PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(2): 1-9
https://doi.org/10.14719/pst.5698

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RESEARCH ARTICLE

Impact of a liquid consortium of plant growth-promoting bacteria on biometrics and yield attributes in sesame (*Sesamum indicum* L.)

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OPEN ACCESS

ARTICLE HISTORY
Received: 10 October 2024
Accepted: 05 February 2025
Available online
Version 1.0 : 24 March 2025
Version 2.0 : 11 April 2025

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE
Parameswari K, Brindavathy R, Gayathry G, Tamilselvi C, Syed AHH, Vijaya GV, Harisudan C, Sathiya K, Thiruvarasan S, Shibi S, Senthamizh K. Impact of a liquid consortium of plant growth-promoting bacteria on biometrics and yield attributes in sesame (*Sesamum indicum* L.). Plant Science Today. 2025; 12(2): 1-9. https://doi.org/10.14719/pst.5698

Abstract

Sesame is an important oilseed crop with great commercial and medicinal value and is used extensively in culinary and cosmetic applications. Meeting the demand for sesame requires the development cultivars with high yield and balanced nutrition. The introduction of bioinoculants into the crop rhizosphere is beneficial for sustaining both productivity and soil health and the co-application of inorganic nutrients and bioinoculants in the crop rhizosphere increases sesame production. Therefore, a study has been done to evaluate the effect of individual bioinoculant and liquid consortium on different parameters of sesame (var. TMV-7). Three year field experiments was conducted (2019 to 2022) at the Oilseed Research Station (TNAU), Tindivanam, Villupuram district (India). The trial was composed of nine treatments comprising individual inoculant and a consortium of *Azospirillum, Bacillus megaterium var. phosphaticum*, *Paenibacillus mucilaginosus* (KRB-9) and pink pigmented facultative methylotrophs (PPFM) and their combination with 100% NPK as recommended dose of fertilizer, 2% KCl and PPFM spray individually and in combination. Their synergistic effects on bacterization were studied using a randomized block design with three replications, in sesame grown under rainfed conditions with zero irrigation. The results indicated that applcation of a bioinoculant consortium in combination with inorganic fertilizers, PPFM and KCl spray, resulted in the highest biomass production, biometrics, physiological parameters, grain yield and seed quality and tuned the cost-benefit ratio to 2.39.

Keywords

Azospirillum; *Bacillus megaterium var. phosphaticum*; *Paenibacillus mucilaginosus*; Pink Pigmented Facultative Methylotrophs (PPFM) ; rhizosphere

Introduction

Sesamum indicum (L.), commonly known as sesame, is an important oilseed crop belonging to the Pedaliaceae family and is recognized for its substantial commercial and medicinal value. The oil content ranges between 45% and 55%. The oil extracted from sesame seeds is notable for its richness in sesamin and sesamolin, compounds known for their antioxidant properties and the high stability they confer to the oil, rendering it resistant to rancidity (1).

In India, the sesame production was 17.64 thousand tonnes, with a productivity of 323.43 kg/hectare, in the year 2022-23. The cultivation area for sesame has expanded significantly in the recent decades; however, the production and productivity levels have remained relatively static. This has led to an increase in the cost of sesame products owing to the higher demand and limited supply. Bridging this gap requires the introduction of high-yielding varieties and implementing improved production protocols. The availability of soil nutrients plays a pivotal role in how the plants overcome the stresses in rainfed situations and both imbalanced nutrition and drought stress are critical determinants of crop productivity. Plant Growth Promoting Rhizobacteria PRPR play a crucial role in mitigating the accumulation of reactive oxygen species (ROS) and associated physiological disorders in plants (2, 3). The production of phytohormones by Plant Growth-Promoting Rhizobacteria (PGPR) and endophytic microbes bolster plant resilience against both biotic and abiotic stresses (4). When these beneficial bio-entities introduced into the rhizosphere, they alter the biofilm in the root region, providing sustained nutrient flow and increasing growth.

Sesame is, generally known for its drought tolerance and thrives in arid and semi-arid regions, with either sufficient rainfall or irrigation. However, cultivation in these regions requires adequate nutrient supplementation from fertilizers and organic sources (5). Continuous intensive cropping has resulted in a decline in soil organic matter content and subsequent nutrient depletion. Prolonged use of chemical fertilizers further reduced the soil microbial population. This leads to disruptions in agro-ecosystems, degradation of soil structure and decline in biological diversity (6).

