Print ISSN : 0972-8813
e-ISSN : 2582-2780

[Vol. 23(3) September-December 2025]

Pantnagar Journal of Research

(Formerly International Journal of Basic and Applied Agricultural Research ISSN : 2349-8765)

G.B. Pant University of Agriculture & Technology
Pantnagar, U.S. Nagar; Uttarakhand, Website : gbpuat.res.in/PJR

PANTNAGAR JOURNAL OF RESEARCH

Vol. 23(3) September-December, 2025

CONTENTS

Frogeye leaf spot (*Cercospora sojina* K. Hara) in soybean: Emerging challenges, resistance genetics and sustainable management strategies 337
SANJEEV KUMAR, LAXMAN SINGH RAJPUT, HEMANT SINGH MAHESHWARI, VANGALA RAJESH, M. RAJENDAR REDDY, PAWAN SAINI, PALAK SOLANKI, JYOTI KAG, MANOJ KUMAR YADAV, JAYWANT KUMAR SINGHand SHIKHA SHARMA

Impact of establishment methods and weed management practices on growth and yield attributes of rice (*Oryza sativa* L.) 350
HIMANSHU, S.K. YADAV, D.K. SINGH and PRATIMA ARYA

Integrated weed management practices in wheat (*Triticum aestivum* L.) under the humid sub-tropical condition of Uttarakhand 355
SHRUTI SINGH, SHIV VENDRA SINGH and RASHMI SHARMA

Foliar supplementation of micronutrients on Palash [*Butea monosperma* (Lam.) Taub.] for enhanced productivity of rangeenilac, *Kerria lacca* (Kerr, 1782) (Hemiptera: Kerridae) 361
PURNIMA KEKTI, P.K. NETAM, DAMINI NISHAD and SOURABH MAHESHWARI

Lagged effects of weather variables on *Helicoverpa armigera* (Hübner) larval population during rabi season 367
RAJNNI DOGRA and MEENA AGNIHOTRI

Influence of nutrients on the flowering attributes of the guava cv. Sardar 377
RAKHI GAUTAM, PRATIBHA and A.K. SINGH

Sequential functional screening and trait-based association of chickpea rhizobacterial isolates using multiple correspondence analysis 384
DEEPANJALI GUPTA, KIRAN P. RAVERKAR, NAVNEET PAREEK, POONAM GAUTAM, SHRI RAM and AJAY VEER SINGH

Evaluation of neutralizing post-vaccination antibody response against Peste des petits ruminants virus in Pantja goat breed of Uttarakhand, India 396
ANUJ TEWARI, AMISHA NETAM, RAJESH KUMAR, SAUMYA JOSHI, S.K. SINGH and R.K. SHARMA

Arbuscular Mycorrhizal Fungi (AMF) Root Colonisation and Glomalin Variability Across Bamboo Species Integrating UV–Vis Spectral Characterisation 402
SHAMLI SHARMA, A.K. VERMA and ASHUTOSH DUBEY

Comparative pyrolysis of agricultural biomass for bio-oil production and in vitro antifungal analysis of developed bio-oil based formulations 412
VAIBHAV BADONI, ASHUTOSH DUBEY, R. N. PATERIYA and A.K. VERMA

Computational exploration of curcumin–p-coumaric acid bioconjugates as potential inhibitors of β-catenin in breast cancer stem cells 423
ANANYA BAHUGUNA and SHIV KUMAR DUBEY

Molecular Docking Analysis of Curcumin–Glucose Conjugate as Potential Modulators of Breast Cancer Stemness via β-Catenin Inhibition **431**
ROHIT PUJARI, MUMTESH SAXENA and SHIV KUMAR DUBEY

Assessment of *Schizophyllum commune* and *Trametes hirsuta* as efficient laccase-producing white-rot fungi **438**
RUKHSANA BANO, DIKSHA BHARTI and AJAY VEER SINGH

Drought stress mitigation and enhancement of maize growth facilitated by the plant growth–promoting bacterium *Serratia* sp. SRK14 **444**
ASHISH KUMAR and AJAY VEER SINGH

Effect of adding turmeric, ginger and black pepper on biochemical parameters of *Cyprinus carpio* **454**
KIRTI SHARMA, DAISY RANI1, MADHU SHARMA and TARANG SHAH

Design and Development of a Four-Wheel Remotely Controlled Weeding Machine **460**
SANDEEP KUMAR SAROJ , JAYANT SINGH, SUMIT KUMAR and SACHIN CHAUDHARY

Analyzing farmers perception towards climate change in Nainital district of Uttarakhand **466**
ABHISHEK KUMAR and ARPITA SHARMA KANDPAL

Study on information seeking behavior of female students of G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand related to menstruation **472**
POOJA TAMTAand SUBODH PRASAD

Drought stress mitigation and enhancement of maize growth facilitated by the plant growth–promoting bacterium *Serratia* sp. SRK14

ASHISH KUMAR and AJAY VEER SINGH*

Biofortification Lab, Department of Microbiology, G. B. Pant University of Agriculture and Technology, Pantnagar -263145 (U.S. Nagar, Uttarakhand)
**Corresponding author's email id: ajaygbpuat@gmail.com*

