the rooting depth by the difference between the field capacity (FC) and the average soil moisture content of all conventional irrigation treatments. Once the total irrigation amount needed to bring the soil moisture to field capacity was calculated for conventional irrigation treatment plots (Fig. 2), the irrigation amount for plots with deficit treatment was calculated by corresponding treatment percentage i.e. I₂ = 0.50) (10).

$$\text{MAD} = 0.5 \times \text{PAW} \dots\dots\dots(i)$$

$$\text{PAW} = \text{FC} - \text{PWP} \dots\dots\dots(ii)$$

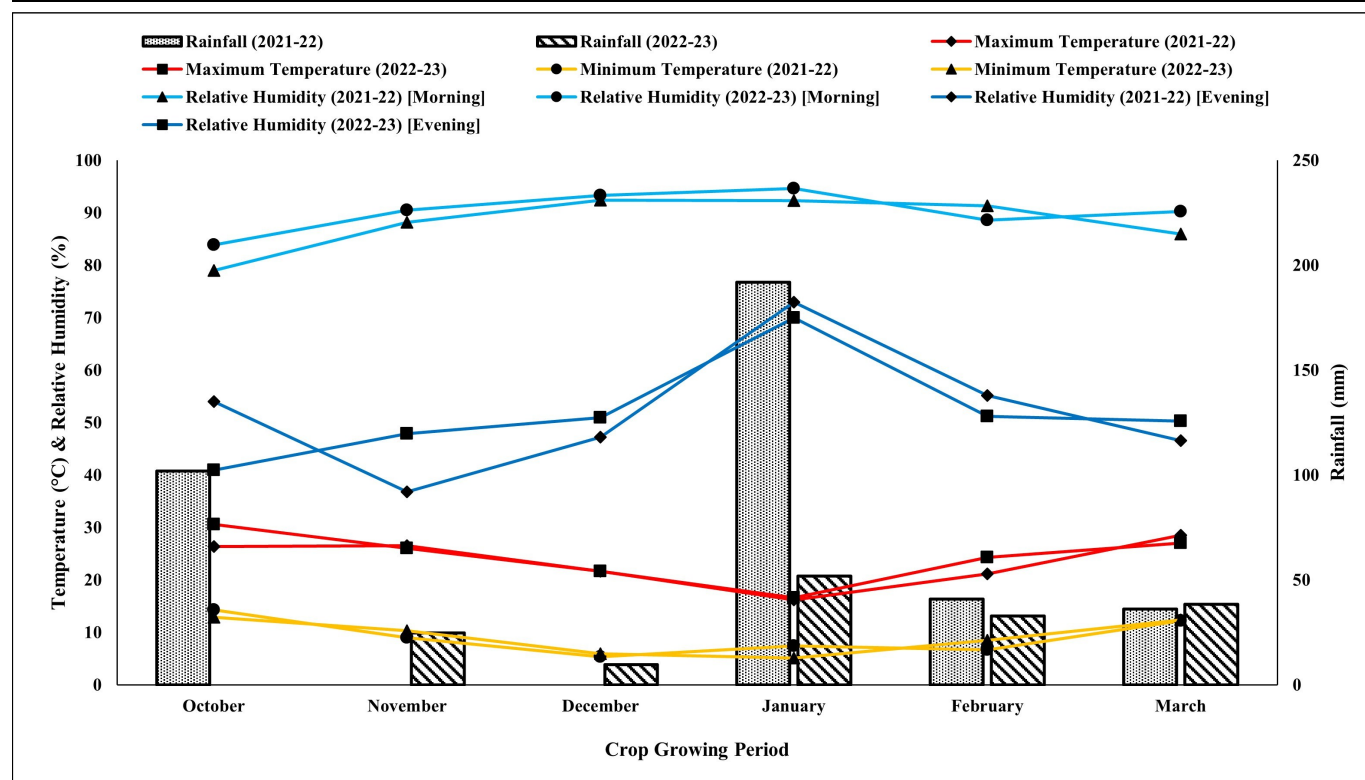
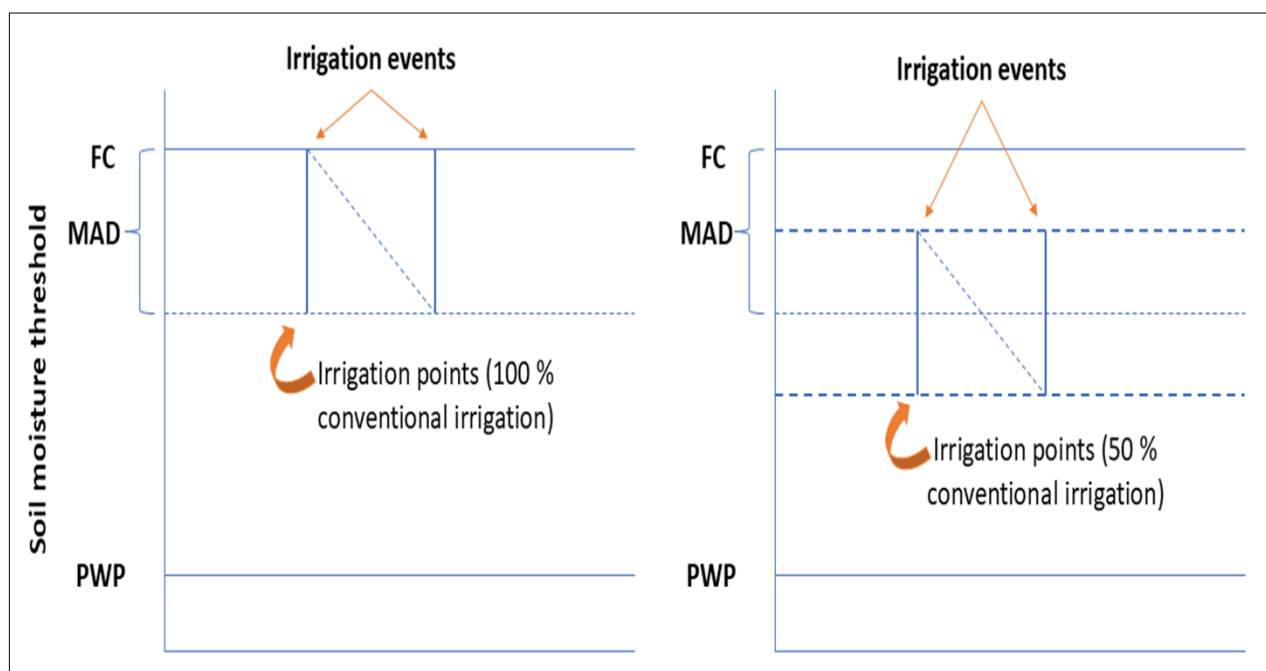
Where PAW means plant available water; FC denotes field capacity; PWP denotes permanent wilting point.

