E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(9): 113-121
Received: 09-07-2025
Accepted: 11-08-2025

Bansilal Verma
Department of Agriculture Sciences, IES University, Bhopal, Madhya Pradesh, India

Dr. Radhey Shyam
Department of Agriculture Sciences, IES University, Bhopal, Madhya Pradesh, India

Rishi Kumar Dwivedi
Department of Agriculture Sciences, IES University, Bhopal, Madhya Pradesh, India

Ravindra Singh Solanki
Department of Agriculture Sciences, IES University, Bhopal, Madhya Pradesh, India

Anil Kumar
Department of Agriculture Sciences, IES University, Bhopal, Madhya Pradesh, India

Corresponding Author:
Bansilal Verma
Department of Agriculture Sciences, IES University, Bhopal, Madhya Pradesh, India

Nurturing rainfed chickpea growth and profitability with hydrogel and foliar nutrition

Bansilal Verma, Radhey Shyam, Rishi Kumar Dwivedi, Ravindra Singh Solanki and Anil Kumar

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i9b.3735

Abstract
Madhya Pradesh boasts the highest production and consumption of pulses in India, with chickpea (*Cicer arietinum* L.) being one of the most important winter season legumes for nutrition and soil health. Despite the importance of chickpea cultivation, especially in the rainfed regions, there are challenges such as water scarcity and low nutrient use efficiency. This study determined the impacts of hydrogel application along with foliar nutrition on the growth, yield, and economic benefits of chickpea cultivation in rainfed conditions of Bhopal, Madhya Pradesh in the 2023-24 rabi season. It utilized a split-plot design with two levels of hydrogel application (0 and 5 kg ha^{-1}) and three levels of nutrition (water, 2% urea, 500 ppm thiourea). Growth, yield, and economic parameters were collected and analyzed. Findings revealed that the application of hydrogel improved early growth traits, root nodule development, and dry matter yield. Moreover, foliar urea improved height, branching, and yield components. Though yields were not significantly different with hydrogel application, 1111.77 kg ha^{-1} of grain yield and economic returns were highest with 2% urea. Use of hydrogel and foliar nutrition enhanced the physiological efficiency and performance of the crop under rainfed conditions. Therefore, urea foliar application, together with hydrogel soil amendment, is proposed as a strategy to enhance chickpea productivity and profitability in water-scarce regions.

Keywords: Chickpea (*Cicer arietinum* L.), hydrogel application, foliar nutrition, crop growth and yield urea foliar spray, economic analysis

1. Introduction

Sustainable crop production is increasingly recognized as critical for soil-plant health, particularly under rainfed conditions. Advances in rhizosphere engineering and seed development research have highlighted their roles in nutrient acquisition, stress resilience, and plant fitness (Solanki *et al*., 2024; Kumar *et al*., 2024) [51, 16]. Sustainable sources such as compost, farmyard manure, and microbial inoculants support resilience and nutrient cycling (Solanki *et al*., 2023; Solanki *et al*., 2023) [50, 52], while some microbial candidates (actinobacteria) based inoculants have shown promise in stress mitigation (Wang *et al*., 2023; Yandigeri *et al*., 2012) [61, 65]. Nitrogen fixing bacteria enhance nitrogen fixation and crop productivity in non-leguminous and leguminous plants (Malviya *et al*., 2021; Solanki *et al*., 2020; Singh R. K. *et al*., 2014; Solanki *et al*., 2019) [20, 40, 36, 46]. Overall, microbial inoculants are now considered vital alternatives to chemical inputs (Patil and Solanki, 2016) [27]. Endophytic microbes, PGPR, and mycorrhizal associations contribute to plant protection and yield stability (Solanki *et al*., 2022; Rai and Solanki, 2023; Verma P. *et al*., 2020; Kashyap B. K. *et al*., 2019) [49, 29, 59, 13]. The broader role of plant microbiomes extends beyond root associations to overall plant health (Singh M. P. *et al*., 2020; Singh P. *et al*., 2019) [33, 35], with sequencing studies revealing high microbial diversity and synergistic interactions that support crop sustainability (Malviya *et al*., 2022; Verma K. K. *et al*., 2024) [21, 58]. Collectively, these studies provide the scientific foundation for integrating hydrogels and foliar nutrition with biological inputs in chickpea farming under rainfed conditions. India, with its predominantly vegetarian population, relies heavily on pulses as a crucial source of high-quality protein. The country is a global leader in pulse production, consumption, and import, contributing to 25% of the world's total pulse production and utilizing 35% of the global pulse area (FAO, 2017) [9]. Beyond providing affordable protein, legumes offer several agricultural benefits, such as improving soil fertility and structure, and serving as excellent components in intercropping, crop rotation, and dry farming systems. They also provide green pods for vegetables and nutritious fodder for livestock. By 2050, India is projected to need 39 million tons of pulses, necessitating an annual growth rate of 2.2% in production to meet the increasing demand (Murugananthi *et al*. 2024) [23].

The chickpea (*Cicer arietinum L.*), also known as gram or Bengal gram, is a key cool-season legume of the Fabaceae family and a staple crop in India (Merga & Haji, 2019) [22]. Its indeterminate growth habit and robust taproot system with extensive lateral branches make it well-suited for various growing conditions. The roots of the chickpea plant are rich in bacterial nodules, which are vital for atmospheric nitrogen fixation, contributing up to 140 kg ha-1 and significantly enhancing soil fertility. With a protein content of 21%, along with being a good source of carbohydrates, minerals, and trace elements, chickpea is a crucial source of nutrition, especially for low-income populations in semi-arid tropical areas where it serves as a protein alternative to meat (Kushwah *et al*. 2020) [17].

India is the world's largest chickpea producer, responsible for 64% of global production (Gaur *et al* 2007) [11]. Chickpea accounts for approximately 30% of the total pulse area and 40% of the nation's total pulse production (Gaur *et al* 2007) [11]. It is the second most cultivated grain legume by smallholder farmers in semi-arid regions worldwide (Varshney *et al*. 2013) [56]. According to the Agricultural Statistics at a Glance 2023 (Ministry of Agriculture & Farmers Welfare), India's total foodgrain production for 2022-23 reached approximately 329.69 million tonnes, with an estimated net sown area of 141.01 million hectares—yielding an average productivity of around 2,339 kg per hectare. In Madhya Pradesh, specifically for the chickpea (gram) crop in the same period, the cultivated area was 21.08 lakh hectares, production stood at 30.95 lakh tonnes, and the average yield was 1,468 kg/ha (https://dpd.gov.in). Chickpea is predominantly grown as a rainfed crop, a practice that plays a significant role in India's agriculture and economy. However, rainfed farming is often limited by inefficient water use, making it crucial to implement strategies that protect crops from drought stress and improve soil water conservation. An essential step toward increasing rainfed productivity is to enhance the soil's capacity to store water and enable the crop to use this stored water more efficiently (Shideed, 2017) [32].