ABSTRACT: Maize (*Zea mays* L.) is a vital global food crop, but drought severely limits its productivity. This study evaluated the potential of a drought-tolerant plant growth-promoting bacterium (PGPB), *Serratia* sp. SRK14, to enhance maize performance under water-limited conditions. The isolate exhibited strong plant growth–promoting traits, including efficient solubilization of zinc (117.24±2.00%), phosphate (136.28±1.88%), and potassium (172.34±0.64%), high siderophore production (136.49±2.63%), and positive indole-3-acetic acid production, indicating its potential to improve nutrient availability and root development. Under polyethylene glycol (PEG-6000)–induced osmotic stress (10–40%), SRK14 maintained appreciable growth up to 30% PEG, demonstrating tolerance to moderate drought stress. Greenhouse evaluation of maize under drought at 45 days after sowing revealed that SRK14 inoculation significantly enhanced plant growth compared with uninoculated controls. Shoot length, shoot fresh weight, and shoot dry weight increased by 9.38%, 49.04% and 9.52%, respectively. Root growth was markedly improved, with increases of 42.86% in root length, 23.53% in root fresh weight, and 24.78% in root dry weight. Inoculated plants indicating better tissue hydration and membrane stability reflected through increased relative water content (46.7%) and reduced relative electrolyte conductivity (30.17%). Additionally, SRK14 enhanced stress mitigation through increased catalase activity (11.49 μmol min-¹ g-¹ FW) and proline accumulation (19.50 mol g-¹ FW). The present study demonstrates that Serratia sp. SRK14 combines strong PGP traits, stress tolerance, and protective effects on plant physiology, highlighting its promise as a bioinoculant for improving maize performance under water-limited conditions.

Key words: Biofilm, drought, exopolysaccharide, polyethylene glycol tolerance, Plant growth promoting bacteria (PGPB)

Drought is a major abiotic stress that severely restricts maize productivity across the globe. It reduces soil water availability, impairing nutrient uptake, and triggering oxidative damage in plant tissues (Khan and Singh, 2021). Under such conditions, plants often exhibit stunted growth, reduced biomass, membrane injury, and disruption of cellular homeostasis, ultimately leading to substantial yield losses (Singh *et al*., 2022). Plant growth promoting rhizobacteria (PGPR) have emerged as an eco friendly strategy to enhance crop resilience to water deficit through several mechanisms, such as enhanced nutrient solubilization, phytohormone production, modulation of root architecture, and induction of antioxidant and osmotic adjustment responses (Upadhayay *et al*., 2022b; Bundela *et al*., 2025). Members of the genus *Serratia* are increasingly recognized as versatile PGPR capable of colonizing the rhizosphere, producing exopolysaccharides and biofilms, and expressing a wide range of traits that can alleviate drought stress (Singh and Jha, 2016). These traits include solubilization of sparingly soluble mineral nutrients, siderophore mediated iron acquisition, and synthesis of auxins such as indole 3 acetic acid, which collectively promote root proliferation and enhance water and nutrient foraging. In addition, EPS and biofilm formation can improve soil aggregation, moisture retention, and bacterial persistence on root surfaces, providing a conducive microenvironment that supports plant growth under limited water conditions (Alchoni*et al*., 2025). Several recent reports have highlighted that drought tolerant *Serratia*strains can simultaneously trigger osmolyte accumulation (proline, soluble sugars), enhance antioxidant enzymes (SOD, CAT, POD) and reduce lipid peroxidation, thereby mitigating oxidative damage in cereals and other crops under water deficit (Gholami *et al*., 2016; Khan *et al*., 2018). However, most of these studies have been conducted either under controlled conditions or with limited

integration of biochemical and physiological in maize, leaving a knowledge gap regarding performance and strain specific plant growth promoting (PGP) repertoires. Despite growing evidence for the role of *Serratia* sp. in plant growth promotion, detailed characterization of individual strains combining osmotic stress tolerance with multifaceted PGP attributes and demonstrable benefits to maize under drought remains limited. The objective of the present study was therefore to evaluate the potential of *Serratia* sp. SRK14 as a drought tolerant plant growth–promoting rhizobacterium. Additionally, the study aimed to determine the effect of SRK14 inoculation on maize growth, physiological and biochemical responses under drought conditions, thereby identifying its suitability as a bioinoculant for improving maize performance in water limited environments.

MATERIALS AND METHODS

Culture retrieval and Polyethylene glycol (PEG) tolerance

The *Serratia* sp. SRK14 was collected from the culture collection of the Department of Microbiology, G. B. Pant University of Agriculture and Technology (GBPUA&T), Pantnagar, India, and its identity was confirmed by 16S rRNA gene sequencing (NCBI accession no. OM302169.1). The drought tolerance potential of *Serratia* sp. SRK14 was evaluated by culturing the strain in nutrient broth containing10, 20, 30, or 40% (w/v) PEG 6000 and incubating the tubes for 24 h at 28±2 ºC, following the methodology of Mustamu *et al*. (2023). Bacterial growth under each PEG level was quantified by measuring optical density (O.D 600 nm), which was used as an index of tolerance to moisture stress.

Mineral solubilization and phytohormone production

The *Serratia* sp. SRK14 was evaluated for various plant growth-promoting traits under non-stress condition.

Zinc solubilization

The bacterial strain was evaluated for zinc solubilizing activity by spot inoculating the strains on to minimal salt agar (MSA) amended with insoluble zinc source (zinc oxide). Afterwards, plates were incubated at 28°C for 5 days, after which zinc solubilization was visualized as clear halos surrounding colonies against the opaque medium (Upadhayay *et al.*, 2022b). The diameter of halo was measured to quantify solubilization efficiency.