The mustard seeds were treated with these microbial inoculants prior to sowing through soil treatment. The soil application of microbial consortia was done using dose of 2.5 kg talc formulation (1 % carboxy methyl cellulose) mixed with 50 kg of well rotten farm yard manure per hectare (11). The talc formulation was properly mixed with farmyard manure (FYM), kept overnight and then applied to the soil by broadcasting before sowing. To avoid microbial cross contamination a buffer zone of 1 m was kept between the sub plots. The details of the microbial consortia used in the experiments are given here as Table 1.

The recommended dose of fertilisers 80:40:20 kg ha⁻¹ (N:P₂O₅:K₂O) were applied through urea, diammonium phosphate (DAP) and muriate of potash (MOP), respectively. The full dose of phosphorus and potassium and half dose of nitrogen were applied as basal at the time of sowing. Remaining nitrogen (N) was applied

Table 1. Description of the microbial consortia used for mitigation of moisture stress in Indian mustard

Name	Type	Microbial composition	Function	Application	Reference
MRD-17	Bacterial strain	<i>Bacillus</i> spp.	Osmotolerant PGPR	Enhances plant growth under drought/salt stress; improves root colonisation	(12)
MKS-6	Bacterial strain	<i>Bacillus</i> spp.	Osmotolerant PGPR	Promotes growth under osmotic stress; aid in nutrient uptake	
Biophos	Liquid bioformulation	<i>Paenibacillus</i> spp.	Phosphate solubilisation	Increases phosphorus availability in soil	(13)
Biophos ⁺	Liquid bioformulation	<i>Kluyvera</i> spp.	Phosphate solubilization	Enhances P availability; potentially improves crop yield	
CRIDA MI-I	Liquid bioformulation	<i>Pseudomonas putida</i> + <i>Paenibacillus favisporus</i> B30	PGPR + Phosphate solubilisation	Synergistic action for plant growth and soil health	(11)
CRIDA MI-II	Liquid bioformulation	<i>Pseudomonas putida</i> P45 + <i>Bacillus amyloliquefaciens</i> B17	PGPR + Phosphate solubilisation	Enhances nutrient uptake; root development and biocontrol	

**Fig. 1.** Monthly meteorological data of the experimental area during the crop growing period (2021–22 and 2022–23).**Fig. 2.** Schematic of soil moisture-based irrigation scheduling for conventional irrigation (100 %) and 50 % deficit irrigation.

at 40 DAS (day after sowing). Mustard variety Giriraj was sown on 20th October 2020 and 28th October 2021, respectively using a seed rate of 5 kg ha⁻¹. The crop was sown in rows 30 cm apart with plant-to-plant distance of ± 10 cm maintained through thinning and gap filling at 15 days after sowing. Two weeding were done at 25 and 45 days after sowing (DAS) during both the years of experimentation. Irrigations were applied as per the treatments of the experiment. The mustard crop was harvested when the silique turned yellow and biomass yield were recorded plot wise.

