E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
www.agronomyjournals.com
2025; 8(2): 324-332
Received: 29-11-2024
Accepted: 02-01-2025

Effect of microbial consortium and soil amendments on post-harvest nutrient availability in saline-sodic inceptisol under a soybean-wheat cropping sequence

Aniket Sunil Gaikwad, BD Bhakare, BM Kamble, RS Thakare, AG Durgude and AM Navale

Aniket Sunil Gaikwad
Ph.D. Research Scholar, Department of Soil Science and Agricultural Chemistry, Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra, India

BD Bhakare
Former Dean (F/A) and Director of Instruction and Ex-Head, Department of Soil Science and Agricultural Chemistry, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra, India

BM Kamble
Head, Department of Soil Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra, India

RS Thakare
Professor, Department of Soil Science, PGI, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra, India

AG Durgude
Senior Scientist (Soils), AICRP on Irrigation Water Management, Department of Agronomy, PGI, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra, India

AM Navale
Head, Department of Plant Pathology and Microbiology, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra, India

Corresponding Author:
Aniket Sunil Gaikwad
Ph.D. Research Scholar, Department of Soil Science and Agricultural Chemistry, Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra, India

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i2e.2588

Abstract

Soil salinity poses significant challenges to sustainable crop production, particularly in Inceptisols. This study investigates the impact of microbial consortia and soil amendments on post-harvest nutrient availability and residual effects in saline-sodic Inceptisol under a soybean-wheat cropping sequence. A field experiment was conducted at the Post Graduate Instructional Research Farm, Department of Soil Science, MPKV, Rahuri, during the 2022-23 and 2023-24 soybean-wheat cropping sequence using a Randomized Block Design with ten treatments replicated thrice. The soybean crop was cultivated during the *kharif* season with different combinations of GRDF, gypsum (100% GR), sulphur ($^1/_5$th of GR), and microbial consortia from Lucknow and VSI. The subsequent *rabi* wheat crop received GRDF and benefited from the residual effects of soil amendments and microbial consortia applied during the preceding soybean crop. Among the treatments, the application of GRDF + Sulphur + Microbial consortia I (T_8) significantly improved soil nutrient availability after soybean harvest, with pooled soil macronutrient values of 254.60 kg ha^{-1} nitrogen, 14.52 kg ha^{-1} phosphorus, 492.47 kg ha^{-1} potassium, and 13.78 mg kg^{-1} sulphur. Micronutrient availability also increased, with iron (5.16 mg kg^{-1}), manganese (5.91 mg kg^{-1}), zinc (0.51 mg kg^{-1}), and copper (1.97 mg kg^{-1}).

These improvements persisted after wheat harvest due to the residual effects of Sulphur and Microbial consortia I along with GRDF, further enhancing soil nitrogen (270.82 kg ha^{-1}), phosphorus (16.17 kg ha^{-1}), potassium (530.90 kg ha^{-1}), and sulphur (16.44 mg kg^{-1}), alongside increased iron (5.51 mg kg^{-1}), manganese (6.35 mg kg^{-1}), zinc (0.54 mg kg^{-1}), and copper (2.06 mg kg^{-1}) availability. The findings suggest that the integration of GRDF + Sulphur (as per $^1/_5$th of GR) + Microbial consortia I of Lucknow (@ 250 mL ha^{-1}) during soybean cultivation, followed by GRDF and the residual effects of these amendments in wheat, is a promising strategy for enhancing soil nutrient availability in saline-sodic soils.

Keywords: Saline-sodic soil, Inceptisol, nutrient availability, residual effect, soil fertility, microbial consortia, halophilic and halotolerant microbes, gypsum, sulphur, nitrogen, phosphorus, potassium, iron, manganese, zinc, copper, soybean and wheat

1. Introduction

Soil health is vital for sustainable agriculture, influencing crop productivity, nutrient cycling, and ecosystem stability (Gaikwad *et al.* 2024) [24]. As a finite resource, soil supports vegetation, forests, and crops, which sustain life directly or indirectly (Gaikwad *et al.*, 2023a) [23]. Healthy soils optimize plant growth and yield (FAO, 2015) [19], but excessive salts degrade their fertility and agricultural potential (Goswami and Deka, 2020) [27]. Salt-affected soils, characterized by high soluble salts and exchangeable sodium, hinder plant productivity by altering soil structure, restricting root growth, and reducing nutrient availability (Rengasamy, 2016) [52].

The FAO's GSASmap (FAO, 2021) [21] identified 424 million hectares of salt-affected topsoil and 833 million hectares of subsoil globally, covering 8.7% of the planet's land area (Lekka *et al.*, 2023) [40]. In India, 6.72 million hectares (2.1% of land) are salt-affected (FAO, 2020) [20], with 44% (2.95 million hectares) saline and 56% (3.77 million hectares) sodic soils (Arora *et al.*, 2016) [9]. The Indo-Gangetic plains contain 2.347 million hectares of salt-affected land (Arora and Sharma, 2017) [6], while Gujarat, Uttar Pradesh, Maharashtra, West Bengal, and Rajasthan account for 75% of India's total salt-affected soils (Mandal *et al.*, 2018) [44].

Maharashtra alone has 0.60 million hectares of salt-affected soil, with Ahmednagar (265,000 ha) being the most impacted district (Singh *et al.*, 2010) [59]. These figures highlight significant soil degradation, particularly in command areas.

Salt-affected soils are commonly found in arid and semi-arid regions (Abdennour *et al.*, 2020) [2], where evapotranspiration exceeds precipitation (Tomaz *et al.*, 2020) [64]. Their formation is driven by natural factors like parent material weathering and coastal proximity (Hopmans *et al.*, 2021) [31], as well as anthropogenic activities including saline irrigation, deforestation, and poor drainage (Dagar *et al.*, 2019) [12]. These conditions degrade soil structure, limit nutrient uptake, and reduce agricultural productivity (Gaikwad *et al.*, 2023b) [25]. The US Salinity Laboratory Staff (Richards, 1954) [53] classified salt-affected soils into three distinct groups: Saline soils (white alkali/solonchak) have high concentrations of chlorides and sulphates of Ca^{2+}, Mg^{2+} and Na^{+}, with SO_4^{2-}, Cl^{-}, and NO_3^{-} as dominant anions, characterised by pHs < 8.5, ECe > 4 dS m^{-1}, SAR < 13, and ESP < 15. Sodic soils (black alkali/solonetz) contain high exchangeable Na^{+} over Ca^{2+} and Mg^{2+}, with CO_3^{2-} and HCO_3^{-} as predominant salts, exhibiting pHs 8.5-10.0, ECe < 4 dS m^{-1}, SAR > 13, and ESP >15. Saline-sodic soils contain both soluble salts and exchangeable sodium, leading to strong alkalinity due to sodium hydrolysis. These soils, with pHs > 8.5, ECe > 4 dS m^{-1}, SAR >13, and ESP >15, remain friable as sodium salts prevent clay dispersion, but leaching often transforms them into sodic soils.

Plants in salt-affected soils face osmotic and nutrient stress. Osmotic stress limits water uptake due to low water potential, while nutrient stress results from ion toxicity (Na^{+}, Cl^{-}, and B) and deficiencies of essential nutrients (N, P, K, Ca, Fe, and Zn). Salinity reduces phosphorus availability as phosphate precipitates with Ca^{2+} (Bano and Fatima, 2009) [10]. In saline-sodic soils, excess Na^{+} hampers K^{+} uptake, disrupting enzymatic functions vital for photosynthesis and protein synthesis, ultimately restricting plant growth (Katiyar-Agarwal *et al.*, 2005) [33].

