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Unlocking the potentiality of halophilic PGPR consortia for salinity-resilient brinjal production

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ABSTRACT

Soil salinization has become a major threat to agricultural sustainability and food security by causing severe crop losses and lot of efforts are being made to reclaiming the salt affected soil. Further, the soil microorganisms, particularly halophilic plant growth promoting rhizobacteria play a pivotal role by facilitating good nutrient cycling, solubilizing minerals, producing phytohormones, suppressing soil-borne pathogens, salinity stress and also sustainable production of the different crops of salt affected sites. In the present investigation, four efficient bacterial isolates *Kosakonia oryzae*, *Serratia surfactant-faciens*, *Citrobacter freundii* and *Azotobacter vinelandii* were used to develop solid, liquid and gel formulations and developed formulations were evaluated on brinjal under pot culture using saline soil. Out of nine treatments imposed, the treatment T₉ receiving 100 % NPK + Gel formulation of Halophilic Bacterial Consortia (HBC) had significantly resulted in enhanced plant growth parameters viz., plant height (92.00 cm) and number of leaves (120.67) followed by T₇ (100 % NPK + liquid formulation of HBC) which resulted plant height (89.67 cm), leaves (116.33) compared to 100 %, 75 % NPK and absolute control treatments. With respect to the yield parameters maximum yield of 24.5 t ha⁻¹ was recorded in T₇ however the absolute control treatment recorded the lowest yield of 13.53 t ha⁻¹. The study provides a sustainable, eco-friendly biofertilizer strategy and serve as biological amendment for reclamation of marginalized saline land, secure crop yields and reduce dependence on chemical inputs in salt-affected agricultural regions and the scale up studies are required to further evaluate the developed consortia under field condition for sustainable production of different crops under salt affected conditions.

Keywords: Halophilic, PGPR consortia, Formulations, Brinjal, Growth, Yield

1. Introduction

Soil salinization, driven by climate change and intensive human activities, has become a major threat to global agricultural sustainability and food security by causing osmotic imbalance, ion toxicity, oxidative stress and severe crop losses. Halotolerant plant growth promoting rhizobacteria (HT-PGPR) are emerging as promising biological agents to alleviate salt induced damage, enhance plant growth and restore saline soils (Li *et al.*, 2025) [1]. Similarly, Abuqamar *et al.*, (2024) [2] revealed, the addition to the rehabilitation of salt degraded soils, halotolerant plant growth promoting rhizobacteria (HT-PGPR) are also effective in stimulating growth, improving nutritional values and yields, and increasing tolerance/resistance to abiotic/biotic stress conditions of plants, thus contributes to the sustainable agriculture under salt affected soil condition. Brinjal (*Solanum melongena* L.) commonly known as eggplant or aubergine, is one of the most important solanaceous vegetable crop cultivated widely in tropical and subtropical regions of the world. In India, it holds a prominent place due to its adaptability to diverse agro-climatic conditions, high yield potential, and year round availability. Brinjal is valued for its nutritional qualities, being a rich source of vitamins, minerals, dietary fiber and bioactive compounds such as anthocyanins and phenolics, which contribute to health benefits. Despite its significance, cultivation faces challenges like soil fertility and input management. Sustainable cultivation practices are therefore crucial to enhance productivity, improve quality, and ensure the crop's contribution to food security and farmer livelihoods.

Scientific design is important to adopt halophilic consortia in agriculture which offers a practical pathway to manage both saline soils and improve brinjal crop productivity in real farming conditions. By introducing salt tolerant microbial consortia, farmers can reduce the negative impact of salinity on plant growth, enhance nutrient cycling and promote healthier root systems which ultimately increases the yields of the crops grown under such situations. This approach not only supports immediate crop resilience, but also contributes to long-term soil restoration, making it a cost-effective and sustainable solution for regions struggling with salinity stress. Therefore, careful monitoring and gradual integration into existing practices, halophilic consortia can become a valuable tool for farmers aiming to secure twin objective of sustainable brinjal production and maintain soil health under challenging environmental conditions.