Phosphate solubilization

The bacterial strain was evaluated for phosphate solubilizing activity by spot inoculating the isolates onto Pikovskaya's agar containing tricalcium phosphate (TCP), followed by incubation at 28°C for 5 days **(**Pikovskaya, 1948). Phosphate solubilizing by bacteria were identified by the appearance of a clear halo zone surrounding the colonies, indicating dissolution of tri calcium phosphate. The diameter of halo was measured to quantify solubilization efficiency.

Potassium solubilization

Bacterial strain in active growth phase was spotted onto Aleksandrov agar plates and incubated at 28°C for 5 days as per Liu *et al*. (2015). Potassium-solubilizing was identified by the formation of clear halo around their colony on the opaque medium, and the size of these halo was measured to assess their potassium solubilization activity.

Siderophore production

Siderophore production was evaluated using a Chrome Azurol S (CAS)–based method adapted from Schwyn and Neilands (1987). In this approach, CAS solution was incorporated into sterile nutrient agar at a ratio of 1:9 (v/v), and the mixture was dispensed into Petri plates and allowed to solidify. After solidification, the bacterial strain was spot inoculated onto the CAS–nutrient agar and incubated at 28°C for five days, while uninoculated plates were maintained as negative controls. Following incubation, strain that developed distinct orange zone surrounding the colony against the blue CAS background was scored as siderophore producers.

Auxin production

Auxin production by the bacterial strain was detected

as indole 3 acetic acid (IAA) using the Salkowski colorimetric method(Gordon and Weber, 1951).An overnight grown bacterial strain was inoculated into sterile nutrient broth amended with L tryptophan (1.0 mg mL^{-1}) as precursor for IAA synthesis.Incubate the culture at 28°C for 48/ h under shaking conditions in the dark. Afterwards,strain was centrifuged at 10,000/ g for 10/ min to obtain a cell free supernatant. A 1.0/ mL aliquot of the supernatant was mixed with 2.0/ mL of Salkowski reagent (typically 1–2% 0.5/ M $FeCl_3$ in 35% perchloric or 50% sulfuric acid) in test tubes. The resulting reaction mixture was left at room temperature for 20–30/ min in the dark to allow color development. Formation of a pink to reddish color indicated IAA production.

Stress tolerance activities

The exopolysaccharide (EPS) was estimated following solvent extraction technique outlined byAzeredo and Oliveira (1996). The bacterial strain was first grown for 48 h and then centrifuged at 10,000/ g for 10/ min to separate the cells from the supernatant containing EPS. The supernatant was collected, and absolute ethanol (1:3 v/v) was added to precipitate the EPS. The mixture was refrigerated overnight to allow complete precipitation which indicates presence of EPS.The biofilm formation was determinedby following a protocol of Zaytsev *et al*. (2020).A bacterial suspension was prepared in 10 mL test tube containing peptone medium following incubation 28°C for 48 hours to allow biofilm development. Afterward, tubes were gently emptied and rinsed twice with phosphate-buffer saline to remove non-adherent cells. The tubes werethenleft to air-dried, after which the remaining adherent cells were stained with 0.1% crystal violet for 15 minutes. The appearance of ring-shaped structure in test tube indicate positive test for biofilm production.

Pot experimentation design

Experimentation condition

The pot experiment was carried out in a net house of Department of Microbiology, College of Basic Sciences and Humanities, Govind Ballabh Pant University of Agriculture & Technology, Pantnagar, Uttarakhand (28°58'N 79°25'E) in the year 2024. The experiment was conducted for 45 days to assess the impact ofthe drought tolerant bacterial strain *Serratia* sp. SRK14 on maize growth under drought conditions. Sterilized soil was filled into 5 kg plastic pots and autoclaved prior to sowing to minimize background microbial interference. Maize seeds (treated or untreated with *Serratia* sp. SRK14) were sown and all pots were kept under uniform greenhouse conditions. Irrigation was applied regularly to all pots for the first 15 days after sowing to ensure uniform seedling establishment. Subsequently, drought stress was imposed in the designated treatments by regulating irrigation to maintain soil moisture at 50% field capacity (FC). Field capacity of the experimental soil was determined gravimetrically prior to sowing by saturating the soil, allowing free drainage, and calculating the moisture content retained after drainage. The experiment was continued up to 45 days after sowing, at which point plant growth and physiological attributes were assessed for comparison between inoculated and uninoculated plants under drought.

Seed sterilization and bacterization

Before sowing, maize seeds of variety DKC9208 were surface sterilized by immersing in 70% ethanol for 1 min, followed by treating with 1% sodium hypochlorite (NaClO) for 5 min and then rinsed trice with sterile distilled water to remove any traces of the disinfectants. The sterile seeds were subsequently used for inoculation with the bacterial strain. The selected *Serratia* sp. strain wascultured in nutrient broth at 28 °C for 24 h until the culture reached an optical density of 1.0 at 600 nm(Kukreti and Singh, 2024). For seed treatment, sterilized seeds were immersed in the freshly prepared bacterial suspension (seed:suspension ratio 1:5, w/v) for 3 h under aseptic conditions. Seeds used as controls were subjected to the same procedure but soaked in sterile nutrient broth without bacterial cells.