The reclamation of salt-affected soils involves physical, chemical, and biological interventions. Effective methods include salt leaching, sub-surface drainage, and irrigation management (Gupta, 2002) [29]. While sub-surface drainage is effective, high costs (Rs. 74,000-1,15,000 per hectare) and operational challenges limit adoption (Raju *et al.*, 2016) [50]. Chemical amendments such as gypsum, calcium chloride, elemental sulphur, and pyrites play a crucial role in reclaiming salt-affected soils (Abrol *et al.*, 1988) [3]. Gypsum is preferred for non-calcareous soils, while acid-based amendments suit calcareous soils (Sharma and Swarup, 1990) [57]. Organic amendments like farmyard manure and press mud also improve soil structure and nutrient availability (Wichern *et al.*, 2006) [66]. However, large-scale chemical treatment remains costly and impractical (Damodaran *et al.*, 2019) [13].

Microbial interventions are emerging as sustainable alternatives for soil reclamation. Halophilic and halotolerant microbes play a crucial role in reducing soil salinity, improving soil structure, and enhancing nutrient availability (Mishra *et al.*, 2021) [45]. These microorganisms facilitate nitrogen fixation and phosphate solubilisation (Hayat *et al.*, 2010) [30], thus contributing to enhanced soil fertility. The application of microbial consortia in conjunction with chemical amendments such as gypsum and sulphur has been shown to improve soil aggregation, reduce sodicity, and promote crop productivity (Lata and Gond, 2019; Schillaci *et al.*, 2019) [39, 56].

The soybean-wheat cropping system is widely practised in India due to its economic and agronomic advantages. However, its sustainability is challenged in saline-sodic soils, where nutrient deficiencies and poor soil health limit crop yields (Feng *et al.*, 2021) [22]. Macronutrients (N, P, K, and S) and micronutrients (Fe, Mn, Zn, and Cu) are often unavailable due to high soil pH and excessive sodium levels, necessitating soil amendments to restore fertility (Hussain *et al.* 2019) [32]. While previous studies have examined the effects of gypsum, sulphur, and microbial inoculants on soil health, their combined impact on post-harvest nutrient availability in sequential cropping systems remains underexplored (Arora *et al.* 2013) [7].

In this context, the present study was conducted to assess the nutrient availability of saline-sodic Inceptisol soil after the harvest of a soybean-wheat crop sequence as influenced by the application of a microbial consortium and soil amendments.

2. Materials and Methods

2.1 Experimental Site

The field experiment on saline-sodic Inceptisol soil, involving a soybean-wheat crop sequence, was conducted at the Post Graduate Instructional Research Farm, Department of Soil Science and Agricultural Chemistry, MPKV, Rahuri, over two consecutive cropping seasons (2022-23 and 2023-24). The experimental site is located at 19º20’26” N latitude, 74º38’53” E longitude, and an altitude of 527.32 meters above mean sea level. This region lies on the Eastern side of the Western Ghat Zone of Maharashtra and falls within a rain shadow area.

2.2 Soil of Experimental Site

Representative composite soil samples were collected from the saline-sodic Inceptisol at a depth of 0-30 cm from the experimental site at the Post Graduate Instructional Research Farm, Mahatma Phule Krishi Vidyapeeth, Rahuri. These samples were analysed before the commencement of the experiment. The experimental soil was classified as Inceptisols, belonging to the fine montmorillonite hyperthermic group within the Sodic Hapludepts family. It was moderately alkaline, with a $pH_{1:2.5}$ of 8.49 and an $EC_{1:2.5}$ of 2.31 dS m^{-1}. The gypsum requirement (GR) was 5.81 t ha^{-1} in 2022 and 4.81 t ha^{-1} in 2023, with an ESP of 21.33%**.** The initial soil fertility assessment indicated low availability of nitrogen (167.31 kg ha^{-1}) and phosphorus (7.96 kg ha^{-1}), while potassium content was exceptionally high (396.57 kg ha^{-1}). The soil was deficient in available sulphur (6.20 mg kg^{-1}) and iron (4.03 mg kg^{-1}), whereas available manganese levels were moderately high (4.96 mg kg^{-1}). Zinc availability was very low (0.32 mg kg^{-1}), whereas copper content was significantly high (1.69 mg kg^{-1}), highlighting the need for targeted soil amendments to address these imbalances.

2.3 Experimental Setup

The field experiment was laid out in a Randomized Block Design with ten treatments, each replicated thrice. The soybean crop was grown first during the *kharif* season, with treatments applied as follows:

T_1: GRDF (50: 75: 45 kg N: P_2O_5: K_2O ha^{-1} + FYM @ 10 t ha^{-1})
T_2: GRDF + Gypsum (as per 100% GR)
T_3: GRDF + Sulphur (as per $^1/_5$th of GR)
T_4: GRDF + Microbial consortia I of Lucknow (@ 250 mL ha^{-1})
T_5: GRDF + Microbial consortia II of VSI (@ 20 Litres ha^{-1})
T_6: GRDF + Gypsum (as per 100% GR) + Microbial consortia I (@ 250 mL ha^{-1})
T_7: GRDF + Gypsum (as per 100% GR) + Microbial consortia II (@ 20 Litres ha^{-1})

T_8: GRDF + Sulphur (as per $^{1}/_{5}$th of GR) + Microbial consortia I (@ 250 mL ha^{-1})
T_9: GRDF + Sulphur (as per $^{1}/_{5}$th of GR) + Microbial consortia II (@ 20 Litres ha^{-1})
T_{10}: Absolute Control

Following the soybean cultivation, the wheat crop was grown during the *rabi* season. Treatments T_1 to T_9 received GRDF (120:60:40 kg N, P_2O_5 and K_2O ha^{-1} + FYM 10 t ha^{-1}). At the same time, T_2 to T_9 benefited from the residual effects of soil amendments and microbial consortia applied during the preceding soybean cultivation, with T_{10} serving as the absolute control.

Treatment-wise, microbial consortia I (Lucknow) was applied by broadcasting, while microbial consortia II (VSI) were applied through drenching. Soil amendments - Gypsum (@ 5.81 in *kharif* 2022 and 4.81 t ha^{-1} in *kharif* 2023) and Sulphur (@ 1.16 in *kharif* 2022 and 0.96 t ha^{-1} in *kharif* 2023) were broadcast onto the soil before sowing the soybean crop. FYM was applied to the soil before sowing soybean and wheat crops, except in T_{10}. For soybean, the full basal dose of N, P_2O_5 and K_2O was applied, except in $T_{10.}$ For wheat, 50% of N was applied as a basal dose, along with the full basal dose of P_2O_5 and K_2O. The remaining 50% N was top-tressed at 21 and 50 DAS, except in T_{10}.

2.4 Collection and Preparation of Soil Sample

The composite and representative saline-sodic Inceptisol soil samples were collected from the 0-30 cm soil depth of the field experiment. The soil samples were air-dried in the shade on paper sheets, gently ground using a wooden mortar and pestle, thoroughly mixed, and sieved through a 2 mm nylon sieve. These prepared samples were used for initial and post-harvest soil nutrient analysis following standard analytical methods. Available nitrogen was determined using the alkaline potassium permanganate method (Subbiah and Asija, 1956) [61], while available phosphorus was estimated using 0.5 *M* $NaHCO_3$ (pH 8.5) as described by Watanabe and Olsen (1965) [65]. Available potassium was analysed using the Neutral *N* NH_4Oac Extraction Method (Knudsen *et al.*, 1982) [36], and available sulphur was determined using the turbidimetric/spectrophotometry method (William and Steinberg, 1959). [67] The available micronutrients, including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), were analysed using the DTPA (pH 7.3) extraction method followed by Atomic Absorption Spectrophotometry (AAS), as outlined by Lindsay and Norvell (1978) [41].

