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Assessing the efficacy of microbial inoculants and consortia on growth, biomass and yield of Amaranth (*Amaranthus caudatus* L.) crop grown in saline soil of Lucknow

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Abstract

Amaranthus (*Amaranthus caudatus* L., Amaranthaceae) is known to have high nutritional value with rich source of micronutrients and dietary minerals of both seeds and leaves. In the present study amaranth was sown in the experimental field at Babasaheb Bhimrao Ambedkar University in a randomized block design (RBD) for two subsequent years during the period from April 2021 to June 2022 and April 2022 to June 2023. The experimental treatments included the application of plant growth-promoting microbes, such as *Bacillus filamentosus*, *Bacillus firmus*, *Aspergillus tamari*, *Aspergillus terreus*, *Aspergillus luchensis* and *Trichoderma lixi* which were tested for their compatibility and colony-forming units. These microbes exhibited various plant growth-promoting activities such as phosphate solubilization, nitrogen fixation, IAA, ammonia and siderophore production. These microbes were firstly immobilised in organic amendments (bentonite, pressmud and molasses in 3:3:4 ratio as a carrier material) and then applied twice in the field at the time of seed sowing and after a month of sowing seed into the soil in comparison to a control of soil only without any microbial or chemical treatments. Moreover, the application of microbial bioinoculants, as consortia of *Bacillus filamentosus* + *Bacillus firmus*, *Aspergillus luchensis* + *Trichoderma lixi* and *Bacillus filamentosus* + *Trichoderma lixi* resulted in significant improvements in growth, biomass and yield responses than the untreated control plants.

Keywords: Amaranth, saline soil, microbes, growth and yield

1. Introduction

Amaranthus (*Amaranthus caudatus* L., Amaranthaceae) is supposed to have high nutritional value with rich source of micronutrients and dietary minerals of both seeds and leaves (Venskutonis & Kraujalis, 2013 and Ghamery *et al.*, 2017) [24, 4]. Due to its resistance to heat, drought, salinity, diseases and pests, it has capability to survive under divergent agro-climatic conditions (Dako *et al.*, 2014) [3]. Taxonomically, it is categorised under pseudo-cereal due to nutritional quality of its grains similar to cereals but produced by botanical families other than Gramineae (Mnkeni *et al.*, 2007) [8]. Amaranth being a salinity tolerant crop contains adequate carbohydrates, protein and dietary fibre (Sarker *et al.*, 2015 and 2020) [18, 21]. Other than this, it is rich source of iron, copper, manganese, zinc, sodium, potassium, magnesium, boron, molybdenum, calcium, phosphorus, sulphur, betalains, betacyanin, β -carotene, betaxanthins, ascorbic acid, polyphenols and flavonoids etc (Ghamery *et al.*, 2017) [4]. These constituents make it a crop with good antioxidant potential. Vegetable amaranth has good adaptability to different abiotic stresses like drought (Sarker & Oba, 2018) [19] and salinity (Sarker & Oba, 2019; Sarker *et al.*, 2020) [20, 21]. Nutritional deficiency including both of minerals and vitamins is a challenge especially among low-income earners. Amaranth as a vegetable and in the form of grain serves as a cost effective, affordable and reasonable solution to it. Amaranth being a crop with low production cost and its ability to survive even in the marginalised land, it is considered as the poor man's vegetable (Rastogi and Shukla 2013) [17]. It contains high lysine, methionine, tryptophan and sulphur containing amino acids. *Amaranthus* contains three times more vitamin C, calcium and niacin in comparison to spinach (Sarker, 2020 and Srivastava, R, 2011) [21, 23].

Amaranth seeds are rich in manganese, nickel, chromium, zinc, copper and selenium (Wolosik and Markowska; 2019) ^[25]. Amaranthus being rich source of various bioactive phytochemicals such as alkaloids, saponins, glycosides, phenolic acids, flavonoids, anthocyanins, amino acids, vitamins, minerals, terpenoids, lipids etc is preferably used for edible purposes as leafy vegetable. It also possesses various properties like antioxidant activity, anti-inflammatory and anti-cancer. Amaranth plant shows antioxidant activity due to the presence of phenolic acids and flavonoids by neutralizing free radicals.