2. Materials and Methods

The study was conducted during 2024–2026 at the Department of Microbiology, College of Agriculture, Shivamogga, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India. The study includes the development of halophilic bacterial consortia formulations to evaluate on brinjal under pot culture conditions using saline soil collected from Hirur region.

Collection of efficient halophilic bacterial isolates

The four efficient halophilic bacterial isolates *Kosakonia oryzae*, *Serratia surfactantifaciens*, *Citrobacter freundii* and *Azotobacter vinelandii* were collected from Department of Microbiology, College of Agriculture, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka.

Compatibility of halophilic bacterial isolates

The collected isolates were tested for their compatibility and based on compatibility test, the isolates were used to develop solid, liquid and gel formulations.

Compatibility analysis

The nutrient agar was poured into sterile petri plates and were allowed to solidify. The plates were then divided into sectors and labelled accordingly. Each bacterial isolate was streaked onto the agar surface in a linear or V-shaped pattern, maintaining a gap of 2–3 mm between adjacent isolates. The inoculated plates were incubated at 28 ± 2 °C for 48 hours. After incubation, the interaction zones between the isolates were carefully observed. The presence or absence of inhibition zones at the intersection of growth lines was recorded. Isolates showing uninterrupted or overlapping growth without any inhibition were considered compatible, while those exhibiting clear inhibition zones were deemed incompatible (Sindhu *et al.*, 2002) [3].

2.4 Development of different formulations

The bacterial isolates compatible to each other were used to develop solid, liquid and gel formulations of the efficient halophilic bacterial consortia and evaluated for their influence on growth and yield of brinjal.

The efficient halophilic bacteria were mixed with talc powder to develop solid formulation as given by Sireesha (2000) [4]. The liquid formulation, pure culture of selected halophilic bacterial isolates was inoculated into fresh medium containing Glycerol and Polyvinylpyrrolidone at 0.5 per cent and incubated for 7 days to attain complete growth and to develop gel formulation, the liquid pure cultures of selected halophilic bacterial isolates were mixed with 1.5 % Sodium Alginate, later using micro pipette press, dip the culture drop by drop in 0.6 % CaCl_2 solution so that the beads will be formed, drain out the excess water and collect the gel beads, the method given by Ohmomo *et al.*, (1988) [5]

2.5 Pot culture studies

A pot culture studies was conducted to assess the effect of efficient bacterial consortial formulations on brinjal using the saline soils collected from Hirur regions (Chitradurga district). The twenty-five days old seedlings of brinjal were transplanted to the pot containing saline soil. Each pot was transplanted with single seedling.

Experimental details

Type of experiment : Pot culture experiment

Location : College of Agriculture, Navile, Shivamogga

Crop : Brinjal

Variety : Rampur Local

Number of repetitions : 3

Number of treatments : 9

Number of plants per pot : 1

Pot weight (Soil + FYM) : 25 kg

Experimental design : Completely Randomized Design (CRD)

Type of soil : Red loamy

NPK : 125: 100: 50 kg ha⁻¹

Treatment details

1.	T ₁ – Absolute control
2.	T ₂ - 75 % NPK
3.	T ₃ - 100 % NPK
4.	T ₄ - 75 % NPK + Solid formulation of HBC
5.	T ₅ - 100 % NPK Solid formulation of HBC
6.	T ₆ - 75 % NPK + Liquid formulation of HBC
7.	T ₇ - 100 % NPK + Liquid formulation of HBC
8.	T ₈ - 75 % NPK + Gel formulation of HBC
9.	T ₉ - 100 % NPK + Gel formulation of HBC

Note:

1. Halophilic bacterial consortia (HBC)
2. Solid formulation of halophilic bacterial consortia @ 12.50 kg/ha
3. Liquid formulation of halophilic bacterial consortia @ 625 ml/ha
4. Gel formulation of halophilic bacterial consortia @ 5 kg/ha
- 5.
6. FYM is common for all treatment and applied as basal dose

Observation recorded

To evaluate the impact of the halophilic bacterial consortia, growth parameters were systematically recorded for all experimental units at 60, 90, 120 Days After Transplanting (DAT). The specific methodologies and standardized protocols employed for the quantification of these morphological and physiological parameters are explained in detail in the subsequent sections.