2.5 Statistical Analysis

The experimental data generated from the present study were statistically analysed using the Analysis of Variance (ANOVA) technique, as described by Panse and Sukhatme (1985) [49].

3. Results and discussion

3.1 Soil Available Macronutrient Content After Harvest of *Kharif* Soybean

The data on the effect of microbial consortium and soil amendments on the available macronutrients (N, P, K and S) content in saline-sodic Inceptisol soil after the harvest of *kharif* soybean in 2022 and 2023 are presented in Table 1.

Available nitrogen content after soybean harvest

The results indicate that following the harvest of *kharif* soybean, the application of GRDF + Sulphur + Microbial consortia I (T_8) significantly improved soil available macronutrient content in saline-sodic Inceptisol soil after the harvest of *kharif* soybean in 2022 and 2023. Among the treatments, T_8 recorded the highest soil available nitrogen content, reaching 238.77 kg ha^{-1} in 2022 and 270.43 kg ha^{-1} in 2023, with a pooled value of 254.60 kg ha^{-1}. This was statistically at par with T_9 (232.29, 265.63, and 248.96 kg ha^{-1}), T_7 (225.52, 260.53, and 243.03 kg ha^{-1}), T_6 (221.38, 257.83, and 239.61 kg ha^{-1}) and T_3 (201.36, 242.23, and 221.80 kg ha^{-1}) across both years and the pooled data, respectively, as well as with T_2 (238.33 and 217.14 kg ha^{-1}) and T_5 (234.73 and 213.09 kg ha^{-1}) in 2023 and the pooled data, respectively, and with T_4 (232.33 kg ha^{-1}) in 2023.

Table 1: Effect of microbial consortium and soil amendments on available macronutrient content in saline-sodic Inceptisol soil after harvest of *kharif* soybean

Tr. No.	**Treatment details**	**Available Nitrogen (kg ha^{-1})**			**Available Phosphorus (kg ha^{-1})**			**Available Potassium (kg ha^{-1})**			**Available Sulphur (mg kg^{-1})**		
		2022	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T_1	GRDF (50:75:45 kg N, P_2O_5 and K_2O ha^{-1} + 10 t FYM ha^{-1})	175.11	222.73	198.92	8.17	11.72	9.95	402.87	452.47	427.67	8.07	11.94	10.00
T_2	GRDF + Gypsum (as per 100% GR)	195.95	238.33	217.14	9.63	13.08	11.36	419.69	478.03	448.86	9.26	13.23	11.25
T_3	GRDF + Sulphur (as per $^{1}/_{5}$th of GR)	201.36	242.23	221.80	10.21	13.73	11.97	423.89	484.42	454.16	9.30	13.31	11.31
T_4	GRDF + Microbial consortia I (@ 250 mL ha^{-1})	187.83	232.33	210.08	8.74	12.07	10.40	413.22	468.20	440.71	9.02	12.66	10.84
T_5	GRDF + Microbial consortia II (@ 20 Litres ha^{-1})	191.44	234.73	213.09	9.12	12.50	10.81	415.81	472.13	443.97	9.12	12.89	11.00
T_6	GRDF + Gypsum + Microbial consortia I	221.38	257.83	239.61	11.06	14.41	12.73	440.71	509.98	475.34	10.63	15.93	13.28
T_7	GRDF + Gypsum + Microbial consortia II	225.52	260.53	243.03	11.40	14.78	13.09	443.63	514.42	479.02	10.75	16.21	13.48
T_8	GRDF + Sulphur + Microbial consortia I	238.77	270.43	254.60	12.74	16.30	14.52	454.30	530.64	492.47	10.93	16.63	13.78
T_9	GRDF + Sulphur + Microbial consortia II	232.29	265.63	248.96	12.07	15.54	13.80	449.12	522.77	485.95	10.85	16.44	13.64
T_{10}	Absolute Control	146.90	182.98	164.94	6.41	8.18	7.29	306.23	362.10	334.17	4.98	7.36	6.17
	S.Em ±	12.98	15.58	14.28	0.63	0.85	0.74	27.06	31.08	29.07	0.59	0.87	0.73
	CD at 5%	38.57	46.30	42.43	1.89	2.53	2.21	80.42	92.34	87.22	1.77	2.60	2.19
	General mean	201.66	240.78	221.22	9.95	13.23	11.59	416.95	479.52	448.23	9.29	13.66	11.48

The observed increase in available nitrogen might be due to sulphur-induced microbial activity, which enhanced organic matter decomposition, thereby facilitating nitrogen mineralisation (El-Kouny, 2009) [16]. Additionally, gypsum application enhanced soil structure, reducing nitrogen losses through leaching and promoting sustained nitrogen availability (Noor *et al.*, 2020). [48]

Available phosphorous content after soybean harvest

As depicted in Table 1, T_8 resulted in the highest soil available phosphorus content, with values of 12.74 kg ha^{-1} in 2022 and 16.30 kg ha^{-1} in 2023, yielding a pooled content of 14.52 kg ha^{-1}, which was statistically at par with T_9 (12.07, 15.54, and 13.80 kg ha^{-1}), T_7 (11.40, 14.78, and 13.09 kg ha^{-1}), and T_6 (11.06, 14.41, and 12.73 kg ha^{-1}) in 2022, 2023 and for the pooled data, respectively. The improvement in available phosphorus may be due to phosphate solubilisation through organic acid production and microbial proliferation (Mahadevaswamy and Nagaraju, 2018) [42]. Furthermore, the reduction in soil pH caused by sulphur application likely enhanced phosphorus solubility, while gypsum contributed to reducing phosphorus fixation, thereby improving its availability (Noor *et al.*, 2020) [48].

Available potassium content after soybean harvest

The significantly highest soil available potassium content was also recorded in T_8 (454.30 kg ha^{-1} in 2022 and 530.64 kg ha^{-1} in 2023), with a pooled value of 492.47 kg ha^{-1}. These results were statistically at par with T_1 to T_9 in both years and the pooled data (Table 1). The higher soil available potassium content may be attributed to sulphur-induced pH reduction, which facilitated potassium release from non-exchangeable pools (Al-Amri *et al.*, 2024) [4]. Additionally, gypsum application likely displaced exchangeable Na^{+} with Ca^{2+}, improving soil structure and enhancing potassium retention (Tejada *et al.*, 2006) [63]. Microbial consortia may have further contributed to potassium solubilisation through the production of organic acids such as oxalate, citrate, acetate, ferulic acid, and coumaric acid, which promote mineral dissolution and proton release, thereby increasing potassium availability (Etesami *et al.*, 2017) [18].

Available sulphur content after soybean harvest

Perusal of the table 1, T_8 led to a significant increase in soil available sulphur content, reaching 10.93 mg kg^{-1} in 2022 and 16.63 mg kg^{-1} in 2023, resulting in a pooled available sulphur content of 13.78 mg kg^{-1}. This increase was statistically at par with T_9 (10.85, 16.44, and 13.64 mg kg^{-1}), T_7 (10.75, 16.21, and 13.48 mg kg^{-1}), and T_6 (10.63, 15.93, and 13.28 mg kg^{-1}) in 2022, 2023 and for the pooled data, respectively, as well as with T_3 (9.30 mg kg^{-1}) and T_2 (9.26 mg kg^{-1}) in 2022 (Table 1). The significant increase in available sulphur content can be attributed to sulphur oxidation into sulphate, with microbial consortia accelerating sulphur mineralisation (Arora *et al.*, 2020) [5]. Additionally, improved soil conditions due to gypsum and GRDF application likely enhanced sulphur retention and availability (Gill *et al.*, 2009) [26].