Amaranth grain contains vitamins (A, B₆, C, E and K), dietary fibre (9-14%), proteins (13-22%), lipids (5-13%), minerals etc (Peter and Gandhi., 2017) ^[16]. Amaranthus spp. is underutilized in terms of its high nutritional value and lesser consumption in comparison to other green leafy vegetables. It is a sustainable food crop for the 21st century (Park *et al.*, 2020) ^[11]. Amaranth grain, also known as Rama's grain or Rajgira in India, is highly nutritious and is a rich source of important amino acids like alanine, valine, leucine, methionine, phenylalanine, proline, arginine, α -amino butyric acid, tryptophan, isoleucine and serine which suggests that amaranth is a substitute to nutrient cereal (pseudo-cereal). As this plant have mechanism of C₄ photosynthesis that supports its better survival under stress conditions of heat and drought. Thus, this plant has immense potential to fill the nutrients gap of affecting vulnerable population inhabiting marginal land area (Park *et al.*, 2020) ^[11].

2. Materials and Methods

2.1 Collection of microbial strains

In the present study, six pre-isolated and well-characterized plant growth-promoting microbial strains were used. These strains include *Bacillus flamentosus* RS3B, *Bacillus firmus* RS7B, *Aspergillus tamaris* RS6F, *Aspergillus terreus* RS10F, *Aspergillus luchensis* RS8F and *Trichoderma lixii* TvR1. The bacteria and fungi used for this study were isolated from Ralegarh Siddi district, Maharashtra, India in 2018 (Kumar *et al.*, 2021) ^[6].

2.2 Revival and plant growth promoting characteristics of microbial inoculants (bacterial and fungal isolates)

The aforementioned microbial strains were revived using appropriate media under controlled laboratory conditions. The fungal strains were revived in potato dextrose agar while the bacterial strains were cultured in nutrient agar. This revival process was carried out at four months intervals under sterile *in vitro* conditions, utilizing a laminar flow hood, a rotary shaker and an incubator maintained at a constant temperature of 25 °C. The plant growth-promoting attributes of these microbes were assessed by testing for specific traits, including phosphate solubilization (Pikovskaya. 1948), indole-3-acetic acid (IAA) production (Bric, Bostock and Silverstone. 1991), siderophore production (Schwyn and Neilands. 1987), ammonia production (Cappuccino and Sherman, 1992), hydrogen cyanide (HCN) production (Lorck. 1948) and asymbiotic nitrogen fixation (assessed on nitrogen-free Jensen medium using standard procedures, as outlined in Table 1).

2.3 Compatibility test

The compatibility of different bacterial and fungal strains was assessed using various growth media. For the bacterial growth medium, 3.25 g of nutrient agar and for the fungal growth medium, 6 g of potato dextrose agar were used. To assess the compatibility of bacteria-fungus interactions, an equal ratio of

nutrient broth (NB) and potato dextrose broth (PDB) was prepared and supplemented with 5% beef extract.

2.4 Colony forming unit (CFU) and immobilisation of bioformulation onto carrier material

Granular carrier-based bioformulations were prepared by immobilising freshly prepared microbial consortia (1×10^4 CFU) onto bentonite: pressmud: molasses mixture in 3:3:4 ratios where molasses act as a binding agent. This organic mixture was further autoclaved for checking any microbial growth. 100g of carrier material was used to immobilise 50ml of bioformulation that was applied in a plot of 12m² area. These granular bioformulations were spread in trays, autoclaved and then sealed in low-density polythene bags for storage (Maheshwari *et al.* 2015). For the chemical fertilizer treatment, 100g of diammonium phosphate (DAP) was applied to a 12m² area, following the guidelines set by the Indian Council of Agricultural Research (ICAR) and the methods outlined by Parveen *et al.* (2023) ^[13]. This experimental setup aimed to assess the effectiveness of the immobilized microbial treatments on amaranth growth and yield under field conditions. The microbial consortia used in this study refer to the combination of compatible microbial inoculants, which can include bacteria-bacteria, fungus-fungus or bacteria-fungus combinations. These inoculants were immobilized on a carrier-based organic amendment after conducting compatibility tests to ensure their effectiveness when used together.