Growth parameters

The observations on growth parameters; plant height, number of leaves and chlorophyll content for each plant in each pot were recorded at 60, 90 and 120 Days After Transplanting (DAT).

Plant height (cm)

The plant height was recorded at 60, 90, 120 DAT and is expressed in centimeters (cm). Measurements were taken from the node on soil surface to the apical meristem of the shoot. This measurement is used to evaluate the bio-availability and nutrient uptake under saline soil condition influenced by the application of halophilic bacterial consortia in brinjal plants.

Number of leaves

The total number of leaves per plant was recorded at 60, 90, 120 DAT to evaluate the stimulatory effect halophilic bacterial consortia on vegetative growth of brinjal under saline soil condition.

Yield parameters

Number of fruits per plant

The total number of fruits from each plant was counted and the average was computed to obtain the mean number of fruits per plant.

Average fruit weight

The weight of each fruit per plant was measured and the weight of each fruit was recorded in grams and the average individual fruit weight was calculated using the following formula:

$$\text{Average fruit weight (g)} = \frac{\text{Cumulative weight of fruits drawn at second and third pickings}}{\text{Total number of fruits}}$$

Fruit yield per plant

Total number of fruits

The weight of fruits from each plant is measured and the average was computed to obtain average fruit yield per plant in grams.

Fruit yield per hectare

The weight of fruits from each plant is measured and the average was computed to obtain average fruit yield per acre in kg.

Statistical analysis

The experiment was conducted in CRD with three replications. The recorded observations were subjected to statistical analysis based on the standard procedures (Panse *et al.*, 1985) [6]. Treatment means were compared using Duncan's Multiple Range Test at the level of significance reported for the respective observations to know the treatment performance (Steel *et al.*, 1960) [7].

Results and discussion

The efficient halophilic bacterial consortia were evaluated for their efficacy on growth and yield of brinjal under pot culture condition using the saline soil (Plate 1)

Plant height (cm)

The application of efficient halophilic bacterial isolates significantly influenced the plant height (Table 1 and Plate 2). The treatment T₉ containing 100 per cent NPK + Gel formulation of HBC recorded highest plant height of 60.33 cm at 60 DAT, 80 cm at 90 DAT and 92 cm at harvest, followed by treatment T₇ (100 per cent NPK + liquid formulation of HBC) due to application of gel and liquid formulations respectively, the higher plant height was recorded due to increase in shoot length primarily driven by increase in nutrient availability, production of Indole-3-Acetic Acid (IAA) and Gibberillic Acid (GA) by halophilic bacterial consortial formulations. These compounds stimulate cellular division and elongation within the stem apical meristem promoting vegetative growth. Similar results were obtained by Sezen *et al.* (2024) [8] who evaluated and reported the effect of liquid halophilic consortia on germination percentage, weight plumule and radicle weight, shoot and root length in brinjal crop. Similarly, the halophilic bacteria can survive and thrive in saline environment, enhance the plant growth by improving nutrient bio-availability of essential nutrients such as nitrogen, phosphorus and potassium in salt-affected soils by nutrient cycling and microbial activity, thereby reducing salt induced stress (Dalia *et al.*, 2024) [9]. The halophilic bacteria promotes better root and shoot development which further enhances the better establishment of plant under saline soil condition

Number of leaves (Number)