This significant improvement in soil available macronutrient content after the harvest of *kharif* soybean in the respective treatments may be attributed to the synergistic effects of sulphur, gypsum, microbial consortia, and FYM. These amendments collectively enhanced nutrient availability, aligning with findings of Khan *et al.* (2007) [34], Singh and Najar (2007) [60], Sharma *et al.* (2013) [58], Gupta *et al.* (2015) [28], Arora *et al.* (2016) [9], Mahrous *et al.* (2016) [43], Sahay *et al.* (2018) [54], Chadha (2020) [11], El-Sonbaty and Abd-Allah (2021) [17] and Kumar *et al.* (2024) [37].

3.2 Soil Available DTPA Micronutrient Content After Harvest of *Kharif* Soybean

The data illustrating the effect of microbial consortium and soil amendments on the available micronutrients (Fe, Mn, Zn and Cu) content in saline-sodic Inceptisol soil following the harvest of *kharif* soybean in 2022 and 2023 are presented in Table 2.

The results reveal that the application of GRDF + Sulphur + Microbial consortia I (T_8) significantly enhanced the availability of all four micronutrients. The highest values for Fe were recorded at 4.81 mg kg^{-1} in 2022 and 5.52 mg kg^{-1} in 2023, with a pooled available Fe content of 5.16 mg kg^{-1}. These results were statistically at par with T_9 (4.73, 5.40, and 5.07 mg kg^{-1}), T_7 (4.53, 5.08, and 4.81 mg kg^{-1}), T_6 (4.43, 4.92, and 4.68 mg kg^{-1}), T_3 (4.36, 4.80, and 4.58 mg kg^{-1}), and T_2 (4.33, 4.76, and 4.55 mg kg^{-1}) in 2022, 2023 and for the pooled data, respectively, as well as with T_5 (4.23, and 4.42 mg kg^{-1}) and T_4 (4.18, and 4.35 mg kg^{-1}) in 2022 and the pooled data, respectively, and with T_1 (4.06 mg kg^{-1}) in 2022 (Table 2). Similarly, T_8 significantly increased soil Zn availability, recording 0.47 mg kg^{-1} in 2022 and 0.54 mg kg^{-1} in 2023, with a pooled Zn content of 0.51 mg kg^{-1}. This increase was statistically at par with T_9 (0.45, 0.52, and 0.49 mg kg^{-1}) and T_7 (0.43, 0.49, and 0.46 mg kg^{-1}) in 2022, 2023 and for the pooled data, respectively, as well as with T_6 (0.40 mg kg^{-1} in 2022, and 0.46 mg kg^{-1} in 2023).

Additionally, T_8 significantly improved the soil available manganese content, recording 5.61 mg kg^{-1} in 2022 and 6.20 mg kg^{-1} in 2023, culminating in a pooled Mn content of 5.91 mg kg^{-1}. These results were statistically at par with T_1 to T_9 in both years and pooled data (Table 2). Likewise, (T_8) resulted in significantly higher available Cu content, recording 1.90 mg kg^{-1} in 2022 and 2.03 mg kg^{-1} in 2023, with a pooled Cu content of 1.97 mg kg^{-1}. These results were statistically at par with T_1 to T_9 in both years and pooled data.

The observed increase in micronutrient availability in the corresponding treatments can be attributed to the combined effect of organic amendments, sulphur application, and microbial inoculation. FYM contributed organic matter, enhancing microbial activity and releasing organic acids and chelators, which increased the solubility and mobility of micronutrients. Sulphur-induced acidification played a crucial role in lowering soil pH, thereby enhancing the availability of Fe, Mn, Zn, and Cu. The addition of gypsum improved soil structure by replacing Na^{+} with Ca^{2+}, facilitating better root proliferation and nutrient uptake. Furthermore, microbial consortia released enzymes, organic acids, and siderophores, preventing nutrient oxidation and maintaining their soluble forms, thereby improving plant availability. These findings align with the mechanisms reported by Ramesh *et al.* (2014) [51], Mahrous *et al.* (2016) [43], Dinesh *et al.* (2018) [14] and El-Sonbaty and Abd-Allah (2021) [17], emphasizing the synergistic role of soil amendments in improving micronutrient availability in saline-sodic soils.

Table 2: Effect of microbial consortium and soil amendments on available DTPA micronutrient content in saline-sodic Inceptisol soil after harvest of *kharif* soybean

Tr. No.	**Treatment details**	**Available Iron (mg kg^{-1})**			**Available Manganese (mg kg^{-1})**			**Available Zinc (mg kg^{-1})**			**Available Copper (mg kg^{-1})**		
		2022	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T_1	GRDF (50:75:45 kg N, P_2O_5 and K_2O ha^{-1} + 10 t FYM ha^{-1})	4.06	4.28	4.17	5.01	5.23	5.12	0.33	0.38	0.36	1.71	1.82	1.77
T_2	GRDF + Gypsum (as per 100% GR)	4.33	4.76	4.55	5.38	5.86	5.62	0.38	0.43	0.40	1.79	1.91	1.85
T_3	GRDF + Sulphur (as per $^1/_5$th of GR)	4.36	4.80	4.58	5.41	5.90	5.66	0.39	0.44	0.42	1.81	1.93	1.87
T_4	GRDF + Microbial consortia I (@ 250 mL ha^{-1})	4.18	4.52	4.35	5.12	5.47	5.29	0.34	0.38	0.36	1.74	1.86	1.80
T_5	GRDF + Microbial consortia II (@ 20 Litres ha^{-1})	4.23	4.60	4.42	5.23	5.63	5.43	0.36	0.40	0.38	1.76	1.88	1.82
T_6	GRDF + Gypsum + Microbial consortia I	4.43	4.92	4.68	5.45	5.96	5.71	0.40	0.46	0.43	1.82	1.94	1.88
T_7	GRDF + Gypsum + Microbial consortia II	4.53	5.08	4.81	5.50	6.04	5.77	0.43	0.49	0.46	1.85	1.98	1.91
T_8	GRDF + Sulphur + Microbial consortia I	4.81	5.52	5.16	5.61	6.20	5.91	0.47	0.54	0.51	1.90	2.03	1.97
T_9	GRDF + Sulphur + Microbial consortia II	4.73	5.40	5.07	5.59	6.16	5.87	0.45	0.52	0.49	1.88	2.01	1.95
T_{10}	Absolute Control	3.22	3.87	3.55	3.80	3.99	3.90	0.21	0.23	0.22	1.27	1.33	1.30
	S.Em ±	0.27	0.30	0.29	0.33	0.36	0.35	0.02	0.02	0.02	0.11	0.12	0.11
	CD at 5%	0.82	0.91	0.86	1.00	1.08	1.04	0.07	0.08	0.07	0.33	0.36	0.34
	General mean	4.29	4.78	4.53	5.21	5.64	5.43	0.38	0.43	0.40	1.75	1.87	1.81

3.3 Soil Available Macronutrient Content After Harvest of *Rabi* Wheat

Soil fertility plays a crucial role in sustaining wheat productivity, particularly in saline-sodic Inceptisol soils, where nutrient dynamics are significantly influenced by amendments and microbial interventions. The data on the residual effect of microbial consortium and soil amendments applied to *kharif* soybean on the available macronutrients (N, P, K and S) content in saline-sodic Inceptisol soil after the harvest of *rabi* wheat in 2022-23 and 2023-24 are presented in Table 3.