2.5 Site Selection, crop selection and sowing of seeds in saline soil

The experimental site for the amaranth field trial was located at the university health centre within the campus of Babasaheb Bhimrao Ambedkar University, Lucknow (26.8467°N, 80.9462°E). The field experiment was conducted using RBD (randomized block design) that is replicated thrice. In the present study, amaranth was grown under saline soil conditions (pH-8.1 and EC 5.42 ds/m) for two subsequent years during the period from April 2021 to June 2022 and April 2022 to June 2023. Hari cholai ganga variety of amaranth was purchased from organic bazaar and was selected for a field trial with a cultivation duration of three months. Amaranthus seeds were sown in month of April 2022 and harvested in the month of June 2023 for first year and April 2023 to June 2024 for the second year. This experimental setup aimed to evaluate the impact of microbial and chemical treatments on the growth and yield attributes of amaranth under saline conditions.

Experimental plots measuring 2 x 2 (4 m²) each were used for planting the amaranth crop. To prevent the runoff of microbial treatments during the rainy season, the boundaries of each plot were surrounded by a 30 cm thick soil barrier. Additionally, a 1-foot gap was maintained between adjacent plots to ensure proper spacing and to minimize any cross-contamination between treatments. Seeds were sown in the first week of April while crop was harvested at the end of June month. After checking their growth promoting attributes of isolated and revived PGPMs (plant growth promoting microbes) were firstly immobilised in organic amendments (bentonite, pressmud and molasses) were applied twice in the field at the time of seed sowing and after a month of seed sowing into the soil, in comparison to diammonium phosphate (DAP) as a chemical fertilizer and a control without any microbial or chemical treatments.

2.6 Estimation of plant growth and yield attributes of Amaranth

The parameters assessed for the growth of the crop included root length, shoot length and total length of plant, leaf parameters like length, width, leaf number and overall yield. Digital weighing balance was used to measure amount of final harvest. These measurements were taken to assess the impact of different treatments on the growth and productivity of the amaranth. These growth metrics were measured and compared against the control, which received no microbial and chemical treatments.

2.7 Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics version 20. To evaluate the significance of the treatments, a one-way analysis of variance (ANOVA) was performed followed by Duncan's multiple range test at a significance level of 5% ($p < 0.05$). This analysis was used to determine the impact of plant growth-promoting microbes (PGPMs) treatments on the growth and yield of amaranth under experimental field conditions. The results are presented as arithmetic means of three replicates microbial treatments with the standard errors to provide an indication of the variability in the data. This statistical approach ensured a robust assessment of the treatment effects and allowed for meaningful comparisons between different microbial treatments.

3. Results

3.1 PGPR attributes of microbial strains

Plant growth-promoting microbes (PGPMs) known for their ability to enhance plant growth through various beneficial mechanisms. The plant growth-promoting attributes of the bacterial and fungal isolates include the production of key bioactive compounds such as indole acetic acid (IAA), ammonia, phosphate, nitrogen, potassium and siderophores production, as given in Table 1. Among all microbial isolates, *T. lixi* showed maximum growth promoting activities like IAA, ammonia, phosphate and siderophore production, followed by *A. terreus* showing IAA, ammonia, phosphate and siderophore production and *B. filamentosus* showing IAA, ammonia, nitrogen and siderophore production. Colony forming unit in bacterial inoculants and spore forming unit in fungal inoculants was checked after the use of carrier material. It was observed that carrier based organic amendments showed better results due to better binding of microbes with organic amendment that facilitated improvement in maintaining microbial population. So, while making consortia or any formulations use of carrier material played a very important role in terms of growth and yield of plants as it is observed to show plant growth promoting activities. These microbial isolates were subsequently evaluated for their colony-forming units (CFU) to assess their viability and effectiveness as shown in Table 2.

3.2 Compatibility test of microbial inoculants

The compatibility tests were essential for identifying compatible strains that could be used together in a microbial formulation or consortia. The experimental treatments included the application of plant growth-promoting microbes, such as *B. filamentosus*, *B. firmus*, *A. tamari*, *A. terreus*, *A. luchensis* and *T. lixi* which were tested for their compatibility and colony-forming units. Final compatible strains with positive compatibility test are mentioned as *B. filamentosus* with *B. firmus*, *A. luchensis* with *T. lixi* and *B. filamentosus* with *T. lixi* as shown in Table 3. Compatibility was assessed by observing the overlapping or inhibition zones between the microbes (Parveen *et al.*, 2023) [13]. In the