Sustainable crop production is increasingly recognized as critical for soil-plant health, particularly under rainfed conditions. Rhizosphere engineering, seed development research, and microbial inoculants have gained prominence for their roles in nutrient acquisition, stress resilience, and plant fitness (Solanki *et al*., 2024; Kumar *et al*., 2024) [51, 16]. Organic inputs such as compost, farmyard manure, Jeevamrit, and Panchagavya are known to enrich beneficial microbial populations, improve soil fertility, and act similarly to plant growth-promoting rhizobacteria (PGPR) (Kumari *et al*., 2019; Kashyap *et al*., 2019; Patil & Solanki, 2016) [15, 14, 27]. Bacilli associated with the chickpea rhizosphere exhibit multifarious plant growth-promoting traits, including pathogen suppression and yield enhancement (Solanki *et al*., 2014; Solanki *et al*., 2012) [43, 42]. Likewise, intercropping systems with legumes such as sugarcane-chickpea improve soil microbiomes, enhance diazotrophic activity, and contribute to long-term nutrient cycling (Solanki *et al*., 2016; Malviya *et al*., 2021; Solanki *et al*., 2018) [44, 20, 45]. Biofilm-forming bacteria, endophytes, and actinobacteria further support stress tolerance, nodulation, and nutrient mobilization, highlighting the broader role of the plant microbiome in agricultural sustainability (Yandigeri *et al*., 2012; Wang *et al*., 2023; Solanki *et al*., 2020; Solanki *et al*., 2022) [65, 61, 41, 49]. Collectively, these studies confirm that microbial inoculants, mycorrhizal associations, and bio-based formulations are promising alternatives to chemical fertilizers and pesticides (Rai *et al*., 2019; Patil & Solanki, 2016) [29, 27].

Despite these biological innovations, rainfed chickpea remains vulnerable to erratic rainfall and limited soil moisture. Improving soil water retention is therefore a key priority for enhancing productivity. A promising solution is the application of hydrogel, a water-absorbing polymer. These cross-linked polymers can absorb an impressive 400 times their dry weight in water and release it slowly as needed by the plant (Behera and Mahanwar, 2020) [4]. By incorporating hydrogel into the soil before sowing, it can retain substantial amounts of water and nutrients, which are then made available to the plant, thereby delaying the permanent wilting point and reducing the need for frequent irrigation. This technique has been shown to improve plant growth even with a limited supply of water and nutrients (Kumar *et al*. 2020) [15].

Another modern crop management technique is foliar nutrition, which involves spraying a liquid fertilizer directly onto the plant canopy. This method is highly efficient, requiring smaller quantities of fertilizer and ensuring that nutrients are supplied directly to the plant (Singh *et al*. 2013). Foliar application of water-soluble fertilizers and bioregulators can enhance crop growth by acting as chemical catalysts that improve physiological and reproductive efficiency (Takankhar *et al*. 2017) [53]. These applications may also boost gene expression for efficient sucrose transport and increase dry matter partitioning, which ultimately leads to higher grain production. By applying water-soluble fertilizers at critical growth stages, nutrient deficiencies and heat stress can be effectively mitigated.

The combined use of hydrogel and foliar nutrition presents a potential strategy to improve photosynthesis, assimilate partitioning, and overall growth and yield of chickpeas under rainfed conditions. This study was conducted during the 2023-24 rabi season to achieve the following objectives: To study the effect of hydrogel application on the growth and yield of chickpea. To identify the most effective source of nutrients through foliar application in chickpea. To evaluate the economic viability of the different treatments.

2. Methods and Materials

2.1 Experimental Site and Climate

Situated at 23.1866° N, 77.3297° E in experimental field of IES University, Bhopal, Madhya Pradesh, the climate features an average annual precipitation of approximately 1,040 mm, largely concentrated during the monsoon months of June through September. In 2023, the region experienced a maximum temperature of 42.8 °C and a minimum low of 6 °C (www.tutiempo.net).

2.2 Soil Characteristics and Field History

The experimental field, located in the IES University, Bhopal region of Madhya Pradesh, had medium to deep black clay loam soil (Vertisols) with a gentle slope from west to east, ensuring good natural drainage. Composite soil samples were randomly collected from the 0-30 cm depth using a screw-type soil auger to assess the initial fertility status. The analysis revealed that the soil was low in available nitrogen (around 190-195 kg ha^{-1}), medium in available phosphorus (14.5-15.0 kg ha^{-1}), and high in available potassium (370-385 kg ha⁻¹). The soil reaction was near neutral with a pH of 7.4, and the electrical conductivity was 0.7 dS m⁻¹, indicating non-saline conditions. The field had a history of a soybean-chickpea cropping system for the past five years, consistent with the dominant pulse-oilseed rotation practiced in this agro-climatic zone.

2.3 Experimental Design and Treatments

The experiment was laid out in a split-plot design with three replications, comprising a total of 18 treatment plots. The main plot factor was hydrogel application at two levels: no hydrogel (control, H_0) and hydrogel at 5 kg ha⁻¹ (H_1). The sub-plot factor was foliar nutrition at three levels: water spray (control, F_1), urea at 2% (F_2), and thiourea at 500 ppm (F_3). This arrangement resulted in six treatment combinations: T_1 (H_0F_1) - no hydrogel with water spray, T_2 (H_0F_2) - no hydrogel with urea 2%, T_3 (H_0F_3) - no hydrogel with thiourea 500 ppm, T_4 (H_1F_1) - hydrogel with water spray, T_5 (H_1F_2) - hydrogel with urea 2%, and T_6 (H_1F_3) - hydrogel with thiourea 500 ppm. The gross plot size was 5.0 m × 3.0 m, with a net plot size of 4.0 m × 2.4 m, and spacing of 1.0 m between plots and 1.5 m between replications.

2.4 Crop and Field Management

The experiment was conducted using the chickpea variety RVG 210 (Raj Vijay Gram 210), a semi-spreading, large-seeded desi type. Field preparation involved one plowing with a disc harrow followed by one cross plowing with a cultivator and subsequent planking to obtain a fine seedbed. A recommended basal fertilizer dose of 20:40:20:20 kg N: P_2O_5:K_2O:S ha⁻¹ was applied uniformly to all plots through DAP, MOP, and bentonite sulphur. Manual sowing was carried out on November 7, 2023, at a seed rate of 80 kg ha⁻¹ with 30 cm row spacing. Seeds were treated with *Rhizobium ciceri* and Phosphate Solubilizing Bacteria (*Bacillus* sp.) @ 5 g kg⁻¹ seed, Thiram @ 2 g kg⁻¹ seed, Vitavax @ 2 g kg⁻¹ seed, and Mo @ 2 g kg⁻¹ seed. The hydrogel treatments (H_0 - no hydrogel, H_1 - hydrogel @ 5 kg ha⁻¹) were incorporated by drilling into the soil prior to sowing. Foliar nutrition treatments (F_1 - water spray, F_2 - urea 2%, F_3 - thiourea 500 ppm) were applied with a hand sprayer at two key growth stages: flowering initiation on December 31, 2023 (54 DAS) and pod development on January 30, 2024 (84 DAS). Plant protection measures included a single spray of Profenofos 40% + Cypermethrin 4% EC to control cutworm and pod borer infestations.