Bioinoculants and organic manures can alleviate these challenges. The former enhances microbial populations, whereas the latter provides nutrients, thereby supporting microbial communities in the rhizosphere. The metabolic activities and processes of the bioinoculants improve nutrient cycling which enriches the soil. In addition, these microbial agents enhance the solubility of mineral nutrients such as phosphorus, potassium and iron and promote plant growth and yield. They also produce growth-promoting substances and hormones and aid plant growth (7). The effect of bioinoculants on sesame has been studied extensively, with consistent results in improving growth and increasing yields (8).

Bioinoculant application in sesame has been shown to increased plant growth, number of capsules per plant, seed quality and yield, seed oil content (3) and nutrient uptake (9), while reducing seedling disease (10). Application of Arbuscular mycorrhizal fungi (AMF) improved the quantity (oil percentage and yield) and quality (unsaturated fatty acids) of sesame oil (11).

Bioinoculant such as *Azospirillum*, phosphobacteria and potash bacteria in combination will increase the productivity of sasame in a sustainable manner. *Azospirillum* serve as a biological N source and promote growth (7) and *Bacillus megaterium var phosphaticum*, a phosphate solubilizing bacteria (PSB) solubilizes phosphorus in the soil by the production of organic acids (12). The potash bacteria *Paenibacillus mucilaginosus* (KRB-9) helps in Si solubilization and release of potassium and helps in micronutrient availability and in disease reduction (13). Pink Pigmented Facultative Methylotrophs (PPFM) mitigate drought stress. Application of KCl through spraying is a help in mitigate drought in sesame (14, 15).

Application of bioinoculants in liquid formulations has several advantages such as higher population load, cell longevity and cell viability. Since the microbes are disseminated through the growth medium, they can withstand newer environments until they start proliferating. In addition, the consortium has a combination of preferred and compatible microbes in a single container with consistent population load. Therefore, consortium in single pack is very cost effective. Individual application of the three different bacterial inoculums *viz.*, *Azospirillum*, PSB and potash bacteria is three times the cost of application of the consortium (three inoculants in one container). The cost of individual inoculum is INR 350 as per the Tamil Nadu Agricultural University Price List. When the three liquid cultures are purchased individually, the cost would be thrice this amount. When the formulation is a liquid consortium priced at INR 350, the farmers can save INR 700 per hectare. Therefore, marginal and small farmers who grow sesame in rainfed condition with minimum inputs will benefit from using these novel combinations. Moreover, few studies using liquid consortium of microbial sources in sesame. With this aim an experiment was planned to investigate the effect of the liquid consortium on the biometrics and yield components of summer sesame.

Materials and Methods

Development of bacterial consortium

Bacterial cultures were obtained from the Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore. To develop of the liquid consortium, the individual cultures of *Azospirillum* (Sp7) , *Bacillus megaterium var phosphaticum* (PSB 1), *Paenibacillus mucilaginous* (KRB-9) and Pink Pigmented Facultative Methylotrophs were cultured in their respective nutrient broths. At the end of log phase, these cultures were mixed to form a consortium and the individual cultures were also maintained for inoculation. At the time of mixing a population load 10^9CFU was maintained. *Azospirillum* was grown in semi-solid nitrogen-free bromothymol blue malate broth for five days; *Bacillus megaterium var phosphaticum*, in nutrient broth for two days; *Paenibacillus mucilaginous*, in modified Alexandrov's broth for three days (16); and PPFM, in AMS broth (Ammonium mineral salts) (17). The cultures were incubated to study their shelf life and population load up to six months. At 30 days interval , aliquots of 1 mL from each samples were drawn to enumerate the population load through serial dilution and plating using their respective growth media (18).

Geographical location of the experimental site

The field experiment was conducted at the Oilseeds Research Station (12°21 N, 79°66´E and 45.6 m above sea-level), Tindivanam, Tamil Nadu, India during the rabi season of three consecutive years, from 2019 to 2022. We evaluated the effect of the bio-inoculants on the biometrics and yield attributes of the sesame var. TMV7. The soil at the experimental site was sandy loam (20.4% coarse sand, 30.6% fine sand, 26.2% silt and 22.6% clay), medium in organic carbon (0.56%), low in available nitrogen (246 kg/ha) and medium in phosphorus (24.1 kg/ha) and potassium (204 kg/ha). During the crop growth season of 2017 and 2018, the monthly mean maximum and minimum temperatures ranged between 35.3 C and 26.4 C and 32.4℃ and 24.9℃, respectively.