Relative water content (RWC) in mustard crop was measured at different stages i.e., pre-flowering using the procedure described by Barrs and Weatherly (14). It is being estimated in percentage (%) from fresh, dry and turgid leaf weight. The RWC was calculated as:

$$\text{RWC (\%)} = \frac{\text{Fresh leaf weight} - \text{Dry leaf weight}}{\text{Turgid leaf weight} - \text{Dry leaf weight}} \times 100 \quad (\text{iii})$$

To estimate oil content in mustard seed, seed samples were placed in an oven at 60–80 °C to remove moisture. Once dried, the seeds were crushed using a pestle-mortar and oil content was assessed by the conventional Soxhlet apparatus (15).

Oil Content (%) =

$$\frac{\text{Weight of flask + petroleum ether extract} - \text{Weight of flask with oil}}{\text{Turgid leaf weight} - \text{Dry leaf weight}} \times 100 \quad (\text{iv})$$

Statistical analysis was conducted and graphs were made using R software version 4.2.2. Additionally, 'F' test of significance was applied to examine the statistical significances among treatments. Statistical analysis of the 2 years data (2021–22 and 2022–23) was done at 5 % level of probability using Duncan's multiple range test (DMRT) to test the difference between the individual means.

Results and Discussion

Yield attributes and yield

Application of conventional irrigation (I₃) though at par with 50 % deficit irrigation (I₂) resulted in significant increase in seed yield and

its attributes i.e., number of silique/plant (236 and 237), seeds/silique (17.48 and 17.61), 1000-seed weight (3.48 and 3.74 g) and seed yield (1569 and 1638 kg ha⁻¹) in Indian mustard than unirrigated (rainfed) treatment during both the years (Table 2). Conventional irrigation levels resulted in a significant 64 % and 62 % increase in mustard seed yield compared to unirrigated plots during both the years of experimentation. Also, the plots with 50 % deficit irrigation led to a substantial enhancement in yield and its associated attributes compared to the unirrigated treatment. The observed increase in seed yield can be fundamentally attributed to the strong positive correlation ($r = 0.87$) existing between the yield and RWC maintained throughout the critical phenological stages of the mustard crop. Sufficient soil moisture availability serves as a primary driver for optimising the internal water status of the plant. This phenological stability is crucial as it ensures the maintenance of cell turgidity and the structural integrity of cellular membrane, thereby facilitating uninterrupted metabolic processes and preventing the degradation of chloroplasts. Under conditions of high soil moisture, the mustard plants likely exhibited enhanced stomatal conductance and increased transpiration rates, which in turn fostered a higher rate of net CO₂ assimilation and the overall production of primary photosynthates. Crucially, favourable moisture availability ensures the efficient partitioning and translocation of these assimilated carbohydrates from source to sink structures, such as developing siliques. By maintaining a high RWC, the mustard crop effectively avoids moisture stress and sustain higher hydrostatic pressure for nutrient transport. This synergy directly improves key yield determining attributes, including the number of siliques per plant and 1000-seed weight (16, 17).

Amongst the microbial inoculation treatments, significant enhancement in both seed yield and its associated attributes was observed with application of CRIDA MI-II (M₅) inoculant at though at par with application of CRIDA MI-I (M₄) and Biophos + Biophos⁺ inoculants (M₃), resulted in significant increase in silique/plant (242 and 244), seeds/silique (18.00 and 18.03), 1000-seed weight (4.48 and 3.79 g) and seed yield (1476 and 1531 kg ha⁻¹). However, it was found to be during both the years of experimentation (Table 2). The application of CRIDA MI-II (M₅) boosted the seed yield of mustard crop by 43 % and 25 % in comparison to the control treatment during both the years, respectively. This might be attributed to the fact that microbial consortia like CRIDA MI-I, CRIDA MI 1 and Biophos + Biophos⁺ help to increase the crop productivity under abiotic stress by improving nutrient and water use efficiency, stimulating root development and activating stress-

Table 2. Effect of different irrigation levels and microbial consortia on yield and its attributes in Indian mustard var. Giriraj