compatibility assessment, the zone of inhibition was used as an indicator of strain incompatibility. A distinct zone of inhibition, where microbial growth is prevented, was observed for non-compatible strains, indicating antagonistic interactions between the organisms. Conversely, compatible strains were characterized by overlapping zones, signifying a lack of antagonism and the establishment of a cooperative interaction between the microorganisms. The overlapping zones indicate that the strains were able to coexist in close proximity without inhibiting each other's growth, which is a key characteristic of compatibility. This method provided a clear visual representation of strain interactions, distinguishing between compatible and non-compatible pairings based on their growth patterns. The proper immobilisation of microbial inoculants onto suitable carrier materials enhanced the retention and stability of the microbes in the soil which improved the bioavailability of essential nutrients, thereby facilitating better nutrient uptake by the crop plants. The application of organic amendments containing immobilized microbial inoculants provides additional benefits by promoting sustainable agricultural practices and supporting enhanced growth of the crops.

3.3 Efficacy of microbial bioformulation on plant growth

Root length was measured to evaluate the development and health of the plant's root system, which is critical for nutrient and water absorption. Among the microbial combinations or carrier-based consortia, improvement in total length response was observed in increasing order as follows: RS3B + RS7B (243.30%), RS3B + TVR1 (314.24%) and RS8F + TVR1 (343.39%) in comparison to control which was untreated soil as shown in Table 4 and Fig 1. These results are an average of two consecutive years with duration of 3-month harvest period, spanning from April to June as mentioned in Table 4 and Table 5. Table 5, Figure 2 and Figure 3 clearly shows leaf parameters like leaf length, leaf width and leaf number with increase value after consortia application. These consortia were found to be most effective in promoting growth compared to individual microbial treatments and control without any microbial treatment.

3.4 Efficacy of microbial bioformulation on amaranth biomass after harvest

Biomass was quantified by weighing oven dried amaranth plant thus reducing water content from fresh weight of amaranth plant. Among carrier based microbial consortia maximum percent increase in biomass was observed with the following combinations of bioformulation RS3B + TVR1 (397.19%) followed by RS8F + TVR1 (523.02%) and RS3B + RS7B (578.94%) in comparison to control without any microbial treatment. These results were obtained during the 3-month growing period, from April to June over two consecutive years, as shown in Table 6 and Fig 4. These studies underline the positive impact of PGPR application on amaranth growth and productivity.

3.5 Efficacy of microbial bioformulation on amaranth yield after harvest

Yield was quantified by measuring the total production of edible amaranth leaves, providing an indicator of the crop's productivity under different treatment conditions. Among carrier based microbial consortia maximum percent increase in yield was observed with the following combinations RS3B + TVR1 (599.77%) followed by RS8F + TVR1 (536.56%) and RS3B + RS7B (402.95%) in comparison to control without any microbial

treatment. These results were obtained during the 3-month growing period, from April to June over two consecutive years, as shown in Table 6 and Fig 5. These studies underline the positive impact of PGPR application on amaranth growth and productivity.

4. Discussion

Amaranth being a salinity tolerant crop with potential of improving food and nutritional security in an era of climate change. One of the most common reasons for adopting this crop in an era of climate change is its survival capability in marginalised soil conditions with good nutritional potential. Our study on crop of *Amaranthus caudatus* L. with application of plant growth promoting microbes clearly signifies that it is rich source of macro as well as micro nutrients, so it can outstand as a good nutritional source, thus supporting sustainable crop production. This study corroborates with the finding of Parra-Cota *et al.*, 2014 [12] who significantly reported that the long-term use of variable growth promoting rhizobacteria resulted in increased growth responses, improved plant biomass and enhanced seed yield in grain amaranth. They also reported that application of plant growth promoting microbes resulted in increased nitrogen use efficiency that supported enhanced growth and biomass. These results are strongly supported by finding of Lata *et al.*, 2025 [7] in which *B. filamentosus* with *B. firmus*, *A. luchensis* with *T. lixxi* and *B. filamentosus* with *T. lixxi* in consortia resulted in enhancing growth and yield responses in cowpea crop. In accordance with the study of Pandey *et al.* (2018) [10] siderophore production by plant growth