2.5 Data Collection and Statistical Analysis

Observations were recorded on three randomly tagged plants in each plot. Morphological parameters such as plant height (cm), number of branches per plant, dry matter accumulation per plant (g), and root nodule number and dry weight (g) were measured. Physiological parameters, including crop growth rate (CGR) and relative growth rate (RGR), were calculated using the formulas proposed by Watson (1952) [62] and Blackman (1919) [5], respectively. Yield attributes and yield data included the number of pods per plant, number of seeds per pod, 100-seed weight (g), biological yield (kg ha⁻¹), grain yield (kg ha⁻¹), and straw yield (kg ha⁻¹). Economic analysis was carried out by estimating the cost of cultivation, gross returns, net returns, and benefit-cost (B\:C) ratio for each treatment. All collected data were statistically analyzed using Analysis of Variance (ANOVA) for a split-plot design, as described by Gomez and Gomez (1984) [12]. The significance of treatment effects was tested using the F-test at a 5% probability level, and Standard Error of the Mean (SEm±) along with Critical Differences (C.D.) were computed to compare treatment means.

3. Results

The effects of experimental variables are presented in the order in which they appear in the analysis of variance (ANOVA) tables: (1) Hydrogel application (2) Foliar nutrition applied at flower initiation and pod development stages (3) Their interaction (Hydrogel × Foliar Nutrition). Only those treatments showing statistically significant differences are discussed in detail, to provide a concise understanding of the trends observed.

3.1 Growth Attributing Parameters

3.1.1 Plant Population: Plant population was recorded at 30 DAS and at maturity. Statistical data are presented in Table 1. The ANOVA revealed that hydrogel and foliar nutrition had no significant effect on plant population at either stage. Among hydrogel treatments, H_1 (5 kg ha⁻¹) recorded a slightly higher plant population compared to H_0. Across foliar treatments, F_2 (Urea 2%) recorded the highest plant populations, whereas the lowest values were recorded in F_1 (water spray/control). Interaction effects were non-significant.

Table 1: Effect of hydrogel and foliar nutrition on plant population at initial and maturity stages of chickpea.

Treatments	Plant population (number of plant m²)	
	30 DAS	At maturity
Hydrogel application		
H0: - 0 kg ha⁻¹ (control)	36.5	35.8
H1: - 5 kg ha⁻¹	38.9	37.9
S.Em. (±)	0.45	0.4
CD at 5%	NS	NS
Sub Plot: Foliar nutrition		
F1: - Water spray (Control)	35.8	34.7
F2: - Urea 2%	38.7	37.8
F3: - Thiourea 500 ppm	39.5	38.6
S.Em. (±)	0.65	0.6
CD at 5%	NS	NS
Interaction: Hydrogel × Foliar nutrition		
S.Em. (±)	0.95	0.9
CD at 5%	NS	NS

3.1.2 Plant Height: Plant height was measured at 30, 50, and 70 DAS, and at maturity (Table 2). Hydrogel application significantly influenced plant height up to 70 DAS. Application of 5 kg ha⁻¹ hydrogel (H1) recorded higher plant height (16.22, 29.41, and 37.54 cm at 30, 50, and 70 DAS, respectively) compared to control (15.37, 28.19, and 36.06 cm). At maturity, differences were non-significant.

Table 2: Effect of hydrogel and foliar nutrition on plant height at different growth and maturity stages of chickpea

Treatments	Plant height plant⁻¹ (cm)			
	30 DAS	50 DAS	70 DAS	At maturity
Main plot: Hydrogel application				
H0: - 0 kg ha⁻¹(control)	15.37	28.19	36.06	43.66
H1: - 5 kg ha⁻¹	16.22	29.41	37.54	44.11
S.Em. (±)	0.02	0.01	0.03	0.13
CD at 5%	0.16	0.09	0.24	NS
Sub Plot: Foliar nutrition				
F1: - Water spray (Control)	15.40	28.47	34.52	41.27
F2: - Urea 2%	16.09	29.45	37.05	44.28
F3: - Thiourea 500 ppm	15.68	27.92	36.25	42.87
S.Em. (±)	0.37	0.66	0.61	0.89
CD at 5%	NS	NS	1.84	2.68
Interaction: Hydrogel × Foliar nutrition				
S.Em. (±)	0.53	0.94	0.86	1.26
CD at 5%	NS	NS	NS	NS

Among foliar nutrition treatments, urea 2% spray (F2) produced maximum height (16.09, 29.45, 37.05, and 44.28 cm at successive stages), followed by thiourea 500 ppm (F3), and whereas the control water spray (F1) showed the lowest values. Significant differences were observed only at 70 DAS and maturity. The interaction between hydrogel and foliar nutrition was found non-significant at all growth stages.

3.1.3 Number of Branches per Plant: Branch numbers were recorded at 30, 50, and 70 DAS, and at maturity (Table 3). Application of hydrogel at 5 kg ha⁻¹ (H_1) significantly increased the number of branches at 30 and 50 DAS (1.44 and 2.66, respectively) compared to control (H_0: 0.96 and 2.17). Foliar nutrition treatments were non-significant at early stages but at 70 DAS and maturity, urea 2% recorded the highest branches (4.33), followed by thiourea 500 ppm (3.72), over water spray control (3.16). Interaction effects were non-significant at all stages.

Table 3: Effect of hydrogel and foliar nutrition on number of branches at different growth and maturity stages of chickpea.

Treatments	Number of branches plant^{-1} (No)			
	30 DAS	50 DAS	70 DAS	At maturity
Main plot: Hydrogel application				
H0: - 0 kg ha^{-1}(control)	0.96	2.17	3.93	3.93
H1: - 5 kg ha^{-1}	1.44	2.66	4.24	4.24
S.Em. (±)	0.01	0.02	0.03	0.03
CD at 5%	0.11	0.15	NS	NS
Sub Plot: Foliar nutrition				
F1: - Water spray (Control)	1.24	2.33	3.16	3.16
F2: - Urea 2%	1.00	2.63	4.33	4.33
F3: - Thiourea 500 ppm	1.52	2.49	3.72	3.72
S.Em. (±)	0.23	0.21	0.27	0.27
CD at 5%	NS	NS	0.83	0.83
Interaction: Hydrogel × Foliar nutrition				
S.Em. (±)	0.33	0.31	0.39	0.39
CD at 5%	NS	NS	NS	NS

3.1.4 Dry Weight per Plant: Dry matter accumulation was significantly influenced by hydrogel at 30 and 50 DAS but not at 70 DAS or maturity (Table 4). The application of hydrogel at 5 kg ha⁻¹ consistently increased the dry weight of plants at all growth stages compared to the control. Significant differences observed at 30 and 50 DAS, but not at later stages. Among foliar nutrition treatments, 2% urea resulted in the highest dry weight, especially at 70 DAS and maturity, followed by thiourea (500 ppm), while water spray showed the lowest values. The interaction between hydrogel and foliar nutrition was statistically non-significant at all stages.