Field layout and the application of the supplements

The field was thoroughly ploughed to obtain fine tilth suitable for sesame sowing. The plot size was 4.0 m × 5.0 m with a spacing of 30 cm between the rows and the plants. The bioinoculants *viz*., *Azospirillum,* PSB and KRB were applied as according to r the treatment schedule. Seed were treated with 125 mL liquid broth (2.4 × 10^{9}CFU) @ per hactare seeds and shade dried for two hours. Similarly each bacterial cultures and consortium were treated separately and dried. Bioinoculants (500 mL per ha) were mixed with FYM applied to the soil before last ploughing. recommended dose of inorganic fertilizers are common for all plots. PPFM spraying at the rate of 2% was applied before flowering and 15 days later, to mitigate the effects of drought; this treatment was compared with the 2% KCl spray.

The trials were laid out in a randomized block design with three replications and nine treatments. The treatment structures were T1: 100% NPK (RDF); T2: T1 + individual inoculum + 2% KCl spray; T3: T1 + individual inoculum + PPFM spray; T4: T1 + individual inoculum + 2% KCl spray + PPFM spray; T5: Control; T6: T1 + Consortium; T7: T1 + Consortium + 2% KCl spray; T8: T1 + Consortium + PPFM spray; and T9: T1 + Consortium + 2% KCl spray + PPFM spray. Irrigation was applied at the time of sowing. The crop was then propagated under rainfed conditions with zero irrigation. The crop had three rainy days in 2019: 20^{th} DAS (23 mm), 27^{th} DAS (17 mm) and 40^{th} DAS (26 mm); five rainy days in 2020: 7^{th} DAS (15 mm), 18^{th} DAS (28 mm), 20^{th} DAS (14 mm), 35^{th} DAS (11 mm) and 50^{th} DAS (19 mm); and four rainy days in 2021: 18^{th} DAS (7 mm), 22^{nd} DAS (21 mm), 25^{th} DAS (18 mm) and 31^{st} DAS (8 mm).

Physiological studies

Physiological parameters such as proline content (19), leaf relative water content (RWC) and SPAD index were analysed to evaluate drought mitigation in these different combinations. RWC was estimated by recording the turgid weight of fresh leaf samples, according to the method described by a previous study (20). The leaf chlorophyll index was measured using a handheld dual-wavelength chlorophyll meter (SPAD 502; Minolta) after two water stress periods.

Data Collection and sample processing

Biometric observations such as plant height, root length, number of branches and plant biomass were recorded at 30^{th} DAS and 45^{th} DAS. Yield attributes *viz*., number of capsules per plant, number of seeds per capsule, single plant yield, test grain weight, yield per hectare and haulms yield kg per ha were recorded. Soil samples were collected for microbial enumeration and initial and final soil nutrient analysis. Plant samples and seeds were collected to assess the nutrient dissolution potential of the test bioinoculant. The data on biometrics, physiological and yield parameters and nutrient analysis were statistically analysed (Table 1 and 4). The soluble protein content was measured using Coomassie brilliant blue G-250 (21). Total oil content was estimated using the Soxhlet apparatus method (22, 23).

Economics

The data for the three years were examined using standard methods formulated by CIMMYT to understand the economics (24). For each intercropping system, partial budgeting was calculated to determine the expenses incurred and the net returns. The PGPR cultures and their concentrations varied among the treatments, where other crop cultivation factors remained the same and were considered constant. The market prices of the inputs during 2019-2020 and 2021-2022 were used

Table 1. Shelf life studies of *Azospirillum*, KRB- 9 and PSB in individual and bio inoculant consortium