promoting bacteria, especially *Bacillus* has been attributed to enhance the availability of iron to the host plant by producing the siderophores resulting in better growth and yield of crop plant. The work carried out by Soumya *et al.*, 2020 [22] on *Pseudomonas fluorescens* clearly represent the role of plant growth promoting rhizobacteria in positive responses for phosphate solubilization, nitrogen fixation, ammonia, indole-3-acetic acid (IAA) and hydrogen cyanide (HCN) production. Similar results were also reported by Patel *et al.*, 2023 [15], use of salinity tolerant plant growth promoting bacteria help them to survive in salinity tolerant stress conditions and showed significant plant growth promoting properties that enhanced the growth of Amaranth crop. Results are supported by the findings of Parveen *et al.*, 2024 [14] who reported increase in growth, biomass and yield of tomato plant after using the compatible combination of microbes with growth promoting traits.

As seen in the findings of Ikhajiagbe *et al.*, 2021 [5], use of plant growth promoting microbes like *Pseudomonas* species resulted in improved and better growth responses in amaranth crop. In accordance to the findings of Chatterjee *et al.*, co-inoculation or consortia of plant growth promoting microbes, in place of using single inoculation resulted in enhancing the growth and yield of plant. Different microbial inoculation with variable growth promoting traits resulted in better nutrients absorption that ultimately results in improving better and enhanced growth, yield responses of plant and sustainable solution to in stressful environment.

Table 1: Plant growth promoting characteristics of microbial inoculants used in amaranth crop

Microbial isolates	IAA production	NH ₃ production	Phosphate (PO ₄ ³⁻) solubilization	Nitrogen fixation	Potassium (K) solubilization	Siderophore production
<i>Bacillus filamentosus</i> (RS3B)	++++	++	-	+	-	++
<i>Bacillus firmus</i> (RS7B)	-	++	-	+	-	++
<i>Aspergillus tamarii</i> (RS6F)	++++	++	++	-	-	-
<i>Aspergillus luchensis</i> (RS8F)	++	+	+	-	++	+
<i>Aspergillus terreus</i> (RS10F)	++	++++	++	-	-	++
<i>Trichoderma lixxi</i> (TVR1)	++++	+++++	++++	++	+++	++++

Abbreviations: (+) production in moderate amount, (+++++) production in high amount, (-) no production.

Table 2: Colony forming unit (cfu) in bacterial inoculants and spore forming unit in fungal inoculants

Microbial inoculants	Microbial density	
	Cell/spore density (cell/g)	Cell/spore density in carrier (cell/g)
<i>B. filamentosus</i>	2.63 X 10 ⁴ ± 1.05 ^a	6.6 X 10 ⁴ ± 2.53 ^b
<i>B. firmus</i>	2.48 X 10 ⁴ ± 1.0 ^{bc}	4.67 X 10 ⁴ ± 2.39 ^{bc}
<i>A. tamarii</i>	2.79 X 10 ⁴ ± 1.34 ^c	3.46 X 10 ⁴ ± 1.50 ^a
<i>A. luchensis</i>	1.36 X 10 ⁴ ± 0.56 ^{bc}	2.67 X 10 ⁴ ± 1.03 ^{bc}
<i>A. terreus</i>	4.95 X 10 ⁴ ± 2.01 ^a	5.72 X 10 ⁴ ± 2.12 ^{ab}
<i>Trichoderma lixxi</i>	6.22 X 10 ⁴ ± 2.43 ^b	7.4 X 10 ⁴ ± 3.10 ^b

Table 3: Compatibility test for microbial isolates

Microbial combination tested	Showing compatibility/ Non-Non-compatibility	Correlation
<i>Bacillus filamentosus</i> + <i>Bacillus firmus</i>	Compatible	Positively correlated
<i>Aspergillus luchensis</i> + <i>Trichoderma lixxi</i>	Compatible	Positively correlated
<i>Aspergillus tamarii</i> + <i>A. luchensis</i>	Non-compatible	Negatively correlated
<i>A. terreus</i> + <i>Trichoderma lixxi</i>	Compatible	Positively correlated
<i>Aspergillus tamarii</i> + <i>A. terreus</i>	Non-compatible	Negatively correlated