Table 4: Effect of hydrogel and foliar nutrition on dry weight plant at different growth and maturity stages of chickpea.

Treatments	Dry weight plant^{-1} (g)			
	30 DAS	50 DAS	70 DAS	At maturity
Main plot: Hydrogel application				
H0: - 0 kg ha^{-1}(control)	0.95	4.28	9.48	26.86
H1: - 5 kg ha^{-1}	1.61	4.73	10.40	28.24
S.Em. (±)	0.01	0.01	0.10	0.36
CD at 5%	0.14	0.09	NS	NS
Sub Plot: Foliar nutrition				
F1: - Water spray (Control)	1.33	4.41	8.33	24.40
F2: - Urea 2%	0.99	5.03	10.06	28.56
F3: - Thiourea 500 ppm	1.58	4.48	9.21	26.13
S.Em. (±)	0.19	0.40	0.65	1.31
CD at 5%	NS	NS	1.97	3.95
Interaction: Hydrogel × Foliar nutrition				
S.Em. (±)	0.27	0.57	0.93	1.86
CD at 5%	NS	NS	NS	NS

3.1.5 Number of Root Nodules per Plant: Root nodules were counted at 40 and 60 DAS (Table 5). Hydrogel significantly influenced nodule number at both stages. H_1 recorded higher counts (18.41 and 22.75) than H_0 (15.50 and 20.56). Among foliar treatments, the lowest nodule numbers (15.90 and 20.73) were recorded in F_3 (Thiourea 500 ppm). Interactions were non-significant.

3.1.6 Dry Weight of Root Nodules: Dry weight of root nodules was recorded at 40 and 60 DAS (Table 5). Hydrogel application at 5 kg ha⁻¹ significantly increased the number of root nodules at both 40 and 60 DAS compared to the control, while the dry weight of root nodules was higher at both stages but statistically significant only at 40 DAS. Among foliar nutrition treatments, 2% urea recorded the highest values for both nodule number and dry weight, followed by thiourea (500 ppm), though differences were statistically non-significant. The interaction effect between hydrogel and foliar nutrition was also non-significant for all parameters.

Table 5: Effect of hydrogel and foliar nutrition on number of root nodules plant and dry weight of root nodules plant at different growth stages of chickpea.

Treatments	Number of root nodules plant^{-1}		Dry weight of root nodules plant-^{1} (mg)	
	40 DAS	60 DAS	40 DAS	60 DAS
Main plot: Hydrogel application				
H0: - 0 kg ha^{-1}(control)	15.35	20.35	40.07	49.63
H1: - 5 kg ha^{-1}	18.23	22.52	45.94	53.06
S.Em. (±)	0.11	0.09	0.15	0.97
CD at 5%	0.63	0.54	0.92	NS
Sub Plot: Foliar nutrition				
F1: - Water spray (Control)	16.41	21.36	41.91	49.17
F2: - Urea 2%	17.02	22.46	46.04	50.49
F3: - Thiourea 500 ppm	15.74	20.52	41.58	52.30
S.Em. (±)	0.80	0.80	3.97	4.46
CD at 5%	NS	NS	NS	NS
Interaction: Hydrogel × Foliar nutrition				
S.Em. (±)	1.13	1.14	5.61	6.31
CD at 5%	NS	NS	NS	NS

3.2 Physiological Parameters

3.2.1 Crop Growth Rate (CGR) and Relative Growth Rate (RGR): Hydrogel application at 5 kg ha⁻¹ showed slightly higher crop growth rate (12.47 g m⁻² day⁻¹ at 50-70 DAS) compared to control, but the differences were statistically non-significant. Among foliar nutrition treatments, 2% urea recorded the highest crop growth rate (8.89 g m⁻² day⁻¹ at 30-50 DAS and 11.06 g m⁻² day⁻¹ at 50-70 DAS) and relative growth rate (0.055 g g⁻¹ day⁻¹ at 30-50 DAS), with significant improvement in crop growth rate during 50-70 DAS and RGR during 50-71 DAS. Interaction effects were non-significant (Table 6).

Table 6: Effect of hydrogel and foliar nutrition on crop growth rate at different growth of chickpea.

Treatments	Crop growth rate (g $m^{-2}day^{-1}$)		Relative growth rate (g g^{-1} day^{-1})	
	30-50 Days interval	50-70 Day interval	30-50 Days interval	50-70 Day interval
Main plot: Hydrogel application				
H0: - 0 kg ha^{-1}(control)	7.33	11.44	0.050	0.034
H1: - 5 kg ha^{-1}	6.86	12.47	0.039	0.035
S.Em. (±)	0.09	0.28	0.001	0.001
CD at 5%	NS	NS	NS	NS
Sub Plot: Foliar nutrition				
F1: - Water spray (Control)	6.77	8.64	0.045	0.027
F2: - Urea 2%	8.89	11.06	0.055	0.030
F3: -Thiourea 500 ppm	6.40	10.40	0.038	0.031
S.Em. (±)	1.03	1.58	0.006	0.004
CD at 5%	NS	4.74	NS	0.01
Interaction: Hydrogel × Foliar nutrition				
S.Em. (±)	1.46	2.24	0.009	0.006
CD at 5%	NS	NS	NS	NS

3.2.2 Yield Attributing Parameters: The study evaluated the effect of hydrogel application and foliar nutrition on yield-attributing traits in the crop. Hydrogel at 5 kg ha⁻¹ (H_1) recorded slightly higher values for number of pods plant⁻¹ (49.04), number of seeds pod⁻¹ (1.28), grain yield plant⁻¹ (8.28 g), and seed index (21.36 g) compared to the control (H_0). Among foliar nutrition treatments, 2% urea (F_2) produced the highest number of pods plant⁻¹ (50.97), grain yield plant⁻¹ (7.92 g), and seed index (21.89 g), followed by thiourea 500 ppm (F_3), while water spray control (F_1) gave the lowest values. The interaction between hydrogel and foliar nutrition was not statistically significant for any parameter, and most differences were non-significant except for number of pods plant⁻¹ and seed index in foliar nutrition treatments (Table 7).

Table 7: Effect of hydrogel and foliar nutrition on number of pods plant, number of seeds pod, grain yield plant, seed index, of chickpea.