Physiological parameters of maize

Relative electrical conductivity (REC)

REC was measured as an indicator of membrane stability following the procedure of Lutts *et al*. (1996).Fresh leaf sample were collected and gently

rinsed with deionized water to remove surface impurities and cut into uniform discs (1 cm²). The leaf pieces were transferred in tubes containing 10 mL of deionized water and kept at 25±2°C for 24 h. After incubation, the electrical conductivity of the solution (EC1) was measured using a conductivity meter.The tubes were then autoclaved at 121°C for 20 min to completely disrupt cell membranes, allowed to cool at room temperature, and the final electrical conductivity (EC2) of the solution was recorded. The percentage ofelectrolyte leakage, expressing membrane injury, was calculated from EC1 and EC2 using the standard percentage formula.

$$\text{Relative electrical conductivity (\%)} = \frac{(EC1)}{(EC2)} \times 100$$

Relative water content (RWC)

Relative water content of leaves was determined following the classical method described by Barrs and Weatherley (1962). Leaf samples (0.2g) were taken from plants and their fresh weight (FW) was recorded immediately after excision. The excised leaves were then placed on distilled water in Petri dishes and left at ambient temperature for 24 h to attain full turgidity, after which the turgid weight (TW) was measured. Afterwards, the tissues were dried in a hot air oven at 70°C for 24 h to obtain the dry weight (DW) of both FW and TW The RWC was calculated as a percentage using FW, TW and DW. values in the conventional formula for leaf water status.

$$\text{RWC (\%)} = \frac{(FW-DW)}{(TW-DW)} \times 100$$

Catalase activity

Catalase activity in maize leaves was determined spectrophotometrically using the method of Beers and Sizer (1952). Fresh leaf tissue (0.5 g) was ground in 5 mL of ice-cold 50 mM phosphate buffer (PBS pH 7.5) and centrifuged at 12,000 rpm for 15 minutes at 4°C. The supernatant was collected and used as the enzyme extract. The reaction mixture was prepared by combining 2.5 mL of 50 mM PBS (pH 7.5) with 0.4 mL of 25 mM hydrogen peroxide. The reaction was started by addition of 0.1 mL of the enzyme extract, and the reduction in absorbance was monitored at 240 nm for 3 minutes using a UV–Visible spectrophotometer. Catalase activity (CAT) was calculated as the quantity of enzyme needed to decompose 1 micromole of H_2O_2 per minute, based on an extinction coefficient of 39.4 mM^{-1} cm^{-1} for H_2O_2 at 240 nm.

Proline content

The proline content in plant leaf samples was determined using a modified method described by Bates *et al*. (1973). Fresh leaf tissue (0.5 g) was ground in 10 mL of 3% (w/v) sulfosalicylic acid with a chilled mortar and pestle. The resulting homogenate was filtered through filter paper (Whatman No. 1). For analysis, 2 mL of the filtrate was combined with 2 mL of acid ninhydrin reagent and 2 mL of glacial acetic acid. The mixture was kept in a boiling water bath at 100°C for 1 hour and then quickly cooled in an ice bath. Subsequently, 4 mL of toluene was added to each tube, and the contents were vortexed to ensure thorough mixing. The toluene (upper) phase, containing the chromophore, was carefully collected, and its absorbance was measured at 520 nm using a visible spectrophotometer, with toluene serving as the blank. Proline concentration was calculated from a standard curve prepared with known concentrations of L-proline and expressed as µmol per gram fresh weight (µmol g^{-1} FW) of leaf tissue.

Statistical analysis

The experimental data were statistically analyzed under a completely randomized design (CRD), with all treatments arranged in replicated (n=3) sets. Mean values and their standard errors were computed using Microsoft Excel, and the processed data were subsequently used to generate graphs in GraphPad Prism (version 9) for visual presentation of the results.

RESULTS and DISCUSSION

Drought tolerance capacity of *Serratia* sp. SRK14

Tolerance of *Serratia* sp. SRK14 to moisture stress was assessed in broth amended with 10–40% PEG 6000. The bar graph shows that the growth of *Serratia* sp. SRK14, measured as optical density,

declines progressively with increasing PEG 6000 concentration from 0 to 40%, indicating increasing osmotic/drought stress tolerance limits. In the absence of PEG (0%), the culture reached an OD of about 1.02 which declined slightly to 0.94 at 10% PEG, indicating that low osmotic stress had only a minor impact on bacterial proliferation. At 20% PEG, OD dropped markedly to 0.61, and further decreased to 0.35 and 0.12 at 30% and 40% PEG(Fig. 1), demonstrating that the strain can still grow under moderate osmotic stress but its proliferation is strongly inhibited at higher PEG levels. These results suggest that SRK14 tolerates moderate osmotic stress but experiences marked growth suppression at higher PEG concentrations, corresponding to severe drought conditions.