With respect to number of leaves at 60, 90 and 120 DAT, from Table 1, treatment T₉ (100 per cent NPK + Gel formulation of HBC) recorded highest number of leaves 60.67 at 60 DAT, 87.67 at 90 DAT and 120.67 at harvest) which was on par with the treatment T₇ (100 per cent NPK + liquid formulation of HBC) *i.e.*, 57.33 at 60 DAT, 88.66 at 90 DAT and 116.33 at harvest, which is due to solubilizing phosphate, fixing nitrogen, and mobilizing potassium in the rhizosphere by the halophilic consortia to ensure a continuous influx of macronutrients that can sustain several active vegetative growth sinks simultaneously and enhancing the expansion of lateral branches thereby increases the number of leaves in inoculated treatment over control in uninoculated treatments faces a severe salt stress, that triggers the oxidative-stress-induced apical dominance and restricts lateral branching to conserve dwindling resources, resulting in a stunted, single-stemmed morphology. The findings are in line with the findings of Mahmuda *et al.* (2023) [10] who reported the stimulation effect of halophilic bacteria on number of leaves, chlorophyll content and biomass of rice seedlings under saline soil conditions.

The application of gel and liquid halophilic formulations have higher microbial density, rapid rhizosphere colonization, extended shelf-life and temperature tolerance due to presence of osmoprotectants, their efficacy is more compared to carrier based formulation due to more prone to rapid desiccation, nutrient exhaustion, and native microbial contamination and lower shelf-life, especially gel formulations exhibit advanced rheological properties that provide excellent root-ad-

hesion and provides physical protection forms a localized microenvironment that retains moisture, shielded the young brinjal roots from localized osmotic shock, and facilitates the uniform distribution of solubilized nutrients, contributing to the higher growth and development under saline soil condition (Fadiji *et al.*, 2024) [11]

3.2 Yield parameters

With respect to yield parameter, the number of fruits per plant, average fruit weight, fruit yield per plant and yield per hectare are presented in Table 2.

Number of fruits per plant (Number)

With respect to the number of fruits per plant, the treatment receiving 100 % NPK + gel formulation of HBC has maximum fruits per plant of 24.33 followed by the treatment T₇ (100 % NPK + liquid formulation of HBC) which had 22.00 which is due to enhanced sink strength promoting greater photosynthates accumulation in developing fruits and storage organs and increases the absolute number of nodes capable of producing flower clusters, additionally halophilic formulation maintains an optimal cytosolic K⁺/Na⁺ ratio and keeps stomata functional, ensuring uninterrupted photosynthesis and nutrient flow to sustain multiple developing fruits over absolute control treatment where due to overproduction of ethylene, which activates the abscission zone at the base of pedicels, causing severe flower and immature fruit drop leads to lower yield. Similar results were also documented by Chaitra *et al.* (2025), who reported the enhanced yield in brinjal crop upon application of halophilic bacterial consortia under saline soil condition.

Average Fruit weight (g)

Fruit weight and sizing depend heavily on water influx during the cell expansion phase and synthesis of indole-3-acetic acid (IAA) and gibberellins within the rhizosphere signals the plant to increase vascular tissue differentiation. Here, the halophilic bacteria help the plant to maintain an optimal cytosolic K⁺/Na⁺ ratio by actively loading potassium (K⁺), which functions as the primary cellular osmoregulatory into the fruit tissues, the plant maintains the osmotic gradient required to draw water into the developing fruit, directly increasing its fresh weight and plumpness. The treatment (100 % NPK + gel formulation of HBC) (T₉) has maximum fruit weight (181.00 g) followed by the treatment T₇ (100 % NPK + liquid formulation of HBC) compared to uninoculated treatments due to restricted cell expansion, reduced stomatal conductance and the disruption of carbohydrate translocation brought on by osmotic stress and sodium ion toxicity in saline soil condition. Similar results were also documented by Ahmad *et al.*, (2018) [12] who reported that *Bacillus subtilis* strain Q3 and *Paenibacillus* sp. strain Q6 for improving cotton growth under alkaline conditions.

Fruit yield per plant and fruit yield per hectare

Crop yield is the cumulative expression of all upstream morpho-physiological parameters, including plant height, branch proliferation, fruit count and average fruit weight which are considerably high in inoculated treatments due to improve soil properties and plant uptake compared to uninoculated treatments, where growth and yield are severely restricted due to salt stress. The Table 2 showed that in treatment (100 % NPK + gel formulation of HBC) (T₉) has maximum fruit yield per plant and per hectare, followed by the treatment T₇ (100 % NPK + liquid formulation of HBC) and lowest was recorded in uninoculated treatments.