Treatments	Yield attributing			
	Number of pods $plant^{-1}$	Number of seeds pod^{-1}	Grain yield $plant^{-1}$(g)	Seed index (g)
Main plot: Hydrogel application				
H0: - 0 kg ha^{-1}(control)	47.91	1.26	7.60	20.78
H1: - 5 kg ha^{-1}	49.04	1.28	8.28	21.36
S.Em. (±)	0.83	0.002	0.13	0.09
CD at 5%	NS	NS	NS	NS
Sub Plot: Foliar nutrition				
F1:-Water spray (Control)	40.23	1.236	6.17	18.45
F2: - Urea 2%	50.97	1.281	7.92	21.89
F3: - Thiourea 500 ppm	46.50	1.271	6.86	20.75
S.Em. (±)	3.04	0.020	0.85	0.80
CD at 5%	12.88	NS	2.54	2.41
Interaction: Hydrogel × Foliar nutrition				
S.Em. (±)	4.30	0.029	1.20	1.14
CD at 5%	NS	NS	NS	NS

3.3 Yield and Harvest Index

3.3.1 Grain, Haulm, and Biological Yield per Plot: The application of hydrogel at 5 kg ha⁻¹ (H1) slightly improved biological yield (2.40 kg plot⁻¹), grain yield (1.06 kg plot⁻¹), and haulm yield (1.34 kg plot⁻¹) compared to the control (H0), though differences were statistically non-significant. Among foliar nutrition treatments, urea 2% (F2) recorded the highest biological yield (2.40 kg plot⁻¹) and grain yield (1.07 kg plot⁻¹), significantly surpassing the water spray control (F1) for these parameters, while haulm yield differences remained non-significant. No significant interaction effects were observed between hydrogel application and foliar nutrition (Table 8).

Table 8: Effect of hydrogel and foliar nutrition on biological yield plot, Grain yield plot, and Haulm yield plot of chickpea.

Treatments	Yield attributing characters		
	Biological yield per plot (kg)	Grain yield per plot (kg)	Haulm yield per plot (kg)
Main plot: Hydrogel application			
H0: - 0 kg ha^{-1}(control)	2.28	1.01	1.28
H1: - 5 kg ha^{-1}	2.40	1.06	1.34
S.Em. (±)	0.03	0.015	0.017
CD at 5%	NS	NS	NS
Sub Plot: Foliar nutrition			
F1: - Water spray (Control)	2.03	0.87	1.16
F2: - Urea 2%	2.40	1.07	1.34
F3: - Thiourea 500 ppm	2.25	0.98	1.27
S.Em. (±)	0.13	0.054	0.079
CD at 5%	0.38	0.162	NS
Interaction: Hydrogel × Foliar nutrition			
S.Em. (±)	0.18	0.076	0.112
CD at 5%	NS	NS	NS

3.3.2 Grain, Haulm, and Biological Yield per Hectare: The results indicated that hydrogel application at 5 kg ha^{-1} (H1) recorded slightly higher biological yield (2497.77 kg ha^{-1}), grain yield (1106.82 kg ha^{-1}), and haulm yield (1390.95 kg ha^{-1}), and harvest index (43.97%) compared to the control (H0), though the differences were statistically non-significant. Among foliar nutrition treatments, urea 2% (F2) produced the highest biological yield (2500.74 kg ha^{-1}), grain yield (1111.77 kg ha^{-1}), haulm yield (1388.97 kg ha^{-1}), and harvest index (44.31%), which were significantly superior to the control (F1) in biological and grain yields. Thiourea 500 ppm (F3) also improved yield attributes over the control but was inferior to urea 2%. Interaction effects between hydrogel and foliar nutrition treatments were statistically non-significant for all parameters (Table 9).

Table 9: Effect of hydrogel and foliar nutrition on biological yield, Grain yield, Haulm yield, Harvest index of chickpea.

Treatments	Biological, Grain, Haulm and Harvest index			
	Biological yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Harvest index (%)
Main plot: Hydrogel application				
H0: - 0 kg ha^{-1}(control)	2374.02	1047.42	1326.60	43.65
H1: - 5 kg ha^{-1}	2497.77	1106.82	1390.95	43.97
S.Em. (±)	32.60	15.79	11.23	0.033
CD at 5%	NS	NS	NS	NS
Sub Plot: Foliar nutrition				
F1: - Water spray (Control)	2115.63	908.82	1205.82	42.60
F2: - Urea 2%	2500.74	1111.77	1388.97	44.31
F3: - Thiourea 500 ppm	2339.37	1021.68	1317.69	43.28
S.Em. (±)	131.58	56.33	52.56	0.76
CD at 5%	394.50	168.88	NS	NS
Interaction: Hydrogel × Foliar nutrition				
S.Em. (±)	186.08	79.67	74.33	1.08
CD at 5%	NS	NS	NS	NS

3.3.3 Economics: Higher costs were incurred under H_1 (₹26,071 ha^{-1}) compared to H_0 (₹22,291 ha^{-1}). Across foliar nutrition treatments, F_5 recorded the highest cost (₹24,454 ha^{-1}), and F_1 the lowest (₹23,974 ha^{-1}). H_1 recorded higher gross returns (₹58,420 ha^{-1}) than H_0 (₹55,505 ha^{-1}). With respect to foliar application, F_5 recorded the highest (₹65,856 ha^{-1}) and F_1 the lowest (₹48,030 ha^{-1}). H_0 recorded a slightly higher net return (₹33,213 ha^{-1}) than H_1 (₹32,350 ha^{-1}). Considering foliar treatments, F_5 recorded the highest (₹41,402 ha^{-1}) and F_1 the lowest (₹24,506 ha^{-1}). The maximum B\:C ratio was recorded in H_0 (2.49) compared to H_1 (2.24). When comparing foliar nutrition sources, F_5 recorded the highest B\:C ratio (2.70), while F_1 recorded the lowest (2.01).