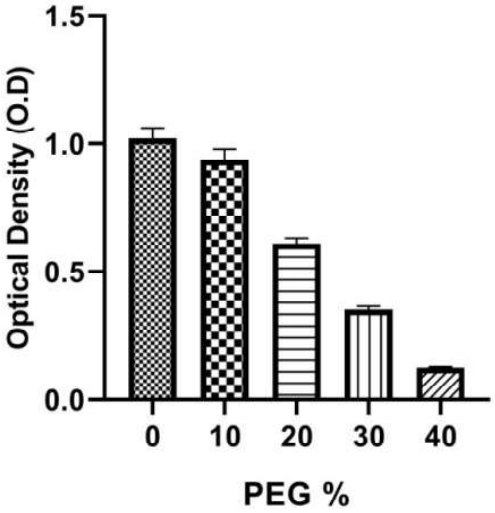

Fig. 1: Optical density of *Serratia sp.* SRK14 under varying levels of Polyethylene glycol (PEG 6000)

Plant growth-promoting (PGP) activities of *Serratia* sp. SRK14

Serratia sp. SRK14 showed efficient solubilization of multiple nutrients and high siderophore production. Zinc solubilization efficiency was 117.24±2.00, phosphate solubilization 136.28±1.88, and potassium solubilization 172.34±0.64, indicating strong mineral-solubilizing potential of the strain. Siderophore production was also high (136.49±2.63), suggesting an enhanced capacity for iron acquisition and indirect plant growth promotion under iron -limited conditions.In addition, SRK14 tested positive for indole acetic acid (IAA) production(Table1), suggesting a direct role in stimulating root growth and overall plant development under stress conditions.

Stress tolerant properties:Exopolysaccharide and biofilm production by *Serratia* sp. SRK14

Serratia sp. SRK14 produced visibly higher amounts of exopolysaccharide and biofilm compared to the uninoculated control, as indicated by the turbid EPS-containing culture (Figure 2a) and the intense crystal violet staining and ring formation on the tube wall (Figure 2b), confirming its strong matrix- and biofilm-forming ability.

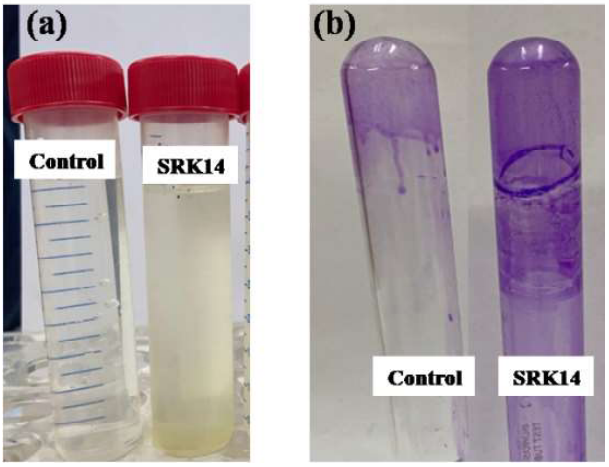

Fig. 2: (a) Exopolysaccharide production and (b) Biofilm formation/production by *Serretia* sp. SRK14

Agronomical parameters

Inoculation with *Serratia* sp. SRK14 significantly enhanced maize growth at 45 dayspost sowing under drought stress compared with the uninoculated control, as reflected in both shoot and root traits. Shoot length increased from approximately 64 cm

Table 1: Plant growth promontory (PGP) activities of *Serratia sp.* SRK14

S.No.	PGP activities	(%)
1	Zinc solubilization	117.24±2.00
2	Phosphate solubilization	136.28±1.88
3	Potassium solubilization	172.34±0.64
4	Siderophore production	136.49±2.63
5	Auxin	+

in the untreated to about 70 cm in SRK14 treated plants, while shoot fresh and dry weights rose from 13.5 to 20.12 g and from 4.20 to 4.60 g, respectively, indicating improved above ground biomass accumulation under moisture deficit. Root parameters showed an even stronger response, with root length increasing from 35 to 50 cm, root fresh weight from 8.5 to 10.5g, and root dry weight from 3.39 to 4.23 g in SRK14 inoculated plants relative to the control, demonstrating enhanced root system development and greater capacity for water and nutrient acquisition under drought. Collectively, these results provide strong evidence that *Serratia* sp. SRK14 mitigated drought induced growth reduction and promoted overall plant vigor at the mid vegetative stage.

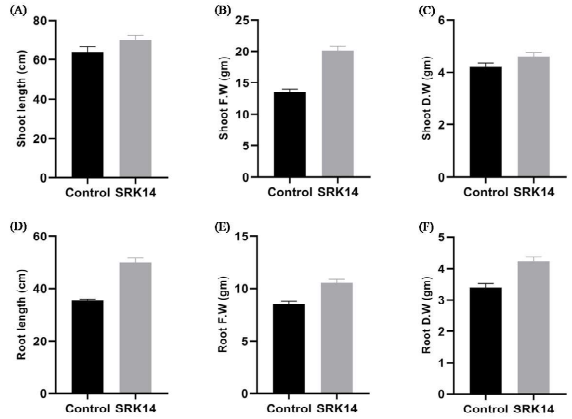

Fig. 3: Effect of *Serratia* sp. SRK14 inoculation on (A) Shoot length (cm), (B) Root length (cm) and (C) Shoot fresh weight (gm), (D) Root fresh weight (gm) and (E) Shoot dry weight (gm), (F) Root dry weight (gm) of maize at 45 days of sowing under drought stress

Plant health parameter

Inoculation with *Serratia* sp. SRK14 improved leaf water status and reduced membrane injury of maize under drought at 45 days compared with the uninoculated control. Relative water content (RWC) increased from 36.20% in the control to about 46.70% in SRK14 treated plants(Fig. 4A), indicating better cellular hydration under moisture stress. In contrast, relative electrolyte conductivity (REC), an indicator of membrane damage, decreased from around 43.69% in the control to 30.17% in inoculated plants(Fig. 4B), showing that SRK14 mitigated drought induced membrane leakage and helped maintain cell integrity.