1. Halophilic Bacterial Consortia (HBC)
2. Solid formulation of Halophilic Bacterial Consortia @ 12.50 kg/ha 3) Liquid formulation of Halophilic Bacterial Consortia @ 625 ml/ha
3. Gel formulation of Halophilic Bacterial Consortia @ 5 kg/ha
4. FYM is common for all treatment
5. Means followed by same letter do not differ significantly
6. DAT= Days After Transplantation

Table 1. Plant height and number of leaves of brinjal influenced by the application of halophilic bacterial consortia formulations

Sl. No.	Treatment	Plant height(cm)			Number of leaves (Number)		
		60 DAT	90 DAT	120 DAT	60 DAT	90 DAT	120 DAT
1.	T ₁ – Absolute control	34.33 ^f	49.00 ⁱ	52.00 ^j	31.67 ^h	42.33 ^h	56.33 ^h
2.	T ₂ - 75 % NPK	44.33 ^e	58.33 ^h	61.33 ^h	43.67 ^g	60.67 ^g	76.33 ^g
3.	T ₃ - 100 % NPK	48.67 ^{de}	60.00 ^g	65.33 ^g	44.33 ^{ef}	65.00 ^f	79.33 ^g
4.	T ₄ - 75 % NPK + Solid formulation of HBC	49.00 ^d	60.67 ^f	71.00 ^f	45.67 ^{ef}	70.33 ^e	88.00 ^f
5.	T ₅ - 100 % NPK Solid formulation of HBC	51.33 ^{cd}	66.33 ^e	75.00 ^e	48.67 ^{de}	71.00 ^e	92.33 ^e
6.	T ₆ - 75 % NPK + Liquid formulation of HBC	53.67 ^c	69.00 ^d	80.67 ^d	52.00 ^{bc}	74.33 ^d	98.00 ^d
7.	T ₇ - 100 % NPK + Liquid formulation of HBC	60.00 ^{ab}	76.33 ^b	89.67 ^b	57.33 ^{ab}	80.66 ^b	116.33 ^b
8.	T ₈ - 75 % NPK + Gel formulation of HBC	56.33 ^b	72.33 ^c	84.33 ^c	54.00 ^b	77.67 ^c	111.33 ^c
9.	T ₉ - 100 % NPK + Gel formulation of HBC	60.33 ^a	80.00 ^a	92.00 ^a	60.67 ^a	87.67 ^a	120.67 ^a
	S. Em ±	0.93	0.95	1.27	1.44	0.98	1.44
	P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	CV	3.16	2.51	2.95	5.14	2.44	2.68
	CD at 5%	2.76	2.84	3.77	4.29	2.93	4.29

Note

1. Halophilic Bacterial Consortia (HBC)
2. Solid formulation of Halophilic Bacterial Consortia @ 12.50 kg/ha
3. Liquid formulation of Halophilic Bacterial Consortia @ 625 ml/ha
3. Gel formulation of Halophilic Bacterial Consortia @ 5 kg/ha
4. FYM is common for all treatment
5. Means followed by same letter do not differ significantly
6. DAT= Days After Transplantation