Available nitrogen content after wheat harvest

Nitrogen is a key determinant of wheat productivity, influencing biomass accumulation and grain protein content. The results indicate that the application of GRDF + Residual effect of Sulphur and Microbial consortia I (T_8) significantly improved the soil available nitrogen content, recording 250.69 kg ha^{-1} in 2022-23 and 290.96 kg ha^{-1} in 2023-24, achieving a pooled available nitrogen content of 270.82 kg ha^{-1}. These results were statistically at par with T_2 to T_9 across both years and the pooled data (Table 3). The observed improvement in soil nitrogen availability may be attributed to the residual effects of sulphur and gypsum, which likely enhanced nitrogen retention and availability. Additionally, microbial consortia may have contributed to nitrogen cycling by increasing microbial activity and biological nitrogen fixation, thereby improving nitrogen assimilation in the soil profile (Arora *et al.*, 2015) [8].

Available phosphorous content after wheat harvest

Phosphorus plays a vital role in root development, energy transfer, and grain filling in wheat. The highest soil available phosphorus content was observed in T_8, recording 14.11 kg ha^{-1} in 2022-23 and 18.24 kg ha^{-1} in 2023-24, leading to a pooled available phosphorus content of 16.17 kg ha^{-1}. These values were statistically at par with T_9 (13.43, 17.37, and 15.40 kg ha^{-1}), T_7 (12.76, 16.53, and 14.65 kg ha^{-1}), and T_6 (12.43, 16.11, and 14.27 kg ha^{-1}) across the respective years and pooled data (Table 3). The enhancement in phosphorus availability was likely due to microbial-mediated solubilisation of insoluble phosphate compounds through the production of extracellular phosphatases and organic acids (Kumar *et al.*, 2017) [38].

Table 3: Residual effect of microbial consortium and soil amendments applied to *kharif* soybean on the available macronutrient content in saline-sodic Inceptisol soil after harvest of *rabi* wheat

Tr. No.	**Treatment details**	**Available Nitrogen (kg ha^{-1})**			**Available Phosphorus (kg ha^{-1})**			**Available Potassium (kg ha^{-1})**			**Available Sulphur (mg kg^{-1})**		
		2022-23	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**	**2022-23**	**2023-24**	**Pooled**
T_1	GRDF (120:60:40 kg N, P_2O_5 and K_2O ha^{-1} + 10 t FYM ha^{-1})	195.45	235.72	215.59	9.93	13.16	11.54	426.80	478.66	452.73	9.42	12.49	10.96
T_2	GRDF + Residual effect of Gypsum	210.56	250.83	230.70	11.19	14.66	12.92	452.36	504.22	478.29	11.40	15.78	13.59
T_3	GRDF + Residual effect of Sulphur	215.44	255.71	235.57	11.77	15.38	13.57	458.75	510.61	484.68	11.46	15.86	13.66
T_4	GRDF + Residual effect of Microbial consortia I	203.06	243.33	223.20	10.30	13.54	11.92	442.53	494.39	468.46	11.04	15.21	13.12
T_5	GRDF + Residual effect of Microbial consortia II	206.06	246.33	226.20	10.68	14.02	12.35	446.46	498.32	472.39	11.18	15.44	13.31
T_6	GRDF + Residual effect of Gypsum and Microbial consortia I	234.94	275.21	255.07	12.43	16.11	14.27	484.31	536.17	510.24	13.26	18.48	15.87
T_7	GRDF + Residual effect of Gypsum and Microbial consortia II	238.31	278.58	258.45	12.76	16.53	14.65	488.75	540.61	514.68	13.44	18.76	16.10
T_8	GRDF + Residual effect of Sulphur and Microbial consortia I	250.69	290.96	270.82	14.11	18.24	16.17	504.97	556.83	530.90	13.71	19.18	16.44
T_9	GRDF + Residual effect of Sulphur and Microbial consortia II	244.69	284.96	264.82	13.43	17.37	15.40	497.10	548.96	523.03	13.59	18.99	16.29
T_{10}	Absolute Control	167.85	203.12	185.49	7.44	9.12	8.28	345.66	378.66	362.16	5.57	9.91	7.74
	S.Em ±	13.99	16.59	15.29	0.73	0.95	0.84	29.46	32.72	31.09	0.73	1.02	0.88
	CD at 5%	41.57	49.29	45.43	2.18	2.83	2.50	87.55	97.23	92.39	2.17	3.05	2.61
	General mean	216.71	256.48	236.59	11.40	14.81	13.11	454.77	504.74	479.76	11.41	16.01	13.71

Available potassium content after wheat harvest

Potassium is essential for enzyme activation, osmotic regulation, and drought resistance in wheat. The treatment involving GRDF + Residual effect of Sulphur and Microbial consortia I (T_8) also resulted in significantly higher soil available potassium content, recording 504.97 kg ha^{-1} in 2022-23 and 556.83 kg ha^{-1} in 2023-24, with a pooled potassium content of 530.90 kg ha^{-1}. These results were statistically at par with T_1 to T_9 in 2022-23, 2023-24, and for the pooled data (Table 3). The increased potassium availability may be due to the residual effect of sulphur in lowering soil pH, thereby promoting potassium release from non-exchangeable pools. Additionally, gypsum application could have improved soil structure by displacing Na^+ with Ca^{2+}, leading to enhanced potassium retention in the root zone. Microbial consortia likely facilitated potassium solubilisation through the production of organic acids such as oxalate, citrate, and acetate, which may have enhanced mineral dissolution and potassium availability.

Available sulphur content after wheat harvest

Sulphur is a critical nutrient for protein synthesis and enzyme function in wheat. The highest soil available sulphur content was recorded in T_8, with 13.71 mg kg^{-1} in 2022-23 and 19.18 mg kg^{-1} in 2023-24, culminating in a pooled sulphur content of 16.44 mg kg^{-1}. This increase was statistically at par with T_9 (13.59, 18.99, and 16.29 mg kg^{-1}), T_7 (13.44, 18.76, and 16.10 mg kg^{-1}), and T_6 (13.26, 18.48, and 15.87 mg kg^{-1}) across both years and pooled data (Table 4). The improvement in soil available sulphur content can be attributed to the residual effects of sulphur oxidation into sulphate, which likely increased sulphur availability. Additionally, microbial consortia may have accelerated sulphur mineralisation, while FYM application could have enhanced sulphur retention in the soil, thereby improving its availability for subsequent crops.

The results suggest that the integrated application of sulphur, gypsum, and microbial consortia played a pivotal role in enhancing macronutrient availability and improving soil conditions for wheat cultivation in saline-sodic Inceptisols. These findings provide a strong foundation for recommending microbial-assisted soil remediation as a sustainable strategy for nutrient management in degraded soils. These results are in agreement with mechanisms reported by Yasmin *et al.* (2007) [68], Kumar *et al.* (2017) [38], Nisha *et al.* (2017) [47], Khandkar *et al.* (2017) [35], Sakore (2021) [55] and Nadeem *et al.* (2023) [46]

3.4 Soil Available DTPA Micronutrient Content After Harvest of *Rabi* Wheat

The data illustrating the residual effect of microbial consortium and soil amendments applied to *kharif* soybean on the available micronutrient (Fe, Mn, Zn and Cu) content in saline-sodic Inceptisol soil following the harvest of *rabi* wheat during 2022-23 and 2023-24 are presented in Table 4.