4. Discussion

This discussion interprets the results of the study on the effects of hydrogel and foliar nutrition on rainfed chickpea, comparing them with existing research to explain the observed outcomes. The improvements in nodulation, dry matter accumulation, and grain yield observed in this study are consistent with earlier reports highlighting the role of diazotrophs and PGPR in enhancing drought tolerance, nutrient uptake, and growth in different crops (Nong *et al*., 2023; Singh P. *et al*., 2023; Singh R. K. *et al*., 2020) [24, 34, 37]. Beneficial endophytes such as *Burkholderia* and *Streptomyces* improve crop resilience under abiotic stress (Malviya *et al*., 2018; Wang *et al*., 2018) [19, 60], while transcriptomic analyses confirm that hormone signaling and gene regulation underlie these microbial-plant interactions (Nong *et al*., 2022; Li *et al*., 2021) [25, 18]. Agronomic interventions that enhance nitrogen use efficiency mirror the yield benefits recorded with foliar feeding (Chattha *et al*., 2022; Pang *et al*., 2022) [8, 26], and complementary roles of mycorrhizae, biofilm-forming bacteria, and *Trichoderma* further validate eco-biological strategies for sustainable agriculture (Solanki *et al*., 2021; Solanki *et al*., 2020; Solanki *et al*., 2019) [48, 40, 46]. *Bacillus*-based antagonists and co-inoculation approaches have shown potential in suppressing soil-borne pathogens (Solanki *et al*., 2012; Solanki *et al*., 2014; Solanki *et al*., 2019) [42, 43, 47], while recent studies report root rot and *Rhizoctonia* as major constraints in legumes under climate variability (Abbas *et al*., 2022; Akber *et al*., 2022) [1, 2]. Mycoremediation and stress-adaptive microbes such as salt-tolerant *Trichoderma* demonstrate additional avenues for resilience building (Kashyap P. L. *et al*., 2019) [13], and proteomic evidence confirms the activation of defense mechanisms during biotic stress (Singh P. *et al*., 2019) [39]. Taken together, these findings support our conclusion that hydrogel application combined with foliar nutrition represents a synergistic and cost-effective strategy, aligning with microbial-based approaches for enhancing chickpea productivity under rainfed conditions.

4.1 Effect on Growth Parameters

Plant growth is a complex process influenced by environmental and management factors. Our findings show that both hydrogel and foliar nutrition positively affected chickpea growth parameters, including plant height, branching, dry weight, and root nodules.

The application of hydrogel at 5 kg ha^{-1} had a significant positive impact on growth parameters up to 50 DAS. This is likely because hydrogels improve the soil's water-holding capacity, creating a buffered environment that reduces drought stress and helps the plants establish a strong root system during the early growth phase (Boatright *et al*., 1997; Borivoj *et al*., 2006) [6, 7]. This aligns with the findings of Woodhouse and Johnson (1991) [63], who noted that superabsorbent polymers enhance water consumption and dry matter production.

Foliar nutrition, applied at the flowering and pod development stages, also positively influenced growth, particularly at 70 DAS and maturity. It consistently led to taller plants, more branches, and greater dry weight. This could be due to the immediate availability of nutrients, which delays senescence and supports continued vegetative and reproductive growth. Similar results were reported by Takankhar *et al*. (2017) [53], who found that NPK foliar sprays improved chickpea growth parameters.

4.2 Effect on Physiological Parameters

The study recorded significant changes in physiological parameters like Crop Growth Rate (CGR) and Relative Growth Rate (RGR). At 30-50 DAS, the control (H0) showed a higher CGR and RGR, but this trend reversed later, with the hydrogel treatment (H1) showing better growth rates from 50-70 DAS. This suggests that the benefits of hydrogel become more pronounced as the crop matures and water availability becomes a limiting factor.

Foliar nutrition significantly affected RGR and CGR from 50-70 DAS. NPK (19:19:19) 0.5% increased CGR, while Salicylic acid 100 ppm increased RGR. This supports the findings of Rehman *et al*. (2011) [30] and Yadav (2015) [64], who noted that bioregulators like salicylic acid can significantly improve physiological parameters and yield in chickpea by enhancing photosynthetic activity.

4.3 Effect on Yield and Economic Parameters

Yield is a direct result of a plant's physiological and biomass-producing processes. Our results show that while hydrogel had a non-significant effect on most yield attributes, it did result in higher values for pods per plant, seeds per pod, and grain per plant compared to the control. These results are consistent with Farjam *et al*. (2014) [10] and Allahyari *et al*. (2013) [3], who found that superabsorbent polymers increased pod numbers in chickpea.

Foliar nutrition significantly improved yield attributes, with NPK (19:19:19) 0.5% and Thiourea 500 ppm yielding the highest number of pods and grain per plant. This is because foliar sprays provide a rapid, efficient supply of nutrients during critical growth stages, directly boosting crop productivity (Venkatesh *et al*., 2012) [57]. For example, Thiourea acts as a cytokinin, delaying senescence and allowing more time for grain filling (Premaradhya *et al*., 2018) [28].

In terms of overall yield, while hydrogel's effect was not statistically significant, the H1 treatment did produce a higher average grain yield (1118 kg ha^{-1}) than the control (1058 kg ha^{-1}). This aligns with Shankarappa *et al*. (2020) [31], who reported similar yield increases with hydrogel in other crops.

Economically, NPK (19:19:19) 0.5% emerged as the most profitable treatment, providing the highest net returns (₹41,402 ha^{-1}) and a superior B:C ratio (2.70). This is attributed to the increased yield outweighing the cost of the treatment. Conversely, despite higher gross returns, the high cost of the hydrogel treatment (H1) led to a lower net return and B:C ratio compared to the control (H0). These results emphasize the importance of balancing input costs with yield gains for practical farm recommendations.

References

1. Abbas A, Mubeen M, Sohail MA, Solanki MK, *et al*. Root rot a silent alfalfa killer in China: Distribution, fungal, and oomycete pathogens, impact of climatic factors and its management. Front Microbiol. 2022;13:961794.
2. Akber MA, Mubeen M, Sohail MA, Khan SW, Solanki MK, *et al*. Global distribution, traditional and modern detection, diagnostic, and management approaches of *Rhizoctonia solani* associated with legume crops. Front Microbiol. 2022. doi:10.3389/fmicb.2022.1091288.
3. Allahyari MS, Damalas CA, Khademian R. Superabsorbent polymers and their applications in agriculture. J Agric Sci Technol. 2013;15(6):1253-66.
4. Behera S, Mahanwar PA. Superabsorbent polymers in agriculture and other applications: A review. Polym-Plast Technol Mater. 2020;59(4):341-56. doi:10.1080/25740881.2019.16472399.
5. Blackman VH. The compound interest law and plant growth. Ann Bot. 1919;33(131):353-60.
6. Boatright JL, Baligar VC, Maranville JW. Impact of water stress on water use efficiency and nitrogen use in sorghum. Commun Soil Sci Plant Anal. 1997;28(13-14):1133-41. doi:10.1080/00103629709369854.
7. Borivoj L, Zivanovic L, Dragana K. The use of hydrogels in agriculture. Agric Eng. 2006;31(1):17-24.
8. Chattha MS, Ali Q, Haroon M, Afzal MJ, Javed T, Hussain S, *et al*. Enhancement of nitrogen use efficiency through agronomic and molecular based approaches in cotton. Front Plant Sci. 2022;13:3380. doi:10.3389/fpls.2022.994306.
9. Food and Agriculture Organization. Food and agriculture organization corporate statistical database: Hazelnut production quantities by country, 2017. 2017.
10. Farjam S, Boroomand Nasab S, Alami Saeid K. The effect of superabsorbent polymer on yield and yield components of chickpea under different irrigation regimes. Int J Adv Biol Biomed Res. 2014;2(3):773-81.
11. Gaur PM, Pande S, Sharma HC, Gowda CLL, Sharma KK, Crouch JH, *et al*. Genetic enhancement of stress tolerance in chickpea: Present status and future prospects. Euphytica. 2007;157(1-2):85-94. doi:10.1007/s10681-007-9401-5.
12. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. John Wiley & Sons; 1984.
13. Kashyap BK, Solanki MK, *et al*. Bacillus as plant growth-

promoting rhizobacteria (PGPR): A Promising Green Agriculture Technology. In: Ansari RA, Mahmood I, editors. Plant Health Under Biotic Stress. Springer; 2019. doi:10.1007/978-981-13-6040-4_11.