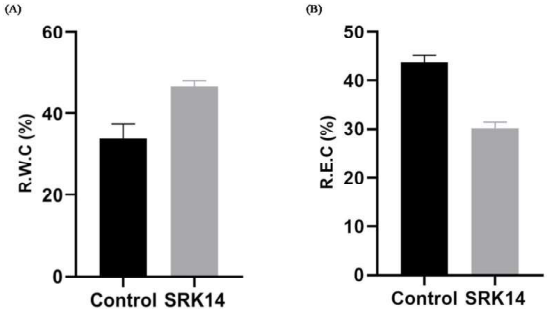

Fig. 4: Effect of *Serratia* sp. SRK14 inoculation on (A) relative water content (RWC) and (B) relative electrolyte conductivity (REC) of maize leaves at 45 days sowing under drought stress

Antioxidant enzyme and proline content in maize

Inoculation with *Serratia* sp. SRK14 enhanced antioxidant defense and osmotic adjustment in maize under drought at 45 days. Catalase (CAT) activity increased from 6.77 nmol min^{-1} g^{-1} F.W. in the uninoculated control to 11.49 nmol min^{-1} g^{-1} F.W. in SRK14 treated plants (Fig. 5A), indicating a stronger capacity to detoxify hydrogen peroxide under stress. Proline content also rose from 12.87 µmol g^{-1} F.W. in the control to 19.50 µmol g^{-1} F.W. with SRK14 treated plants (Fig. 5B), reflecting improved osmotic regulation and protection of cellular structures during drought.

The present study elucidated the effects of *Serratia* sp. SRK14 on maize growth under drought stress

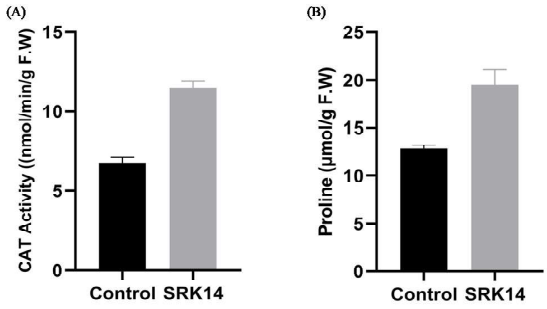

Fig. 5: Effect of *Serratia* sp. SRK14 inoculation on (A) Catalase (CAT) activity and (B) Proline content in maize leaves at 45 days of sowing under drought stress

and demonstrated its role in improving plant performance and resilience in water-limited environments. Inoculation with *Serratia* sp. SRK14 alleviated drought-induced growth inhibition in maize through a combination of direct plant growth-promoting (PGP) traits and physiological protection mechanisms. The significant increases observed in shoot and root length, as well as fresh and dry biomass, indicated that SRK14 improved crop vigor under moisture deficit. These findings are consistent with earlier reports showing that efficient plant growth-promoting bacteria (PGPB) enhance cereal growth under drought stress (Singh and Jha, 2016; Bundela *et al*., 2023; Singh *et al*., 2025). Similarly, Khan *et al*. (2021) reported that inoculation with *Serratia marcescens* RRN II 2 and *Pseudomonas* sp. RRC I 5 enhanced root and shoot length and improved wheat yield under drought stress. The stronger response of root traits compared with shoot traits suggested that *Serratia* sp. SRK14 preferentially stimulated below-ground development, thereby enhancing soil exploration and improving water and nutrient uptake under drought conditions. This response aligned with the high zinc, phosphate, and potassium solubilization efficiencies of SRK14 and its positive indole-3-acetic acid (IAA) production, traits known to promote root proliferation and nutrient foraging in stressed plants (Upadhayay *et al*., 2022b; Khan *et al*., 2023; Khan *et al*., 2024). Supporting these observations, Kour *et al*. (2020) reported that drought-adaptive phosphorus-solubilizing *Pseudomonas libanensis* EU-LWNA-33 improved seed germination and growth parameters in wheat. The physiological analyses further supported a protective role of *Serratia* sp. SRK14 against drought stress. The higher relative water content recorded in inoculated plants indicated better maintenance of tissue hydration, likely resulting from improved root architecture, exopolysaccharide (EPS)-mediated enhancement of soil water retention, and biofilm-assisted root colonization. These mechanisms are known to facilitate a more stable water supply to plants under moisture deficit. In agreement with this, Naseem *et al*. (2024) reported that EPS-producing bacteria such as *Bacillus cereus* EPB17 and *Pseudomonas aeruginosa* EPB19 helped retain soil moisture and improved crop water status under drought conditions.Concurrently, the reduction in relative electrolyte conductivity observed in SRK14-inoculated plants reflectedlower membrane injury, indicating improved membrane stability under dehydration stress. The enhanced catalase activity and increased proline accumulation provided a mechanistic explanation for this protection. Elevated catalase activity enhances the detoxification of hydrogen peroxide and mitigates oxidative stress (Khan and Singh, 2021), while proline functions as an osmoprotectant that stabilizes proteins and membranes and contributes to osmotic adjustment in plants (Singh *et al*., 2022). Collectively, these responses demonstrated that SRK14 primed both antioxidant defense and osmotic adjustment pathways in maize under drought stress.The *in vitro* characterization of SRK14 supportedthe plant-based findings and explained its functional performance under drought conditions. The ability of the strain to maintain growth at moderate PEG-6000 concentrations confirmed its tolerance to osmotic stress, a prerequisite for effective survival and activity in a drying rhizosphere (Khan and Singh, 2021; Kour *et al*., 2020). Although optical density declined at higher PEG levels, sustained growth at 20–30% PEG indicated that SRK14 remained metabolically active under drought intensities relevant to field conditions. Moreover, robust EPS and biofilm production enhanced its ecological fitness by promoting strong root adherence and creating hydrated micro-niches in the rhizosphere, thereby buffering both the bacterium and the host plant against rapid fluctuations in soil water potential (Naseem *et al*., 2024). Such traits are widely associated with drought-mitigating PGPB and further support the suitability of SRK14 for rhizosphere applications. Collectively, the findings of this study positioned *Serratia* sp. SRK14 as a promising bioinoculant for maize cultivation under water-limited conditions. Its combined abilities to solubilize essential nutrients, produce IAA, tolerate osmotic stress, form EPS and biofilms, and enhance plant water status, antioxidant capacity, and osmotic adjustment suggested that SRK14 operates through multiple, complementary mechanisms to sustain maize growth during drought. Future research should