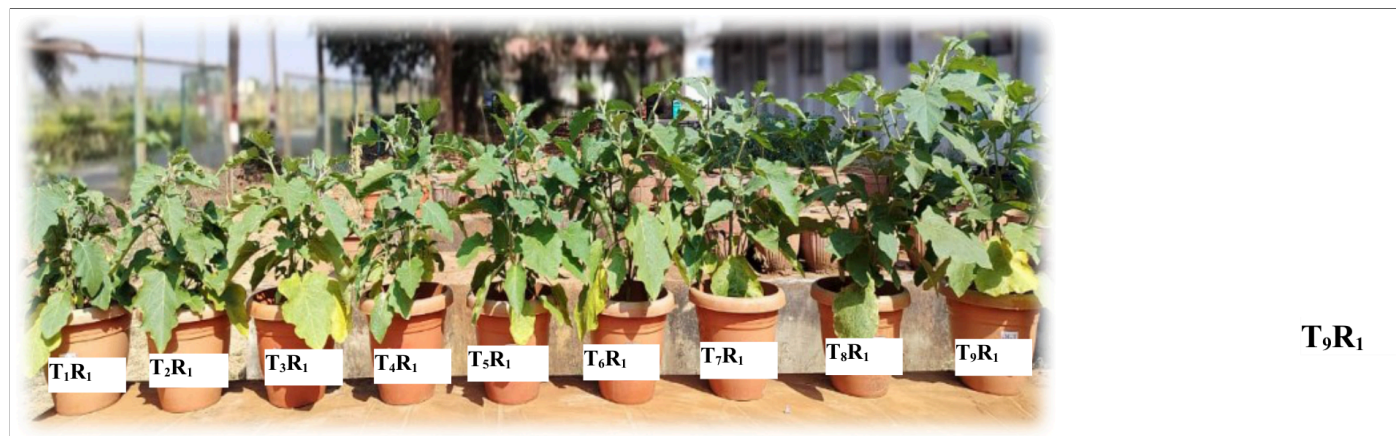
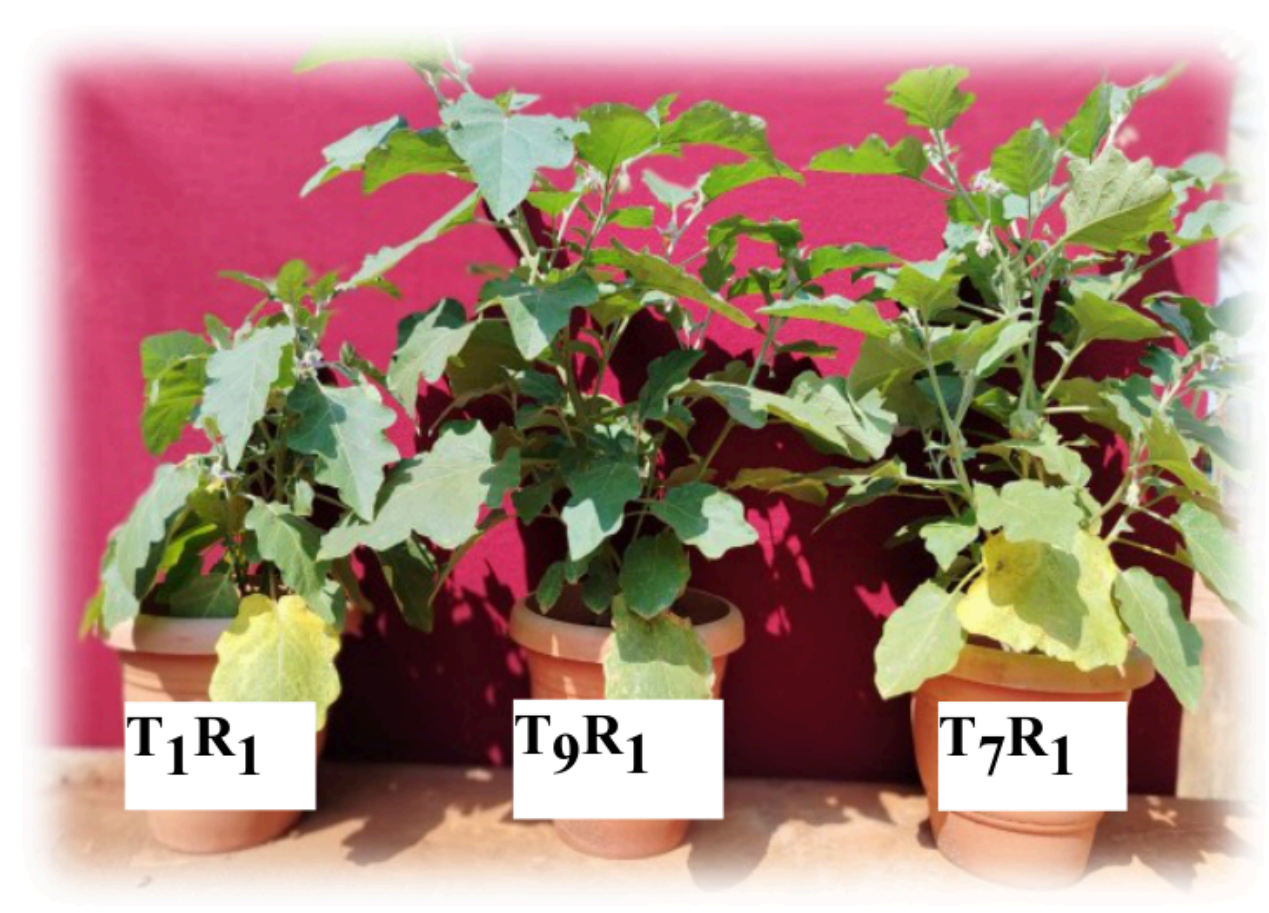