Treatments	Number of silique plant ⁻¹		Seeds silique ⁻¹		1000-seed weight (g)		Seed yield (kg ha ⁻¹)	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
Irrigation levels								
I ₁ : Unirrigated (rainfed)	199 ^b	202 ^b	15.71 ^b	15.83 ^b	2.95 ^b	3.28 ^b	955 ^b	1008 ^b
I ₂ : 50 % Deficit irrigation	227 ^a	228 ^a	17.10 ^a	17.22 ^a	3.38 ^a	3.67 ^a	1445 ^a	1538 ^a
I ₃ : Conventional irrigation	236 ^a	237 ^a	17.48 ^a	17.61 ^a	3.48 ^a	3.74 ^a	1569 ^a	1638 ^a
Microbial consortia								
M ₁ : MRD-17	212 ^b	216 ^c	16.44 ^b	16.82 ^c	3.24 ^b	3.51 ^b	1296 ^b	1327 ^b
M ₂ : MKS-6	205 ^{bc}	210 ^c	16.31 ^b	16.33 ^c	3.14 ^b	3.42 ^b	1257 ^b	1314 ^b
M ₃ : Biophos + Biophos ⁺	234 ^a	232 ^b	17.49 ^a	17.42 ^b	3.44 ^a	3.69 ^a	1432 ^a	1478 ^a
M ₄ : CRIDA MI-I	236 ^a	236 ^{ab}	17.58 ^a	17.64 ^{ab}	3.41 ^a	3.72 ^a	1447 ^a	1502 ^a
M ₅ : CRIDA MI-II	242 ^a	244 ^a	18.00 ^a	18.03 ^a	3.48 ^a	3.79 ^a	1476 ^a	1531 ^a
M ₆ : Control	192 ^c	196 ^d	14.76 ^c	15.07 ^d	2.93 ^c	3.25 ^c	1028 ^c	1217 ^c
Interaction of different entries at same fertility level	NS							
Interaction of different fertility levels at same entries	NS							

Values having common letter(s) in a column do not differ significantly at $p \leq 0.05$ as per DMRT.

tolerance mechanism by boosting antioxidant metabolism, secondary metabolites and osmolyte content (18). However, the interaction effect between the irrigation levels and microbial consortia was found to be insignificant during both the years of experimentation.

Oil content and oil yield

The oil content and oil yield of mustard was significantly influenced by irrigation levels and microbial consortia during both the years of study. Significantly highest oil content (38.87 and 39.02 %) and oil yield (609.62 and 639.24 kg ha⁻¹) were observed under conventional irrigation (I₃) which remained at par with 50 % deficit irrigation (I₂) (Table 3). The minimum value of oil content and oil yield were recorded in unirrigated (rainfed) treatment (I₁). This might be due to fact that the adequate soil moisture improves root activity, nutrient solubility and uptake, which are essential for sustained photosynthesis and efficient assimilate partitioning towards developing seeds. Favourable moisture conditions also enhance enzymatic activity involved in lipid biosynthesis, particularly during seed filling, leading to improved oil accumulation (19).

Amongst the microbial consortia, the significantly highest value of oil content (39.04 and 39.16 %) and oil yield (577.16 and 600.08 kg ha⁻¹) under CRIDA MI-II (M₅) which was statistically at par with CRIDA MI-I (M₄) and Biophos+Biophos⁺ (M₃) (Table 3). The enhancement in oil content and oil yield under microbial consortia treatments may be attributed to improved nutrient solubilisation, enhanced root proliferation and better moisture utilisation facilitated by beneficial microbial activity. The microbial inoculants, particularly phosphate-solubilising and plant growth-promoting rhizobacteria, might have increased the availability and uptake of key nutrients such as phosphorus, sulphur and micronutrients essential for oil biosynthesis. Additionally, these microbes could have stimulated the production of phytohormones like auxins and cytokinins, improving photosynthetic efficiency and assimilate partitioning towards the developing seeds. The synergistic action of multiple microbial strains likely strengthened plant metabolic processes, leading to enhanced synthesis and accumulation of oil in seeds through better energy balance and carbon allocation within the plant system (20). The interaction was found to be non-significant during both the years of experimentation.