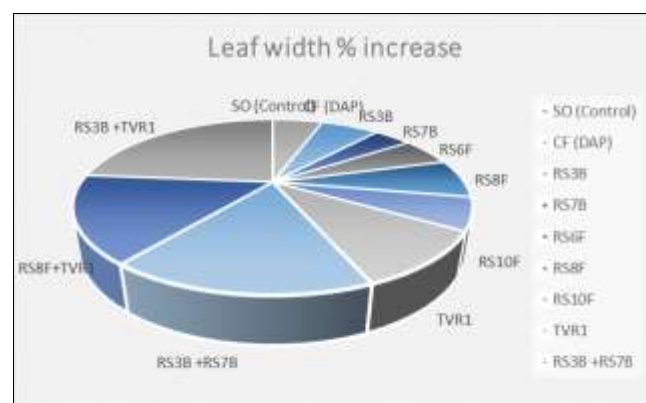
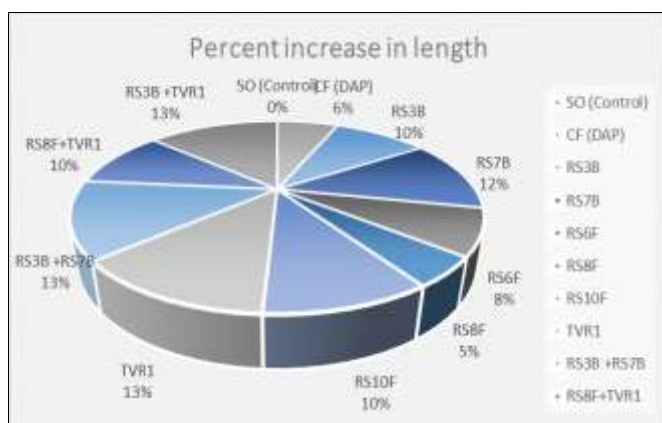
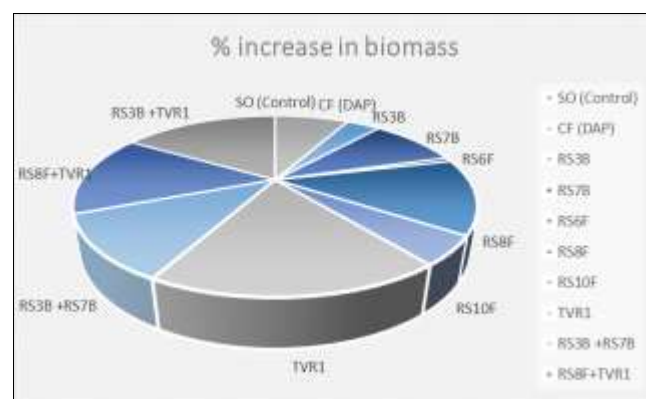
Table 4: Determination of growth attributes (root length, shoot length and total length) of amaranth crop with growth promoting bacterial, fungal microbial inoculants and consortia application

Treatments	Root Length (cm)	Shoot Length (cm)	Total Length (cm)
SO (Control)	7.13±0.70711 ^a	26.33±1.41 ^a	33.55±1.76 ^a
CF (DAP)	16.45±0.91924 ^{cd}	68.03±0.94752 ^c	84.7±1.55 ^c
RS3B	17.48±0.82024 ^d	91.315±0.72832 ^e	110.88±2.29 ^e
RS7B	17.065±0.23335 ^{cd}	116.23±0.46669 ^g	133.315±0.26 ^g
RS6F	14.4±0.70711 ^b	81.165±1.64756 ^d	95.395±2.59 ^d
RS8F	20.16±1.88798 ^e	51.73±1.1738 ^b	72.2±2.64 ^b
RS10F	11.96±2.59508 ^b	103.41±5.58614 ^f	116.18±7.04 ^f
TVR1	22.29±1.18087 ^e	113.1±2.82843 ^g	135.73±4.48 ^g
RS3B +RS7B	21.3±0.9 ^c	119.345±1.43543 ^c	138.985±0.34 ^c
RS8F+TVR1	23.81±2.66579 ^b	115.665±3.34462 ^c	155.18±16.19 ^c
RS3B +TVR1	24.94±0.30406 ^c	118.41±3.3234 ^c	142.015±5.53 ^c

Abbreviation: T1- Soil only (Control), T2- DAP, T3- *Bacillus filamentosus*, T4- *Bacillus firmus*, T5- *Aspergillus tamarii*, T6- *Aspergillus luchensis*, T7- *Aspergillus terreus*, T8- *Trichoderma lixi*, T9- *B. filamentosus* + *B. firmus*, T10- *A. luchensis* + *T. lixi*, T11- *B. filamentosus* + *T. lixi*