Treatments	Population Load				
	30 DAI ($x10^{9}$ cfu ml^{-1})	60 DAI ($x10^{9}$ (cfu ml^{-1})	90 DAI ($x10^{9}$(cfu ml^{-1})	120 DAI ($x10^{9}$(cfu ml^{-1})	150 DAI ($x10^{9}$(cfu ml^{-1})
Azospirillum	21.45 (10.33)	28.09 (10.45)	16.13 (10.21)	11.80 (10.07)	8.33 (9.92)
PSB	23.73 (10.38)	21.50 (10.33)	13.88 (10.14)	10.05 (10.00)	7.89 (9.90)
KRB 9	22.66 (10.36)	20.23 (10.31)	12.75 (10.11)	11.10 (10.05)	8.62 (9.94)
Azospirillum in consortium	20.80 (10.32)	22.58 (10.35)	13.96 (10.14)	10.11 (10.00)	9.63 (9.98)
PSB in consortium	25.34 (10.40)	22.63 (10.35)	18.72 (10.27)	14.80 (10.17)	9.06 (9.96)
KRB in consortium	26.65 (10.43)	21.80 (10.34)	10.72 (10.03)	10.21 (10.01)	8.42 (9.93)
SEd	0.39	1.68	1.21	2.41	0.64
CD (p=0.05)	0.86	3.61	2.61	5.18	1.39

*Numbers in parenthesis are log transformed values for calculating the partial budget of different intercropping systems.

Statistical analysis

Analysis of variance (ANOVA) was performed using the SAS software (SAS Institute, 1999). The data for individual years were analysed and the homogeneity of variances was tested using the Bartlett's chi-square test. Aitken's square root transformation was used to analyze data with heterogeneous variances. The combined analysis was performed using the PROC GLM procedure considering the years as fixed effects. The critical difference (CD) at 5% probability and P values were used to evaluate the differences among the treatment means. The graphs were developed using the STAR IRRI package (International Rice Research Institute, Philippines).

Results and Discussion

We analyzed data collected over a three-year period to gain insights into nutrient dynamics and their physiological impact on plant metabolism and yield. The mean data are summarized in Table 1 and the subsequent data on physiology in Table 3, yield and economics in Table 4 and are graphically represented in Fig. 1-5. Substantial differences were observed, aligning with the effects of various treatments.

Plant-microbe associations are a key relationship that forms a complex ecological community that has positive impacts on plant growth and productivity through their interactions and metabolic activities. Changes in the rhizosphere region enables better nutrients absorption and adaptation to abiotic stresses (25). The richness of soil microbial communities translates to sustained good productivity. Continuous cropping and chemical applications have altered these natural effects. Reversing this through external application of biological sources increases the production and productivity. In light of this, we investigated the effects of different microbial types on plant growth, yield and seed quality in sesame. This study was conducted in rainfed condition for all the imposed treatments, for all 3 years. The mean values obtained from the 3 years indicate significant differences in growth, yield and economics.

Shelf-life studies

The compatibility of bacteria was initiated using in the cross streak method and the profused growth showed their compatibility. The individual cultures of *Azospirillum*, phosphobacteria (PSB) and potash releasing bacteria (KRB-9) and their combination were grown in broths and subjected to shelf-life studies for up to 5 months period. The cultures had sufficient population loads of up to 10^9 colony forming units (CFU) for 5 months (Fig. 3, 4 and 5; Table1). In a similar study with *Azospirillum* and phosphobacteria consortium, it was found that the bacterial population had persisted for up to 2 years with good bacterial load, with negligible microbial contaminations in the broth and with good cell viability and shelf life (26); this is in conformity with the results of the shelf life experiment.

Biometric observations

Application of bioinoculants in conjunction with 100 % of the recommended dose of NPK and the consortium with 2% KCl and PPFM (Pink Pigmented Facultative Methylotrophs) spray yielded the most favorable results in terms of plant biometrics and yield (Table 2). This treatment led to a remarkable increase in plant height, which reached 141.8 cm, with a concomitant increase in biomass production. In addition, enhanced growth patterns were consistently observed across all three stages in the plots treated with PPFM in combination with KCl. Application of the bioinoculant consortium supplemented with inorganic fertilizers, along with both PPFM and KCl spray, resulted in the highest biomass production at 47.0 g at the harvest stage. The combination of PPFM with the consortium yielded a biomass of 43.6 g with a plant height of 136.7cm, where as the individual inoculam with both PPFM and KCl spray had a plant height of 124.3 cm and plant biomass of 43.2g. The associative symbiont, *Azospirillum* with its nitrogen-fixing and plant growth-promoting activities possibly facilitates root growth and expansion, enhancing water, nutrient and mineral uptake, thereby promoting plant growth. In addition, foliar spraying with PPFM likely contributed to higher biomass production.