Microbial population

The microbial inoculants have capacity to colonise, survive and persist, along with their interaction with the native microbial community in the root zone. The different irrigation levels and microbial consortia resulted in significant increase in the total microbial population namely bacteria, fungi and actinomycetes in soil during both the years of experimentation (Table 4). Amongst the irrigation level, significantly highest value of total microbial population (12.15 and 12.46 cfu g⁻¹) was observed in conventional irrigation (I₃) which was found to be at par with 50 % deficit irrigation (I₂). The minimum total microbial population was recorded in unirrigated (I₁) treatment during both the years of study. Similarly, in microbial consortia, significantly highest total microbial population (12.16 and 12.40 cfu g⁻¹) was found in CRIDA MI-II (M₅) which was statistically at par with CRIDA MI-I (M₄) and Biophos+Biophos⁺ (M₃). The Fig. 3 revealed that amongst the bacteria population was normally distributed and the population of bacteria ranged between 5.56 and 5.88 cfu g⁻¹ and the interquartile range (IQR) i.e., more than 50 % of the treatments (25 to 75 %) lied between the range 5.71 to 5.82 cfug⁻¹ with a median range of 5.77 cfug⁻¹ and mean of 5.75 cfug⁻¹. The fungi population in the soil was negatively skewed and the fungi population ranged between 3.56 cfu g⁻¹ to 3.91 cfu g⁻¹ interquartile range of 3.65 cfug⁻¹ to 3.79 cfug⁻¹ with the median of 3.73 cfug⁻¹ and mean value of 3.72 cfu g⁻¹. Similarly, actinomycetes population was negatively skewed with the values ranging from 2.34 to 2.73 with lower quartile value of 2.42 cfu g⁻¹ and upper quartile at 2.60 cfu g⁻¹ with a mean and median value of 2.52. The perusal of the mean data of two years on total microbial population revealed that among the total microbial population in the soil, the bacteria's constituted the maximum population (48 %) followed by fungi (31 %) and actinomycetes (21 %), respectively (Fig. 4). This might be due fact that Increased soil moisture content in the soil can increase the microbial activity by providing more substrate to the microbial population through faster disintegration and decomposition as a result of hydrolysis of crop residues. This helps increasing the carbon content as well as the microbial population viz, bacteria, fungi and actinomycetes for enhancing carbon inputs to the soils. Also, the microbial inoculants also enhance the plant growth by increasing the availability of mineral nutrients in the soil rhizosphere and the plants nourish the rhizosphere microbiome with carbon and N metabolites through root exudation. Previous researchers reported that the beneficial

Table 3. Effect of different irrigation levels and microbial consortia on economics and quality of Indian mustard var. Giriraj

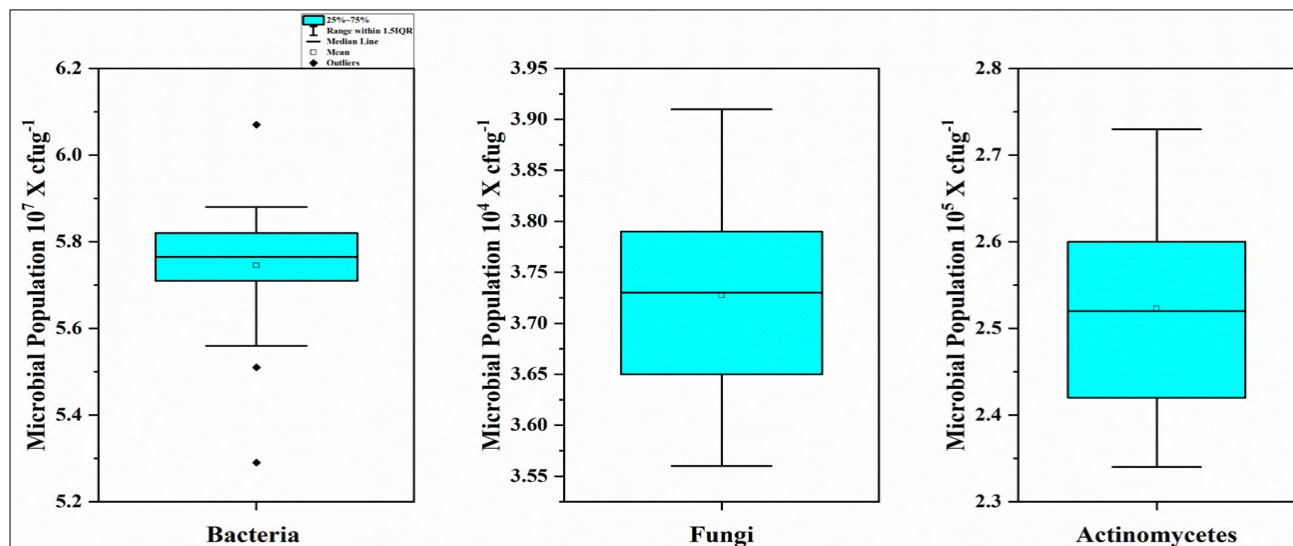
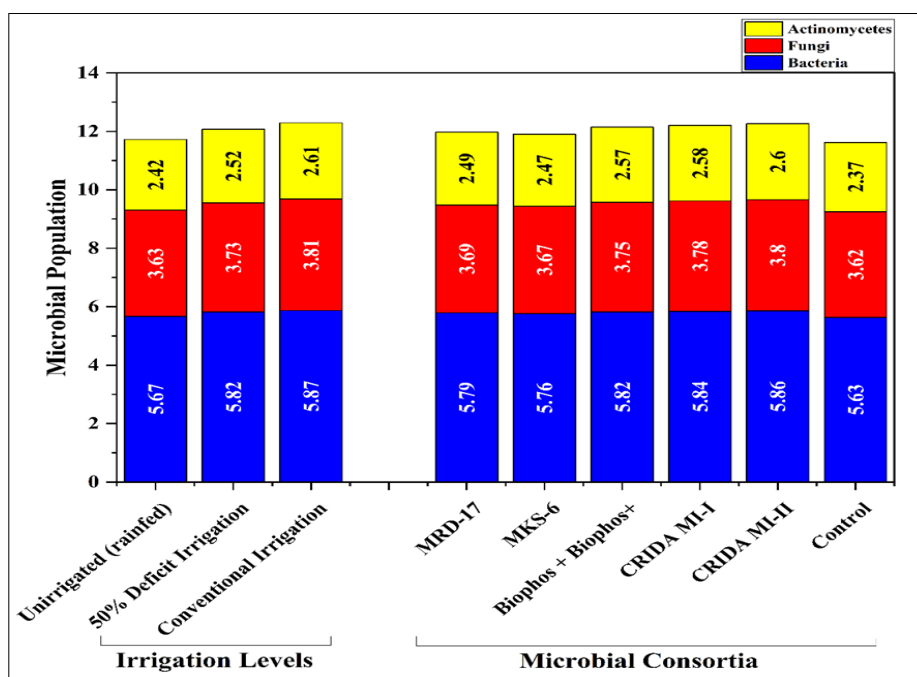
Treatments	Net Return (\$ ha ⁻¹)		B:C Ratio		Oil content (%)		Oil yield (kg ha ⁻¹)	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
Irrigation Levels								
I ₁ : Unirrigated (rainfed)	362.06 ^b	442.14 ^b	1.69 ^b	2.06 ^b	37.63 ^b	37.87 ^b	359.48 ^b	386.56 ^b
I ₂ : 50 % deficit irrigation	636.56 ^a	766.57 ^a	2.70 ^a	3.25 ^a	38.44 ^{ab}	38.60 ^{ab}	555.27 ^a	593.82 ^a
I ₃ : Conventional irrigation	696.52 ^a	816.79 ^a	2.78 ^a	3.26 ^a	38.87 ^a	39.02 ^a	609.62 ^a	639.24 ^a
Microbial consortia								
M ₁ : MRD-17	548.42 ^b	622.00 ^b	2.31 ^b	2.63 ^b	38.43 ^{ab}	38.54 ^{ab}	499.19 ^b	516.76 ^b
M ₂ : MKS-6	524.94 ^b	630.68 ^b	2.21 ^b	2.66 ^b	38.41 ^{ab}	38.49 ^{ab}	484.13 ^b	512.05 ^b
M ₃ : Biophos + Biophos ⁺	630.61 ^a	728.79 ^a	2.66 ^a	3.08 ^a	38.33 ^{ab}	38.51 ^{ab}	547.91 ^a	571.16 ^a
M ₄ : CRIDA MI-I	639.66 ^a	744.72 ^a	2.70 ^a	3.14 ^a	37.90 ^b	38.32 ^b	550.37 ^a	576.76 ^a
M ₅ : CRIDA MI-II	657.10 ^a	763.18 ^a	2.77 ^a	3.22 ^a	39.04 ^a	39.16 ^a	577.16 ^a	600.08 ^a
M ₆ : Control	389.54 ^c	561.63 ^c	1.67 ^c	2.40 ^c	37.75 ^b	37.92 ^b	389.99 ^c	492.44 ^c
Interaction of different entries at same fertility level	NS							
Interaction of different fertility levels at same entries	NS							