The findings indicate that integrated nutrient management strategies significantly enhanced soil micronutrient availability, with the highest improvements recorded in T_8 (GRDF + Residual Effect of Sulphur and Microbial Consortia I). After the harvest of *rabi* wheat, T_8 exhibited a significantly higher soil available iron content, recording 5.11 mg kg^{-1} in 2022-23 and 5.90 mg kg^{-1} in 2023-24, contributing to a pooled available iron content of 5.51 mg kg^{-1}. These results were statistically at par with T_2 to T_9 in both years and for the pooled data (Table 4). Likewise, T_8 significantly improved the soil available manganese content, with values of 6.09 mg kg^{-1} in 2022-23 and 6.61 mg kg^{-1} in 2023-24, resulting in a pooled available manganese content of 6.35 mg kg^{-1}. These results were statistically at par with T_2 to T_9 in both years and for the pooled data, as well as with T_1 (5.12 and 5.28 mg kg^{-1}) in 2023-24 and the pooled data.

Moreover, T_8 recorded a significant increase in soil available zinc content, with values of 0.50 mg kg^{-1} in 2022-23 and 0.57 mg kg^{-1} in 2023-24, yielding a pooled available zinc content of 0.54 mg kg^{-1}. This increase was statistically at par with T_9 (0.48, 0.55, and 0.52 mg kg^{-1}), T_7 (0.46, 0.52, and 0.49 mg kg^{-1}), and T_6 (0.43, 0.49, and 0.46 mg kg^{-1}) in 2022-23, 2023-24, and for the pooled data, respectively. Similarly, T_8 consistently resulted in significantly higher soil available copper content, recording 2.00 mg kg^{-1} in 2022-23 and 2.13 mg kg^{-1} in 2023-24, culminating in a pooled available copper content of 2.06 mg kg^{-1}. These results were statistically at par with T_1 to T_9 in both years and for the pooled data (Table 4).

Table 4: Residual effect of microbial consortium and soil amendments applied to *kharif* soybean on the available DTPA micronutrient content in saline-sodic Inceptisol soil after harvest of *rabi* wheat

Tr. No.	Treatment details	Available Iron (mg kg^{-1})			Available Manganese (mg kg^{-1})			Available Zinc (mg kg^{-1})			Available Copper (mg kg^{-1})		
		2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	GRDF (120:60:40 kg N, P_2O_5 and K_2O ha^{-1} + 10 t FYM ha^{-1})	4.14	4.39	4.27	5.12	5.44	5.28	0.35	0.40	0.38	1.76	1.88	1.82
T_2	GRDF + Residual effect of Gypsum	4.52	5.00	4.76	5.75	6.22	5.98	0.40	0.46	0.43	1.86	1.99	1.93
T_3	GRDF + Residual effect of Sulphur	4.55	5.05	4.80	5.79	6.27	6.03	0.42	0.47	0.44	1.89	2.02	1.95
T_4	GRDF + Residual effect of Microbial consortia I	4.33	4.72	4.52	5.36	5.78	5.57	0.36	0.41	0.39	1.80	1.92	1.86
T_5	GRDF + Residual effect of Microbial consortia II	4.39	4.81	4.60	5.52	5.97	5.74	0.38	0.43	0.41	1.83	1.95	1.89
T_6	GRDF + Residual effect of Gypsum and Microbial consortia I	4.64	5.19	4.92	5.85	6.34	6.10	0.43	0.49	0.46	1.90	2.03	1.96
T_7	GRDF + Residual effect of Gypsum and Microbial consortia II	4.77	5.38	5.07	5.93	6.43	6.18	0.46	0.52	0.49	1.94	2.07	2.00
T_8	GRDF + Residual effect of Sulphur and Microbial consortia I	5.11	5.90	5.51	6.09	6.61	6.35	0.50	0.57	0.54	2.00	2.13	2.06
T_9	GRDF + Residual effect of Sulphur and Microbial consortia II	5.02	5.76	5.39	6.05	6.57	6.31	0.48	0.55	0.52	1.97	2.10	2.04
T_{10}	Absolute Control	3.45	3.99	3.72	3.88	4.09	3.99	0.22	0.24	0.23	1.30	1.35	1.33
	SEm ±	0.28	0.32	0.30	0.35	0.37	0.37	0.02	0.02	0.02	0.11	0.12	0.12
	CD at 5%	0.86	0.95	0.90	1.06	1.11	1.10	0.07	0.08	0.08	0.35	0.37	0.36
	General mean	4.49	5.02	4.75	5.53	5.97	5.75	0.40	0.45	0.43	1.82	1.94	1.88

The significant increase in available micronutrient content after wheat harvest might be due to the synergistic effects of FYM, sulphur, gypsum, and microbial consortia, which could have collectively enhanced soil fertility and nutrient dynamics. The organic matter in FYM likely stimulated microbial activity, thereby increasing the solubilisation of iron, manganese, zinc, and copper through the release of organic acids and chelating compounds. The residual effects of sulphur and gypsum may have contributed to soil structural improvement and induced favourable pH modifications, which in turn enhanced micronutrient availability. Additionally, microbial consortia possibly played a crucial role by producing siderophores and other bioactive compounds that facilitated iron and manganese solubilisation, while also promoting zinc and copper mobilisation through enzymatic activity and organic complex formation. This integrated approach therefore contributed to a sustained release and improved retention of micronutrients, ensuring their availability for subsequent crops in the wheat-soybean rotation. These results align with mechanisms reported by Tariq *et al.* (2007) [62], Abdelhamid *et al.* (2013) [1], Kumar *et al.* (2017) [38], El-Kamar (2020) [15] and Nadeem *et al.* (2023) [46], supporting the use of bio-organic strategies for soil fertility improvement and sustainable crop production in salt-affected soils.

4. Conclusion

In conclusion, the application of GRDF + Sulphur + Microbial consortia I (T_8) significantly enhanced soil nutrient availability after soybean harvest in both years. This treatment improved macronutrient levels (N, P, K, and S) while also enriching the soil with essential micronutrients (Fe, Mn, Zn, and Cu). Moreover, the residual effects of sulphur and microbial consortia, along with GRDF, sustained these benefits after wheat harvest, leading to continued soil fertility improvement over two consecutive *rabi* seasons. Therefore, applying GRDF + Sulphur (as per $^{1}/_{5}{}^{th}$ of GR) + Microbial consortia I of Lucknow (@ 250 mL ha^{-1}) in the preceding crop, followed by GRDF with the residual effects of sulphur and microbial consortia in the succeeding crop, is recommended as an effective strategy for improving soil health in saline-sodic soils.

5. Acknowledgement

The author extends sincere gratitude to the Department of Soil Science and Agricultural Chemistry, Post Graduate Institute, MPKV, Rahuri, Dist. Ahmednagar, Maharashtra, India, for providing the essential facilities required to undertake this research. Profound appreciation is also expressed to the research guide and colleagues for their generous encouragement and constructive criticism throughout the successful completion of this study. Additionally, heartfelt thanks are extended to the SARTHI Institute for its financial support.