Plant growth and biometrics were higher in plants treated with the consortium, the recommended fertilizers

Table 2. Effect of biological source of nutrients on growth, productivity and seed quality of sesame (2019-2022)

Treatments	Plant height (cm)	Plant biomass (g)	No. of capsules plant^{-1}	Plant nutrient uptake (%)				Seed quality (%)					
				N	P	K	S	N	P	K	S	Protein	Oil %
T1- 100 % NPK (RDF)	111.0	37.4	87.7	1.45	0.33	1.23	0.12	3.22	0.46	1.93	0.34	18.2	42.0
T2- T1 + individual inoculum + 2 % KCl spray	112.1	40.6	99.0	1.56	0.29	1.21	0.13	2.75	0.52	1.94	0.37	19.3	43.4
T3- T1 + individual inoculum + PPFM spray	117.6	41.0	88.3	1.67	0.34	1.37	0.13	3.14	0.51	1.96	0.37	19.9	43.3
T4- T1 + individual inoculum + 2 % KCl spray + PPFM spray	124.3	43.2	101.0	1.69	0.36	1.35	0.15	3.18	0.53	1.99	0.38	19.7	44.5
T5- Control	105.5	33.4	79.3	1.41	0.28	1.18	0.11	2.21	0.47	1.81	0.33	17.4	35.3
T6- T1 + Consortium	116.6	42.2	97.3	1.53	0.33	1.32	0.13	3.29	0.52	1.96	0.40	19.6	44.5
T7- T1 + Consortium + 2 % KCl spray	118.0	43.6	84.0	1.67	0.34	1.43	0.15	3.29	0.53	2.02	0.41	20.4	44.0
T8- T1 + Consortium + PPFM spray	136.7	43.2	103.3	1.67	0.39	1.44	0.16	3.34	0.53	2.17	0.41	20.7	46.4
T9 - T1 + Consortium + 2 % KCl spray + PPFM spray	141.8	47.0	110.6	1.74	0.39	1.48	0.17	3.47	0.57	2.35	0.42	21.8	47.2
SEm±	2.07	0.68	1.77	0.02	0.01	0.02	0.003	0.07	0.01	0.03	0.01	0.23	0.89
CD (P=0.05)	6.22	2.04	5.30	0.06	0.02	0.06	0.010	0.20	0.02	0.08	0.02	0.68	1.78

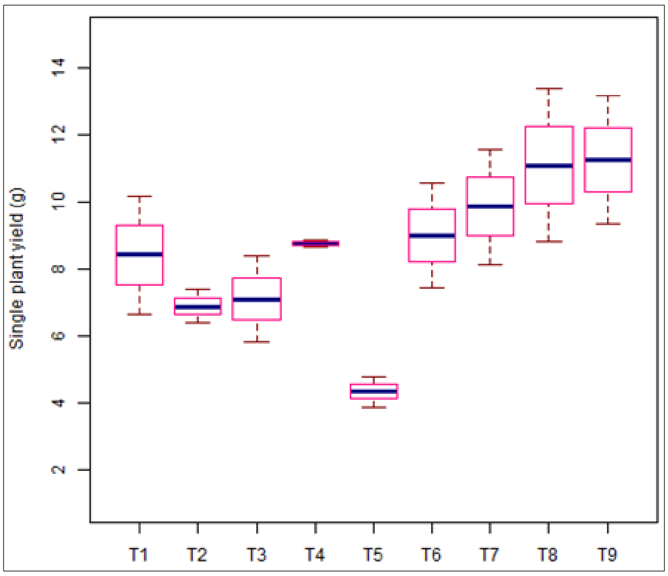

Fig. 1. Effect of biological source of nutrients on the single plant yield (g) of Sesame.

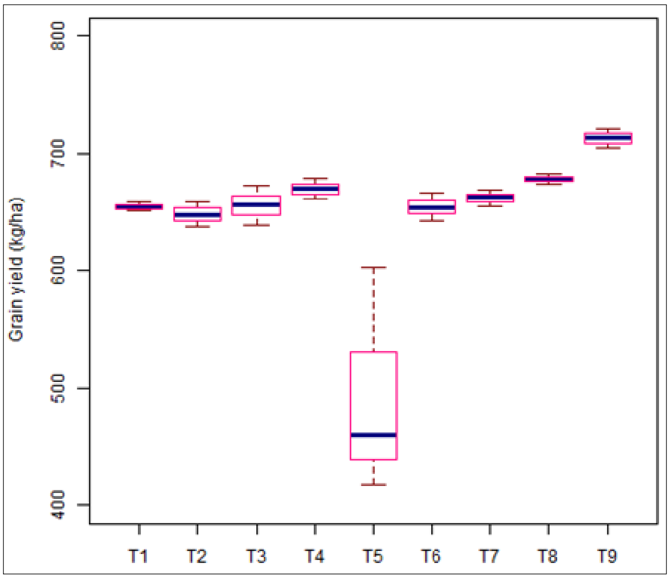

Fig. 2. Effect of biological source of nutrients on the grain yield per ha (kg) of Sesame.