Values having common letter(s) in a column do not differ significantly at $p \leq 0.05$ as per DMRT; Dollar rate: \$ 83.64.

Table 4. Effect of different irrigation levels and microbial consortia on microbial population of Indian mustard var. Giriraj

Treatments	Bacteria (10^7 cfug $^{-1}$)		Fungi (10^4 cfug $^{-1}$)		Actinomycetes (10^5 cfug $^{-1}$)		Total microbial population (cfug $^{-1}$)	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
Irrigation levels								
I ₁ : Unirrigated (rainfed)	5.51 ^b	5.67 ^b	3.59 ^b	3.67 ^b	2.38 ^b	2.46 ^b	11.61 ^c	11.84 ^b
I ₂ : 50 % Deficit irrigation	5.70 ^{ab}	5.87 ^a	3.68 ^{ab}	3.78 ^a	2.47 ^{ab}	2.57 ^a	11.92 ^b	12.23 ^a
I ₃ : Conventional irrigation	5.79 ^a	5.94 ^a	3.76 ^a	3.86 ^a	2.56 ^a	2.66 ^a	12.15 ^a	12.46 ^a
Microbial consortia								
M ₁ : MRD-17	5.63 ^{bc}	5.79 ^{bc}	3.64 ^{bc}	3.75 ^{bc}	2.44 ^b	2.55 ^b	11.77 ^b	12.10 ^b
M ₂ : MKS-6	5.58 ^{bc}	5.76 ^{bc}	3.62 ^{bc}	3.73 ^c	2.42 ^b	2.53 ^b	11.83 ^b	12.16 ^b
M ₃ : Biophos + Biophos ⁺	5.71 ^{ab}	5.87 ^{ab}	3.70 ^{ab}	3.80 ^{ab}	2.53 ^a	2.61 ^a	12.02 ^a	12.29 ^a
M ₄ : CRIDA MI-I	5.72 ^{ab}	5.88 ^{ab}	3.74 ^a	3.83 ^a	2.54 ^a	2.62 ^a	12.09 ^a	12.33 ^a
M ₅ : CRIDA MI-II	5.81 ^a	5.95 ^a	3.76 ^a	3.85 ^a	2.56 ^a	2.64 ^a	12.16 ^a	12.40 ^a
M ₆ : Control	5.53 ^c	5.69 ^c	3.58 ^c	3.66 ^d	2.32 ^c	2.43 ^c	11.50 ^c	11.78 ^c
Interaction of different entries at same fertility level	NS							
Interaction of different fertility levels at same entries	NS							