6. References

1. Abdelhamid M, Eldardiry E, El-Hady MA. Ameliorate salinity effect through sulphur application and its effect on some soil and plant characters under different water quantities. Agric Sci. 2013;4:39-47.
2. Abdennour MA, Douaoui A, Piccini C, Pulido M, Bennacer A, Bradaï A, *et al*. Predictive mapping of soil electrical conductivity as a proxy of soil salinity in south-east of Algeria. Environ Sustain Indic. 2020;8:100087.
3. Abrol IP, Yadav YS, Massoud FI. Salt-affected soils and their management. Soils Bulletin No. 39. FAO; 1988. p. 131.
4. Al-Amri M, Souissi Y, Menezes-Blackburn D, Al-Mayahi A, Al-Ismaily S, Al-Siyabi B, *et al*. Bacterial communities associated with the oxidation of elemental sulphur in calcareous soils of Oman. J Soil Sci Plant Nutr. 2024;1-14.
5. Arora NK, Fatima T, Mishra J, Mishra I, Verma S, Verma R, *et al*. Halo-tolerant plant growth-promoting rhizobacteria for improving productivity and remediation of saline soils. J Adv Res. 2020;26:69-82.
6. Arora S, Sharma V. Reclamation and management of salt-affected soils for safeguarding agricultural productivity. J Safe Agric. 2017;1:1-10.
7. Arora S, Bhuva C, Slanki RB, Rao GG. Halophytes for bio-saline agro-forestry and phytoremediation of coastal saline lands. J Soil Water Conserv. 2013;12:252-259.
8. Arora S, Singh YP, Singh AP, Mishra VK, Sharma DK. Integrated effect of pressmud, chemical amendments and microbial bioinoculant on sodic soil reclamation productivity of rice-wheat. In: Advances in Soil and Water Resource Management for Food and Livelihood Security in Changing Climate. 2015. p. 519-528.
9. Arora S, Singh YP, Vanza M, Sahni D. Bioremediation of saline and sodic soils through halophilic bacteria to enhance agricultural production. J Soil Water Conserv. 2016;15(4):302-305. Doi: 10.5958/2455-7145.2016.00027.8
10. Bano A, Fatima M. Salt tolerance in *Zea mays* (L.) following inoculation with Rhizobium and Pseudomonas. Biol Fertil Soils. 2009;45:405-413.
11. Chadha D. Improving health of salt-affected soils through microbial formulations. M.Sc. (Agri.) Thesis submitted to Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, India; 2020.
12. Dagar JC, Yadav RK, Singh A, Singh NT. Historical perspectives and dynamics of nature, extent, classification, and management of salt-affected soils and waters. In: Dagar JC, *et al*., editors. Research developments in saline agriculture. Springer Nature Switzerland AG; 2019.
13. Damodaran T, Mishra V, Jha S, Pankaj U, Gupta G, Gopal R. Identification of rhizosphere bacterial diversity with promising salt tolerance, PGP traits and their exploitation for seed germination enhancement in sodic soil. Agric Res. 2019;8:36-43.
14. Dinesh R, Srinivasan V, Hamza S, Sarathambal C, Gowda SJ, Ganeshamurthy AN, *et al*. Isolation and characterization of potential Zn solubilizing bacteria from soil and its effect on soil Zn release rates, soil available Zn and plant Zn content. Indian Institute of Spice Research. 2018;173-186.
15. El-Kamar FA. Evaluation of some soil conditioners on some properties of salt-affected soil and wheat productivity and quality. J Soil Sci Agric Eng Mansoura Univ. 2020;11(7):307-314.
16. El-Kouny HM. Growth and quality response of sugar beet (*Beta vulgaris* L.) grown on calcareous soil to compost, elemental sulphur and nitrogen applications. Egypt J Soil Sci. 2009;49(4):505-518.
17. El-Sonbaty AE, Abd-Allah YAM. Improving the characteristics of saline clay soils and their effect on the productivity of faba bean. J Soil Sci Agric Eng. 2021;12(5):327-335.
18. Etesami H, Emami S, Alikhani HA. Potassium solubilizing bacteria: mechanisms, promotion of plant growth, and future prospects. J Soil Sci Plant Nutr. 2017;17(4).
19. FAO. Healthy soils are the basis for healthy food production. Food and Agriculture Organization; 2015. Available from: https://www.fao.org/soils-2015/news/news-