14. Kashyap PL, Solanki MK, *et al*. Biocontrol potential of salt-tolerant Trichoderma and Hypocrea isolates for the management of tomato root rot under saline environment. J Soil Sci Plant Nutr. 2019. doi:10.1007/s42729-019-00114-y.
15. Kumar A, Solanki MK, Wang Z, Solanki AC, Singh VK, Divvela PK. Revealing the seed microbiome: Navigating sequencing tools, microbial assembly, and functions to amplify plant fitness. Microbiol Res. 2024;279:127549.
16. Kumar R, Yadav S, Singh V, Kumar M, Kumar M. Hydrogel and its effect on soil moisture status and plant growth: A review. J Pharmacogn Phytochem. 2020;9(3):1746-53.
17. Kushwah A, Bindra S, Singh I, Dixit GP, Sharma P, Srinivasan S, *et al*. Advances in chickpea breeding and genomics for varietal development and trait improvement in India. In: Accelerated plant breeding, volume 3: Food legumes. Springer International Publishing; 2020. p. 31-66. doi:10.1007/978-3-030-41866-3_2.
18. Li C, Wang Z, Nong Q, Lin L, Xie J, Mo Z, *et al*. Physiological changes and transcriptome profiling in Saccharum spontaneum L. leaf under water stress and re-watering conditions. Sci Rep. 2021;11(1):1-14.
19. Malviya MK, Solanki MK, *et al*. Beneficial Linkages of Endophytic Burkholderia anthina MYSP113 towards Sugarcane Growth Promotion. Sugar Tech. 2018. doi:10.1007/s12355-019-00703-2.
20. Malviya MK, Solanki MK, *et al*. Sugarcane-Legume Intercropping Can Enrich the Soil Microbiome and Plant Growth. Front Sustain Food Syst. 2021;5:606595. doi:10.3389/fsufs.2021.606595.
21. Malviya MK, Li CN, Lakshmanan P, Solanki MK, *et al*. High-Throughput Sequencing-Based Analysis of Rhizosphere and Diazotrophic Bacterial Diversity Among Wild Progenitor and Closely Related Species of Sugarcane (Saccharum spp. Inter-Specific Hybrids). Front Plant Sci. 2022;13:829337. doi:10.3389/fpls.2022.829337.
22. Merga B, Haji J. Economic importance of chickpea: Production, value, and world trade. Cogent Food Agric. 2019;5(1):1615718. doi:10.1080/23311932.2019.16157184.
23. Muruganathi D, Shivakumar KM, Palanichamy NV, Prabha SA, Somasundaram E, Rohini A, *et al*. Demand and supply projections for pulses in India. Legume Res. 2024;47(8):1335-41.
24. Nong Q, Lin L, Xie J, Mo Z, Malviya MK, Solanki MK, *et al*. Regulation of an endophytic nitrogen-fixing bacteria GXS16 promoting drought tolerance in sugarcane. BMC Plant Biol. 2023;23(1):573.
25. Nong Q, Malviya MK, Solanki MK, *et al*. Sugarcane root transcriptome analysis revealed the role of plant hormones in the colonization of an endophytic diazotroph. Front Microbiol. 2022. doi:10.3389/FMICB.2022.924283.
26. Pang F, Solanki MK, *et al*. Streptomyces can be an excellent plant growth manager. World J Microbiol Biotechnol. 2022;38(11):1-2.
27. Patil HJ, Solanki MK. Microbial inoculant: Modern era of fertilizers and pesticides. In: Microbial Inoculants in Sustainable Agricultural Productivity. Springer; 2016. p. 319-43.
28. Premaradhya N, Ramesh S, Vageesh TS. Effect of thiourea and salicylic acid on growth and yield of chickpea (*Cicer arietinum* L.). Int J Curr Microbiol Appl Sci. 2018;7(5):2314-20. doi:10.20546/ijcmas.2018.705.270.
29. Rai S, Solanki MK. Beneficial endophytic Trichoderma functions in plant health management. In: Microbial Endophytes and Plant Growth. Academic Press; 2023. p. 233-44.
30. Rehman H, Basra SMA, Afzal I, Farooq M. Seed priming with ascorbic acid improves seedling growth in wheat (*Triticum aestivum* L.) under saline conditions. J Agron Crop Sci. 2011;197(4):284-92. doi:10.1111/j.1439-037X.2010.00464.x.
31. Shankarappa TH, Jagadeesha N, Nagaraj N. Response of maize to application of hydrogel under different levels of irrigation and nitrogen. Int J Curr Microbiol Appl Sci. 2020;9(5):2165-73. doi:10.20546/ijcmas.2020.905.246.
32. Shideed K. Rainfed agriculture and food security in dry areas. In: Water, energy & food sustainability in the Middle East: The sustainability triangle. Springer International Publishing; 2017. p. 299-340. doi:10.1007/978-3-319-48920-9_17.
33. Singh MP, Singh P, Singh RK, Solanki MK, *et al*. Plant Microbiomes: Understanding the Aboveground Benefits. In: Phytobiomes: Current Insights and Future Vistas. Springer; 2020. p. 51-80.
34. Singh P, Singh RK, Li HB, Guo DJ, Sharma A, Verma KK, *et al*. Nitrogen fixation and phytohormone stimulation of sugarcane plant through plant growth promoting diazotrophic Pseudomonas. Biotechnol Genet Eng Rev. 2023;40(1):31-50. doi:10.1080/02648725.2023.2177814.
35. Singh P, Singh RK, Singh MP, Song QQ, Solanki MK, *et al*. Soil: Microbial cell factory for assortment with beneficial role in agriculture. In: Singh DP, *et al*., editors. Microbial Interventions in Agriculture and Environment. Springer; 2019. p. 77-101. doi:10.1007/978-981-13-8391-5_4.
36. Singh RK, Kumar DP, Solanki MK, *et al*. Multifarious plant growth promoting characteristics of chickpea rhizosphere associated Bacilli help to suppress soil-borne pathogens. Plant Growth Regul. 2014;73:91-101.
37. Singh RK, Singh P, Li HB, Song QQ, Guo DJ, Solanki MK, *et al*. Diversity of nitrogen-fixing rhizobacteria associated with Sugarcane: a comprehensive study of plant-microbe interactions for growth enhancement in Saccharum spp. BMC Plant Biol. 2020;20(240). doi:10.1186/s12870-020-02400-9.
38. Singh P, Singh RK, Li HB, Guo DJ, Sharma A, Lakshmanan P, *et al*. Diazotrophic bacteria Pantoea dispersa and Enterobacter asburiae promote sugarcane growth by inducing nitrogen uptake and defense-related gene expression. Front Microbiol. 2020;11:600417.
39. Singh P, Song QQ, Singh RK, Li HB, Solanki MK, *et al*. Proteomic Analysis of the Resistance Mechanisms in Sugarcane during *Sporisorium scitamineum* Infection. Int J Mol Sci. 2019;20(3):569. doi:10.3390/ijms20030569.
40. Solanki MK, *et al*. Assessment of Diazotrophic Proteobacteria in sugarcane rhizosphere when Intercropped with Legumes (Peanut and Soybean) in the Field. Front Microbiol. 2020;11:1814. doi:10.3389/fmicb.2020.01814.
41. Solanki MK, *et al*. Plant and soil-associated biofilm-forming bacteria: Their role in green agriculture. In: New and Future Developments in Microbial Biotechnology and Bioengineering: Microbial Biofilms. Elsevier; 2020. p. 151-