Values having common letter(s) in a column do not differ significantly at $p \leq 0.05$ as per DMRT.

**Fig. 3.** Inter quartile distribution of bacteria, fungi and actinomycetes microbial population under different irrigation levels and microbial consortia in Indian mustard.**Fig. 4.** Effect of different irrigation levels and microbial consortia on microbial population of Indian mustard.

microbes aid in nutrient uptake, regulate phytohormones and enhance the plant's resistance to abiotic stress (21). However, the interaction effect between the irrigation levels and microbial consortia was found to be insignificant during both the years of experimentation.

Relative water content

Relative water content is considered as important parameter to assess the capability of plant to drought tolerance. The Fig. 5 reveals that application of conventional irrigation (I_3) levels recorded higher value of RWC (72.11 and 73.9%) followed by 50% deficit irrigation (I_2) during both the year of experimentation. Higher RWC under improved irrigation regimes reflects better plant water status, which is critical for maintaining turgor pressure, stomatal conductance and metabolic activity under water stress. Adequate soil moisture facilitates efficient water uptake by roots, sustaining cell expansion and photosynthetic processes, thereby preventing dehydration-induced cellular damage. Plants with higher RWC can maintain membrane integrity, enzyme activity

and nutrient transport, enhancing physiological stability during moisture fluctuations (22, 23). Among the different microbial consortia, the higher value of RWC was observed with application of CRIDA MI-II (M_5) (76.33 and 77.4%) followed by CRIDA MI-I (M_4) and Biophos+Biophos* (M_3) than other treatments. Superior relative water content under specific microbial consortia arises from their multifaceted plant growth-promoting mechanisms, including exopolysaccharide production that enhances soil aggregation and water retention around roots, thereby improving hydraulic conductivity and moisture availability to plant tissues. These consortia, often comprising *Pseudomonas* and *Bacillus* strains, solubilise phosphorus, produce indole acetic acid to stimulate root proliferation for better water uptake and synthesise osmoprotectants like proline to maintain cellular turgor and membrane stability under stress. Additionally, they modulate rhizosphere microbial communities, fostering symbiotic interactions that boost nutrient acquisition and mitigate oxidative damage, ultimately sustaining physiological functions such as stomatal regulation and photosynthesis. This integrated action