validate these results under multi-location field trials, evaluate long-term effects on yield and grain quality, and develop formulation strategies to maintain SRK14 viability and efficacy under field conditions. Additionally, molecular profiling of drought-responsive pathways in maize colonized by SRK14 wouldhelp elucidate the signaling mechanisms underlying the observed physiological benefits and guide the development of synergistic microbial consortia for drought-resilient agriculture.

CONCLUSION

Maize is a vital cereal and forage crop and its productivity and yield are significantly impacted by drought stress throughout its growth stages. This study confirms that *Serratia* sp. SRK14 exhibited a robust combination of stress tolerance and plant growth promoting traits, enabling maize plants to better withstand drought. The strain tolerated moderate PEG induced osmotic stress, produced abundant exopolysaccharides and biofilm, and expressed strong PGP activities, including high Zn, P and K solubilization, siderophore production and IAA synthesis, supporting improved nutrient availability and rhizosphere colonization. Inoculated maize plants showed enhanced shoot and root growth, higher relative water content, reduced membrane damage, and elevated catalase activity and proline accumulation, indicating strengthened antioxidant and osmotic adjustment responses under water deficit. In summary, the present results demonstrate that *Serratia* sp. SRK14 effectively mitigates drought induced growth and physiological impairments and has strong potential as a bioinoculant for improving maize performance in water limited environments.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Department of Microbiology, G. B. Pant University of Agriculture and Technology, Pantnagar (U.S. Nagar), Uttarakhand, India for providing laboratory facilities, resources, and institutional support essential for conducting this research.

REFERENCES

Alchoni, S., Rani, P., Kumar, A., Manoharlal, R., Pasrija, R., GVS, S. and Singh, A. V. (2025). Harnessing microbes for drought stress mitigation: a promising approach for water stress management in plants. In *Climate Change and Agricultural Ecosystems,* Woodhead Publishing,Pp. 169–198.

Azeredo, J. and Oliveira, R. (1996). A new method for precipitating bacterial exopolysaccharides. *Biotechnology Techniques*, 10: 341–344.

Barrs, H. D. and Weatherley, P. E. (1962). A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Australian Journal of Biological Sciences*, 15(3): 413–428.

Bates, L. S., Waldren, R. P. and Teare, I. D. (1973). Rapid determination of free proline for water-stress studies. *Plant and Soil*, 39: 205–207.

Beers, R. F. and Sizer, I. W. (1952). A spectrophotometric method for measuring the breakdown of hydrogen peroxide by catalase. *Journal of Biological Chemistry*, 195(1):133–140.

Bundela, V., Kukreti, B., Khan, A., Kumar, A., Singh, T. and Singh, A. V. (2023). Evaluation of soybean-based endophytic bacterium *Pseudomonas moraviensis* PSSI3for itsmultifarious plant growth promoting potential in soybean (*Glycine max* (L.) Merr.). *Biological Forum – An International Journal*, 15(12):267–277.

Bundela, V., Saini, N., Kumar, A., Singh, A. V. and Ranjan, P. (2025). Microbial synergy for zincand iron biofortification: enhancing crop nutrition through plant–microbe interactions. *Journal of Advances in Biology & Biotechnology*, *2*8(7): 898–918.

Gholami, M., Shahsavani, S. and Nezarat, S. (2016). The multifarious PGPR *Serratiamarcescens* CDP 13 augments induced systemic resistance and tolerance of wheat to salinity and drought. *PLoS One*, 11(6): e0155026.

Gordon, S. A. and Weber, R. P. (1951). Colorimetric estimation of indoleacetic acid. *Plant Physiology*, 26(1): 192.

Khan, A. and Singh, A. V. (2021). Multifarious effect of ACC deaminase and EPS producing *Pseudomonas* sp. and *Serratia marcescens* to augment drought stress tolerance and nutrient status of wheat. *World Journal of Microbiology and Biotechnology*, 37(12): 198.