64. doi:10.1016/b978-0-444-64279-0.00012-8.

42. Solanki MK, *et al*. Characterization of mycolytic enzymes of Bacillus strains and their bio-protection role against *Rhizoctonia solani* in tomato. Curr Microbiol. 2012;65(3):330-6.
43. Solanki MK, *et al*. Characterization of antagonistic-potential of two Bacillus strains and their biocontrol activity against *Rhizoctonia solani* in tomato. J Basic Microbiol. 2014;53:1-9.
44. Solanki MK, *et al*. Sugarcane Intercropping Cultivation Influenced the Soil Properties and Enhanced the Diversity of Vital Diazotrophic Bacteria. Sugar Tech. 2016;19(2):136-47.
45. Solanki MK, *et al*. Rhizospheric and Endospheric Diazotrophs Mediated Soil Fertility Intensification in Sugarcane-Legume Intercropping Systems. J Soil Sediments. 2018;19:1911-27. doi:10.1007/s11368-018-2156-3.
46. Solanki MK, *et al*. Co-Inoculation of Different Antagonists Can Enhance the Biocontrol Activity Against *Rhizoctonia solani* in Tomato. Antonie van Leeuwenhoek. 2019. doi:10.1007/s10482-019-01290-8.
47. Solanki MK, *et al*. Helpful linkages of Trichoderma in the Mycoremediation and Mycorestoration. In: Ansari RA, Mahmood I, editors. Plant Health Under Biotic Stress. Springer; 2019. doi:10.1007/978-981-13-6040-4_2.
48. Solanki MK, *et al*. Mycorrhizal fungi and its importance in plant health amelioration. In: Microbiomes and Plant Health. Academic Press; 2021. p. 205-23.
49. Solanki MK, *et al*. Microbial endophytes' association and application in plant health: an overview. In: Microbial Endophytes and Plant Growth. 2022. p. 1-18.
50. Solanki MK, Mandal A, Medeiros FHVD, Awasthi MK. Editorial: Emerging frontiers of microbial functions in sustainable agriculture. Front Microbiol. 2023;13:1128267. doi:10.3389/fmicb.2022.1128267.
51. Solanki MK, Joshi NC, Singh PK, Singh SK, Santoyo G, de Azevedo LCB, *et al*. From concept to reality: Transforming agriculture through innovative rhizosphere engineering for plant health and productivity. Microbiol Res. 2024;127553.
52. Solanki MK, Verma KK, Dastogeer KM, Mora-Poblete F, Mundra S. Microbial Resilience in Plant Nutrient Management Towards Sustainable Farming. Front Microbiol. 2023;14:1280811.
53. Takankhar VG, Gaikwad SS, Kharat SO. Effect of foliar application of water soluble fertilizers on growth, yield and quality of chickpea (*Cicer arietinum* L.). Int J Chem Stud. 2017;5(5):1736-9.
54. Takankhar VG, Karanjikar PN, Bhoye SR. Effect of foliar nutrition on growth, yield and quality of chickpea (*Cicer arietinum* L.). Int J Chem Stud. 2017;5(4):296-9.
55. Tutiempo Network SL. Climate data for Bhopal, Madhya Pradesh, India - 2023. 2024. Retrieved from https://www.tutiempo.net.
56. Varshney RK, Mohan SM, Gaur PM, Gangarao NVPR, Pandey MK, Bohra A, *et al*. Achievements and prospects of genomics-assisted breeding in three legume crops of the semi-arid tropics. Biotechnol Adv. 2013;31(8):1120-34. doi:10.1016/j.biotechadv.2013.01.001.
57. Venkatesh MS, Patil BC, Koppalkar BG. Effect of foliar application of nutrients on growth and yield of chickpea. Karnataka J Agric Sci. 2012;25(3):415-8.
58. Verma KK, Joshi A, Song XP, Singh S, Kumari A, Arora J, *et al*. Synergistic interactions of nanoparticles and PGPR enhancing soil-plant systems: a multigenerational perspective. Front Plant Sci. 2024;15:1376214. doi:10.3389/fpls.2024.1376214.
59. Verma P, Solanki AC, Solanki MK, *et al*. Linkages of Microbial Plant Growth Promoters Toward Profitable Farming. In: Phytobiomes: Current Insights and Future Vistas. Springer; 2020. p. 163-90.
60. Wang Z, Solanki MK, *et al*. Draft Genome Analysis Offers Insights Into the Mechanism by Which Streptomyces Chartreusis WZS021 Increases Drought Tolerance in Sugarcane. Front Microbiol. 2018;9:3262. doi:10.3389/fmicb.2018.03262.
61. Wang Z, Solanki MK, Kumar A, Solanki AC, Pang F, Ba ZX, *et al*. Promoting Plant Resilience against Stress by Engineering Root Microenvironment with Streptomyces Inoculants. Microbiol Res. 2023;127509.
62. Watson DJ. The physiological basis of variation in yield. Adv Agron. 1952;4:101-45. doi:10.1016/S0065-2113(08)60307-7.
63. Woodhouse J, Johnson MS. Effect of superabsorbent polymers on survival and growth of crop seedlings. Agric Water Manag. 1991;20(1):63-70. doi:10.1016/0378-3774(91)90035-H.
64. Yadav R. Effect of salicylic acid on physiological growth parameters of chickpea (*Cicer arietinum* L.). Int J Sci Res. 2015;4(5):50-2.
65. Yandigeri MS, Malviya N, Solanki MK, *et al*. Drought-tolerant endophytic actinobacteria promote growth of wheat (*Triticum aestivum*) under water stress conditions. Plant Growth Regul. 2012;68(3):411-20