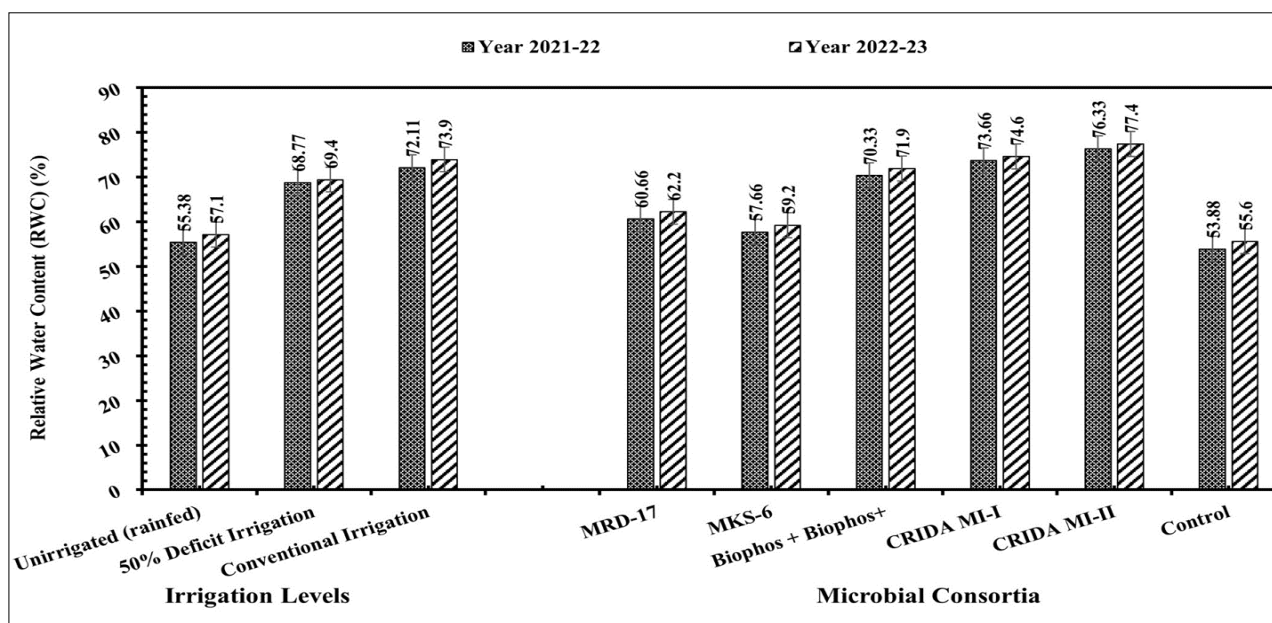


Fig. 5. Effect of different irrigation levels and microbial consortia on relative water content (%) of Indian mustard during the year 2021–2022 and 2022–2023.

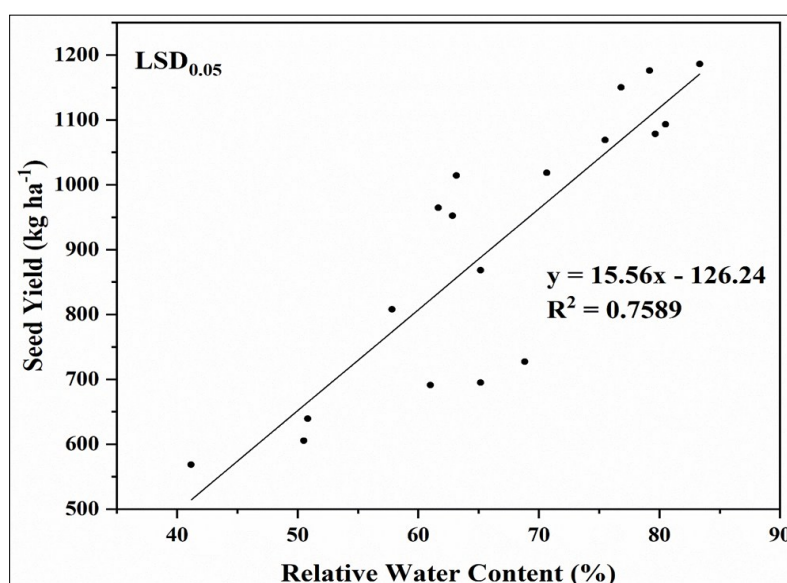


Fig. 6. The correlation between mean seed yield (kg ha^{-1}) and mean relative water content (%) of Indian mustard under different moisture regimes and microbial consortia.

elevates plant drought resilience by optimising water use efficiency at the root-soil interface (24, 25). A significantly positive correlation ($r = 0.87$) was observed between the seed yield and relative water content of the Indian mustard crop during both the years of experimentation (Fig. 6).

Economics

Significantly the higher net return (\$ 696.52 and \$ 816.79 ha⁻¹) and B:C ratio (2.78 and 3.26) were obtained under the conventional irrigation (I₃) which was statistically at par with 50 % deficit irrigation (I₂) (\$ 636.56 and \$ 766.57 ha⁻¹) and was found to be the most economical treatments than unirrigated (I₁) treatment. Amongst microbial inoculation, maximum net return (\$ 657.10 and \$ 763.18 ha⁻¹) and B:C ratio (2.77 and 3.22) were recorded with the application of CRIDA MI-II (M₅) microbial consortia which was remained at par with application of CRIDA MI-I (M₄) (\$ 639.66 and \$ 744.72 ha⁻¹) and Biophos+Biophos⁺ (M₃) (\$ 630.61 and \$ 728.79 ha⁻¹) and the lowest net returns were recorded in control (M₆) treatment (\$ 389.54 and \$ 561.63 ha⁻¹) during both the years of experimentation (Table 3). These findings highlight the economic benefits of combined use of irrigation levels and microbial inoculants in mustard crops, suggesting an opportunity for enhance resource efficiency and increased productivity and profitability through use of microbial consortia.

Conclusion

Based on 2 years of experimentation it may be concluded that application of CRIDA MI II microbial consortia containing *Pseudomonas putida* + *Paenibacillus favisporus* strain B30 with 2 irrigations at flowering and seed filling stage was found to be the most economical treatment with maximum net benefit to cost ratio (B:C) and thus can be recommended for higher profitability and productivity of Indian mustard crop under subtropical conditions of North-Western Himalayas.

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Authors' contributions

RB and VB wrote the original manuscript and prepared the tables and figures. MG, BK and DC reviewed the manuscript. MS, AS, VG, SKR and NP participated in sequence alignment. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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