Khan, A., Singh, A. V., Kukreti, B., Pandey, D. T., Upadhayay, V. K., Kumar, R. and Goel, R. (2024). Deciphering the impact of cold-adapted bioinoculants on rhizosphere dynamics, biofortification, and yield of kidney bean acrossvaried altitudinal zones. *Science of the Total Environment*, 927:172204.

Khan, A., Singh, A. V., Pareek, N., Arya, P., Upadhayay, V. K., Jugran, A. K. and Goel, R. (2023). Credibility assessment of cold-adaptive *Pseudomonas jesennii* MP1 and *P. palleroniana* N26 on growth, rhizosphere dynamics, nutrient status and yield of kidney bean cultivated in Indian Central Himalaya. *Frontiers in Plant Science*, 14: 1042053.

Khan, N., Bano, A., Zandi, P., et al. (2018). *Serratia liquefaciens* KM4 improves salt stress tolerance in maize by regulating antioxidant enzymes, proline and phenolic contents. *Frontiers in Microbiology*, 9: 160.

Kour, D., Rana, K. L., Sheikh, I., Kumar, V., Yadav, A. N., Dhaliwal, H. S. and Saxena, A. K. (2020). Alleviation of drought stress and plant growth promotion by *Pseudomonas libanensis* EU-LWNA-33, a drought-adaptive phosphorus-solubilizing bacterium. *Proceedings of the National Academy of Sciences, India Section B:Biological Sciences*, 90(4): 785–795.

Kukreti, B. and Singh, A. V. (2024). Unlocking the biofortification potential of *Serratia marcescens* for enhanced zinc and iron content in wheat grains. *Pantnagar Journal of Research*, 22: 1.

Liu, Z., Li, Y. C., Zhang, S., Fu, Y., Fan, X., Patel, J. S. and Zhang, M. (2015). Characterization of phosphate-solubilizing bacteria isolated from calcareous soils. *Applied Soil Ecology*, 96: 217–224.

Lutts, S., Kinet, J. M. and Bouharmont, J. (1996). Effects of salt stress on growth, mineral nutrition and proline accumulation in relation to osmotic adjustment in rice (*Oryza sativa* L.) cultivars differing in salinity resistance. *Plant Growth Regulation*, 19(3): 207–218.

Mustamu, N. E., Tampubolon, K., Basyuni, M., Al-Taey, D. K., Janabi, H. J. K. A. and Mehdizadeh, M. (2023). Drought stress induced by polyethylene glycol (PEG) in local maize at the early seedling stage. *Heliyon*, 9(9): e20209.

Naseem, M., Chaudhry, A. N., Jilani, G., Alam, T., Naz, F., Ullah, R. and Zaman, S. (2024). Exopolysaccharide-producing bacterial cultures of *Bacillus cereus* and *Pseudomonas aeruginosa* in soil augment water retention and maize growth. *Heliyon*, 10(4): e26104.

Pikovskaya, R. I. (1948). Mobilization of phosphorus in soil in connection with the vital activity of some microbial species. *Mikrobiologiya*, 17: 362–370.

Schwyn, B. and Neilands, J. B. (1987). Universal chemical assay for the detection and determination of siderophores. *Analytical Biochemistry*, 160(1): 47–56.

Singh, J., Singh, A. V., Upadhayay, V. K., Khan, A. and Chandra, R. (2022). Prolific contribution of *Pseudomonas protegens* in zinc biofortification of wheat by modulating multifaceted physiological response under saline and non-saline conditions. *World Journal of Microbiology and Biotechnology*, 38(12): 227.

Singh, R. P. and Jha, P. N. (2016). The multifarious PGPR *Serratia marcescens* CDP-13 augments induced systemic resistance and enhanced salinity tolerance of wheat (*Triticum aestivum* L.). *PLoS One*, 11(6): e0155026.

Singh, T., Kothari, M., Mishra, S., Singh, A. V., Verma, A. K., Shankhdhar, D. and

Shankhdhar, S. C. (2025). Synergistic effect of zinc solubilizing bacteria and consortia on the zinc marker enzymes and gaseous exchange parameters in rice (*Oryza sativa* L.) for zinc biofortification. *Plant Physiology and Biochemistry*, 223: 109807.

Upadhayay, V. K., Singh, A. V., Khan, A. and Sharma, A. (2022a). Contemplating the role of zinc-solubilizing bacteria in crop biofortification: an approach for sustainable bioeconomy. *Frontiers in Agronomy*, 4: 903321.

Upadhayay, V. K., Singh, A. V., Khan, A., Singh, J., Pareek, N. and Raghav, A. (2022b). FE-SEM/EDX based zinc mobilization analysis of *Burkholderia cepacia* and *Pantoea rodasii* and their functional annotation in crop productivity, soil quality, and zinc biofortification of paddy. *Frontiers in Microbiology*, 13: 852192.

Zaytsev, E. M., Britsina, M. V., Ozeretskovskaya, M. N., Mertsalova, N. U. and Bazhanova, I. G. (2020). Sensitivity of biofilms of vaccine and freshly isolated *Bordetella pertussis* strains to antibiotics. *Journal of Microbiology, Epidemiology and Immunobiology*, 97(6): 529–534.

Received: December 11, 2025
Accepted: December 22,2025