Table 5: Determination of leaf parameters number, length and width with growth promoting bacterial, fungal microbial inoculants and consortia application

Treatments	Number of Leaves	Leaf Length (cm)	Leaf width (cm)
SO (Control)	10.16±0.70 ^{bc}	4.24±0.58	2.88±0.25 ^d
CF (DAP)	39.33±1.88 ^a	7.43±0.28	3.495±0.19 ^{ab}
RS3B	46.665±0.94 ^{bc}	6.76±0.14	3.58±0.11 ^c
RS7B	44.83±2.12 ^c	6.91±0.12	3.33±0.24 ^{cd}
RS6F	49.165±2.59 ^a	7.44±0.40	3.495±0.23 ^a
RS8F	52.995±1.88 ^{ab}	6.80±0.42	3.7±0.14 ^{ab}
RS10F	55.33±0.70 ^d	7.33±0.56	3.56±0.33 ^d
TVR1	64.83±1.65 ^{cd}	7.36±0.04	4.03±0.60 ^e
RS3B +RS7B	73.83±2.59 ^c	7.83±0.28	4.79±0.51 ^c
RS8F+TVR1	73.165±1.88 ^b	8.33±0.18	4.70±0.14 ^{de}
RS3B +TVR1	76.33±1.88 ^a	8.8±0.14	5.59±0.19 ^c

**Fig 2:** Percent increase in leaf length (cm) of Amaranth**Fig 3:** Percent increase in leaf width (cm) of Amaranth**Fig 1:** Percent increase in total length of plant (cm)**Fig 4:** Percent increase in biomass of Amaranth

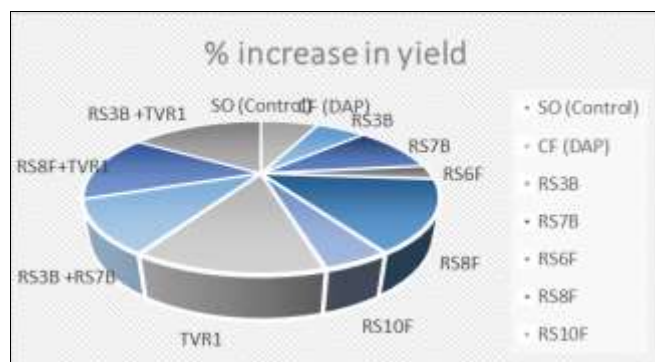


Fig 5: Percent increase in Yield of Amaranth

5. Conclusion and Future Perspectives

Amaranth being salinity-tolerant crop has unique adaptive mechanisms that allows it to thrive under challenging conditions and its cultivation contributes to a more sustainable agricultural practice. Given the growing global concerns over soil salinization and food security, amaranth presents a viable solution, promoting crop biomass and yield. Therefore, promoting the cultivation of amaranth can help establish resilient farming systems that benefit to the farmers, consumers and the environment respectively. Ammonia-producing microbial inoculants are valuable tools for sustainable agriculture, reducing the dependence on synthetic nitrogen fertilizers. Similarly, microbial involvement in potassium availability is vital for plant growth, agricultural productivity, improved stress resilience and better yields. This microbial activity is integral to sustainable farming practices, as it optimizes potassium acquisition and minimizes the need for synthetic fertilizers. Salinity stress negatively impact the growth, yield and quality of amaranth making it an economically important crop, thus nullifying the negative consequences of salinization. Hence, it is imperative to conclude that the successful application of plant growth-promoting microbes (PGPMs) in a well-designed agroecosystem stimulates the plant growth, enhance nutrient availability to plant and enhances the yield in a sustainable manner in an agro-ecosystem. Despite a profound understanding of amaranth responses to salinity stress systematic studies on field experiments are still insufficient and needed to be explored further.

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7. Authors contributions

RPS: Supervision, Conceptualization, Validation, Reviewing and Editing. NKA: Validation, Reviewing and Editing. SL: Investigation, Methodology, Data analysis and compilation, Writing and Editing original draft, Tables and Figures.

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Declarations

Competing interests

The authors declare no competing interests.

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