detail/en/c/277682/
20. FAO. Mapping of salt-affected soils: Technical specifications and country guidelines. FAO; 2020. Rome.
21. FAO. Global map of salt-affected soils (GSASmap). Food and Agriculture Organization of the United Nations; 2021. Available from: https://www.fao.org/soils-portal/data-hub
22. Feng C, He C, Wang Y, Xu H, Xu K, Zhao Y. Genome-wide identification of soybean shaker K (+) channel gene family and functional characterization of GmAKT1 in transgenic Arabidopsis thaliana under salt and drought stress. J Plant Physiol. 2021;266:153529.
23. Gaikwad AS, Bhakare BD, Kamble BM, Thakare RS, Durgude AG. Salinity dynamics: Exploring causes and consequences. Agri Articles. 2023;3(5). Available from: http://www.agriarticles.com. ISSN: 2582-9882.
24. Gaikwad AS, Bhakare BD, Kamble BM, Thakare RS, Durgude AG. Soil microbiome: Applications and mechanisms for salinity stress mitigation in plant and soil ecology: A review. Int J Adv Biochem Res. 2024;8(3):923-946. doi: 10.33545/26174693.2024.v8.i3k.875
25. Gaikwad AS, Margal PB, Titirmare NS. Soil degradation and remediation: Strategies for restoring soil quality. In: Chaware SA, *et al.*, editors. Advances in Soil Science. 1(16):349-390. New Delhi: Bright Sky Publications; 2023. Available from: http://dx.doi.org/10.5281/zenodo.8330919
26. Gill JS, Sale PWG, Peries RR, Tang C. Changes in soil physical properties and crop root growth in dense sodic subsoil following incorporation of organic amendments. Field Crops Res. 2009;114:137-146. doi: 10.1016/j.fcr.2009.07.018
27. Goswami M, Deka S. Plant growth-promoting rhizobacteria-Alleviators of abiotic stresses in soil: A review. Pedosphere. 2020;30(1):40-61. Available from: http://refhub.elsevier.com/B978-0-323-90568-8.00002-X/rf0195
28. Gupta M, Srivastava PK, Singh SB, Singh N, Tewari SK. Organic amendments with plant growth promoting fungi support paddy cultivation in sodic soil. Commun Soil Sci Plant Anal. 2015;46(18):2332-2341.
29. Gupta SK. A century of subsurface drainage research in India. Irrig Drain Syst. 2002;16:69-84. doi: 10.1023/A:1015525405522
30. Hayat R, Ali S, Amara U, Khalid R, Ahmed I. Soil beneficial bacteria and their role in plant growth promotion. A review. Ann Microbiol. 2010;60:579-598.
31. Hopmans JW, Qureshi AS, Kisekka I, Munns R, Grattan SR, Rengasamy P, *et al*. Critical knowledge gaps and research priorities in global soil salinity. In: Sparks DL, editor. Advances in Agronomy. 2021;169:1-191. Academic Press.
32. Hussain S, Shaukat M, Ashraf M, Zhu C, Jinand Q, Zhang J. Salinity stress in arid and semi-arid climates: Effects and management in field crops. In: Climate Change and Agriculture. Intech Open; 2019. Available from: http://10.0.22.140/intechopen.87982
33. Katiyar-Agarwal S, Verslues P, Zhu JK. Plant nutrition for food security, human health and environmental protection. In: Li CJ, editor. Mechanisms of Salt Tolerance in Plants. Beijing: Tsinghua University Press; 2005. p. 44-45.
34. Khan HR, Syeed SMA, Ahmed FA, Shamim HM, Oki Y, Adachi T. Response of sunflower to sulfidic materials and magnesium sulphate as sulphur fertilizer. J Biol Sci. 2007;7(6):888-895.
35. Khandkar UR, Tiwari SC, Sharma RK, Verma SK, Meena RL, Kaledhonkar MJ. Relative efficiency of amendments for reclamation of sodic Vertisols and their effects on crop production. J Soil Salinity Water Qual. 2017;9(2):187-193.
36. Knudsen DA, Peterson GA, Pratt PF. Lithium, sodium, and potassium. In: Page AL, editor. Methods of soil analysis. Agronomy Monograph 9. Madison, Wisconsin: American Society of Agronomy, Soil Science Society of America; 1982. p. 225-246.
37. Kumar H, Chinchmalatpure AR, Shukla M, Camus D, Gorain B. Halophilic microbial formulations for improving crop productivity and soil health under saline Vertisols of Gujarat. Indian J Agron. 2024;69(1):61-64.
38. Kumar M, Singh R, Kumawat RN. On-farm performance of wheat grown on sodic soils irrigated with high RSC water in arid regions of Rajasthan. J Soil Water Conserv. 2017;16(3):279-284. doi: 10.5958/2455-7145.2017.00041.8.
39. Lata R, Gond SK. Plant growth-promoting microbes for abiotic stress tolerance in plants. In: Role of plant growth promoting microorganisms in sustainable agriculture and nanotechnology. Elsevier; 2019. p. 89-105.
40. Lekka C, Petropoulos GP, Triantakonstantis D, Detsikas SE, Chalkias C. Exploring the spatial patterns of soil salinity and organic carbon in agricultural areas of Lesvos Island, Greece, using geoinformation technologies. Environ Monit Assess. 2023;195:391. doi: 10.1007/s10661-023-10923-5.
41. Lindsay WL, Norvell WA. Development of DTPA soil tests for Zn, Fe, Mn, and Cu. Soil Sci Soc Am J. 1978;42:421-428.
42. Mahadevaswamy Y, Nagaraju Y. Role of halophilic microorganisms in agriculture. J Pharm Phytochem. 2018;7(3):1063-1071.
43. Mahrous MS, Abd El-Azeem SM, Ahmed MA. Effect of applying some soil amendments and distance between drains on quality and productivity of soybean grown under saline conditions. J Soil Sci Agric Eng Mansoura Univ. 2016;7(12):937-946.
44. Mandal S, Raju R, Kumar A, Kumar P, Sharma PC. Current status of research, technology response, and policy needs of salt-affected soils in India: A review. J Indian Soc Coastal Agric Res. 2018;36:40-53.
45. Mishra P, Mishra J, Arora NK. Plant growth-promoting bacteria for combating salinity stress in plants - Recent developments and prospects: A review. Microbiol Res. 2021;252:126861.
46. Nadeem SM, Hanif A, Khan MY, Waqas MR, Ahmad Z, Ashraf MR, *et al*. Elemental sulphur with sulphur oxidizing bacteria enhances phosphorus availability and improves growth and yield of wheat in calcareous soil. Arch Agron Soil Sci. 2023;69(9):1494-1502.
47. Nisha R, Kiran B, Kaushik A, Kaushik CP. Bioremediation of salt-affected soils using cyanobacteria in terms of physical structure, nutrient status, and microbial activity. Int J Environ Sci Technol. 2017;15(3):571-580.
48. Noor RS, Hussain F, Abbas I, Muhammad UM, Sun Y. Effect of compost and chemical fertilizer application on soil physical properties and productivity of sesame (*Sesamum indicum* L.). Biomass Conversion Biorefinery. 2020.
49. Panse VG, Sukhatme PV. Statistical methods for agricultural workers. 4th ed. New Delhi: Indian Council of Agricultural Research; 1985. p. 157-165.
50. Raju R, Thimmappa K, Kumar P, Kumar S, Tripathi RS. Reclamation of saline soils through subsurface drainage technology in Haryana: An economic impact analysis. J Soil

Salinity Water Qual. 2016;8:194-201.

51. Ramesh A, Sharma SK, Sharma MP, Yadav N, Joshi O. Plant growth-promoting traits in Enterobacter cloacae isolated from soybean rhizosphere and its impact on growth and nutrition of soybean. Agric Res. 2014;3(1):53-66.
52. Rengasamy P. Soil salinization. Oxford Research Encyclopedia of Environmental Science. 2016.
53. Richards LA. Diagnosis and improvement of saline and alkali soils. USDA Handbook 60. Washington, DC: US Department of Agriculture; 1954. p. 83-100. Available from: https://cir.nii.ac.jp/crid/1570291224519518080 and https://www.ars.usda.gov/
54. Sahay R, Singh AK, Arora S, Singh A, Tiwari DK, Mauyra RC, *et al*. Effect of halophilic bioformulations on soil fertility and productivity of salt-tolerant varieties of paddy in sodic soil. Int J Curr Microbiol Appl Sci. 2018;1:1174-1179.
55. Sakore GD. Reclamation of sodic soil by application of different amendments and its response to onion-maize crop sequence. Ph.D. (Agri.) Thesis. Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra; 2021.
56. Schillaci M, Gupta S, Walker R, Roessner U. The role of plant growth-promoting bacteria in the growth of cereals under abiotic stresses. In: Root Biology-Growth, Physiology, and Functions. IntechOpen; 2019.
57. Sharma P, Swarup A. Microbial oxidation of pyrites in relation to its efficiency for reclamation of alkali soils: Annual Report. Central Soil Salinity Research Institute, Karnal, India; 1990.
58. Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA. Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus. 2013;2(1):587-601. doi: 10.1186/2193-1801-2-587.
59. Singh G, Bundela DS, Sethi M, Lal K, Kamra SK. Remote sensing and geographic information system for appraisal of salt-affected soils in India. J Environ Qual. 2010;39:5-15.
60. Singh SR, Najar GR. Productivity and nutrient uptake of soybean (*Glycine max*) as influenced by bioinoculants and FYM under rainfed conditions. Indian J Agron. 2007;52(4):325-329.
61. Subbiah BV, Asija GL. A rapid procedure for the estimation of available nitrogen in soils. Curr Sci. 1956;25:259-260.
62. Tariq M, Hammed S, Malik KA, Hafeez FY. Plant root-associated bacteria for zinc mobilization in rice. Pak J Bot. 2007;39(1):245-253.
63. Tejada M, Garcia C, Gonzalez JL, Hernandez MT. Use of organic amendment as a strategy for saline soil remediation: Influence on the physical, chemical, and biological properties of soil. Soil Biol Biochem. 2006;38:1413-1422.
64. Tomaz A, Palma P, Fialho S, Lima A, Alvarenga P, Potes M, *et al*. Risk assessment of irrigation-related soil salinization and sodification in Mediterranean areas. Water. 2020;12(12):3569.
65. Watanabe FS, Olsen SR. Test of ascorbic acid methods for phosphorus in water and sodium bicarbonate extract of soil. Proc Soil Sci Am. 1965;21:677-678.
66. Wichern J, Wichern F, Joergensen RG. Impact of salinity on soil microbial communities and the decomposition of maize in acidic soils. Geoderma. 2006;137:100-108.
67. William CH, Steinberg A. Soil sulphur fraction as chemical indices of available sulphur in some Australian soil. Aust J Agric Res. 1959;10:340-350.
68. Yasmin N, Blair G, Till R. Effect of elemental sulphur, gypsum, and elemental sulphur-coated fertilizers, on the availability of sulphur to rice. J Plant Nutr Soil Sci. 2007;30:79-91.