Plate 1. General view of the pot culture experiment of brinjal with efficient halophilic bacterial consortial formulations.



Note: **T₁**: Absolute control
T₉: 100 per cent RDF + Gel formulation of HBC
T₇: 100 per cent RDF + Liquid formulation of HBC
HBC: Halophilic Bacterial Consortia
RDF: Recommended Dose of Fertilizers

Plate 2. Effect of halophilic bacterial consortia formulations on plant height and number of leaves

Conclusion

The treatment receiving 100 per cent NPK + Gel formulation of HBC recorded the highest growth and yield parameters indicating the efficiency of gel formulation of HBC under saline soil condition with im-

proved soil biochemical properties, which had significantly increased the yield of brinjal by 20 per cent compared to recommended dose of fertilizers, where the halophilic bacterial consortia facilitated the

availability of nutrients to the crop under saline conditions. The application of halophilic bacteria has improved the soil physiochemical properties viz., increase in soil organic carbon content and high nutri-

ent retention in both plant and soil which play a better role in sustainable soil health management.

Table 2. Number of fruits per plant, average fruit weight, fruit yield per plant and fruit yield per hectare influenced by the application of halophilic bacterial consortia formulations

Sl. No.	Treatment	Fruits per plant(no.)	Average fruit weight(g)	Fruit yield per plant (kg)	Fruit yield per hectare (t/ha)
1.	T ₁ – Absolute control	6.67 ^h	63.33 ⁱ	0.42 ^h	13.53 ⁱ
2.	T ₂ - 75 % NPK	10.33 ^g	70.67 ^h	0.72 ^g	17.50 ^h
3.	T ₃ - 100 % NPK	11.67 ^{fg}	76.33 ^g	0.89 ^g	18.32 ^g
4.	T ₄ - 75 % NPK + Solid formulation of HBC	13.67 ^f	86.00 ^f	1.17 ^f	19.28 ^f
5.	T ₅ - 100 % NPK Solid formulation of HBC	16.33 ^e	93.33 ^e	1.52 ^e	20.07 ^e
6.	T ₆ - 75 % NPK + Liquid formulation of HBC	18.00 ^d	151.33 ^d	2.72 ^d	20.83 ^d
7.	T ₇ - 100 % NPK + Liquid formulation of HBC	22.00 ^b	173.67 ^b	3.82 ^b	23.78 ^b
8.	T ₈ - 75 % NPK + Gel formulation of HBC	19.67 ^c	161.00 ^c	3.16 ^c	21.71 ^c
9.	T ₉ - 100 % NPK + Gel formulation of HBC	24.33 ^a	181.00 ^a	4.40 ^a	24.25 ^a
	S. Em ±	0.70	1.29	0.81	0.29
	P	< 0.01	< 0.01	< 0.01	< 0.01
	CV	7.67	1.90	6.73	6.57
	CD at 5%	2.08	3.63	2.42	0.86

Note :

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