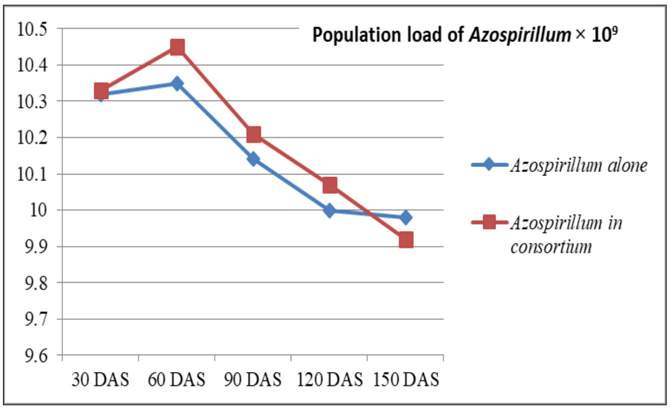

Fig. 3. Population of *Azospirillum* in individual and in consortium.

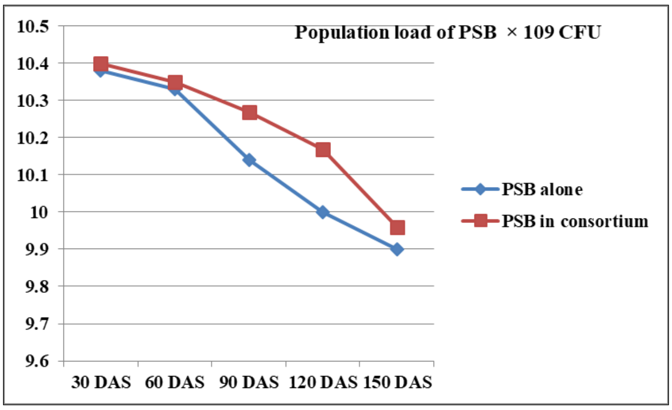

Fig. 4. Population of *Bacillus megaterium var phosphaticum* in individual and in consortium.

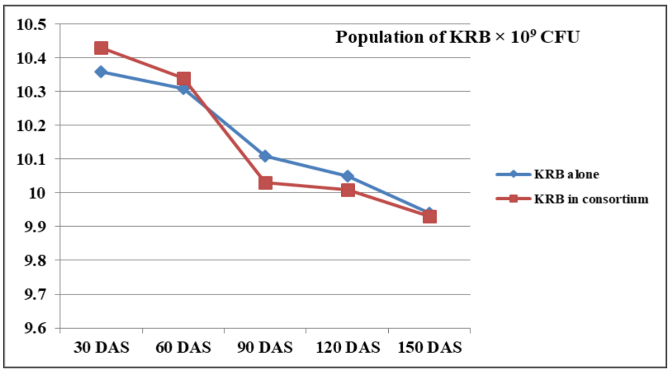

Fig. 5. Population of *Paenibacillus mucilaginous* (KRB-9) in individual and in consortium.

dose and 2% KCl and PPFM spray. In this study, bioinoculants such as *Azospirillum* and methylotrophs supported plant growth by providing both nutrient and growth promoting substances. Similar findings have been reported previously for sesame (27, 28). PPFM, a phyllosphere endophytic bacterium, produces growth-promoting hormones, that enhance growth. *Methylobacterium* strains present on plant leaves stimulate seed germination and plant growth, possibly through the production of phytohormones (15, 29). Some strains of these pink prokaryotes produce the cytokinin zeatin, while others produce indole acetic acid (30). The application of PPFM and KCl played a significant role in promoting growth; therefore, in this study, foliar sprays of PPFM likely contributed to higher biomass production.

Physiological parameters

Physiological parameters such as relative water content, total chlorophyll and proline content exhibited substantial improvements. The combined application of biofertilizers in the form of consortium, along with inorganic, a 2% KCl and a PPFM foliar spray, resulted in a significant increase in various physiological parameters (Table 3). Improvements in the total chlorophyll content were observed in all the treatments at 30 DAS, 60 DAS and at harvest. Treatments with bioinoculant consortium and inorganic fertilizers with PPFM and KCl spray recorded total chlorophyll contents of 38.5, 55.8 and 37.7 at 30 DAS, 60 DAS and at harvest, respectively. A similar trend was observed for the relative water content at 89.7, 97.8 and 90.2% and for the proline content at 2.45, 2.67 and 2.61 μmol g^{-1} fw at 30 DAS, 60 DAS and at harvest. Proline is a signaling molecule that triggers mitochondrial function, cell proliferation and gene expression, offering protection to plants under stress conditions (31, 32). In addition, a continuous potassium supply from the rhizosphere enhances drought tolerance by promoting photosynthesis and regulating plant hormones in sesame (33). Application of KCl and PPFM spraying, performed twice during the flowering stage at fortnightly intervals, improved stress tolerance; K source from potash bacteria and KCl spray was a twin enforcement for K nutrition crop metabolism.

Yield

Marked improvements were observed capsule numbers, single

Table 3. Effect of biological source of nutrients on crop physiology of sesame (2019-2022)

Treatments	Total Chlorophyll (SPAD Value)			Relative water content (%)			Proline content (μmol g^{-1} fw)		
	30 DAS	60 DAS	Harvest	30 DAS	60 DAS	Harvest	30 DAS	60 DAS	Harvest
T1- 100 % NPK (RDF)	32.4	47.0	31.8	80.1	87.3	80.5	1.60	1.74	1.70
T2- T1 + individual inoculum + 2 % KCl spray	35.8	51.9	35.1	85.7	93.4	86.1	1.92	2.09	2.04
T3- T1 + individual inoculum + PPFM spray	35.1	50.9	34.4	85.9	93.6	86.3	1.80	1.96	1.92
T4- T1 + individual inoculum + 2 % KCl spray + PPFM spray	36.4	52.8	35.7	87.1	95.0	87.6	1.96	2.14	2.09
T5- Control	34.8	50.5	34.1	80.2	87.5	80.6	1.62	1.77	1.73
T6- T1 + Consortium	34.9	50.6	34.2	81.2	88.5	81.6	1.65	1.80	1.76
T7- T1 + Consortium + 2 % KCl spray	36.7	53.2	36.0	87.8	95.7	88.2	2.01	2.19	2.14
T8- T1 + Consortium + PPFM spray	37.4	54.2	36.7	87.7	95.5	88.1	1.86	2.03	1.98
T9 - T1 + Consortium + 2 % KCl spray + PPFM spray	38.5	55.8	37.7	89.7	97.8	90.2	2.45	2.67	2.61
SEd	0.31	0.44	0.30	0.62	0.68	0.63	0.046	0.050	0.049
CD (P=0.05)	0.92	1.33	0.90	1.87	2.04	1.88	0.137	0.149	0.146

Table 4. Effect of biological source of nutrients on the grain yield (kg ha^{-1}) and economics of sesame

Treatments	Grain Yield (Kg/ha)*				Cost of cultivation*			Gross Income (Rs.)*			Net Income (Rs.)*			BC ratio*		
	2019- 20	2020-21	2021-22	Mean	2019-20	2020-21	2021-22	2019-20	2020-21	2021-22	2019-20	2020-21	2021-22	2019-20	2020-21	2021-22
T1- 100 % NPK (RDF)	658.3	651.0	655	654.77	32470	32550	32455	72413	71610	72050	39943	39060	39595	2.23	2.20	2.22
T2- T1 + individual inoculum + 2 % KCl spray	638.0	658.5	648	648.17	32640	32630	32550	70180	72435	71280	37540	39805	38730	2.15	2.22	2.19
T3- T1 + individual inoculum + PPFM spray	639.3	672.7	656	656.00	32710	32740	32800	70323	73997	72160	37613	41257	39360	2.15	2.26	2.20
T4- T1 + individual inoculum + 2 % KCl spray + PPFM spray	660.7	678.3	670	669.67	33185	33310	33200	72677	74613	73700	39492	41303	40500	2.19	2.24	2.22
T5- Control	500.7	418.0	460	459.57	30940	31070	31040	55077	45980	50600	24137	14910	19560	1.78	1.48	1.63
T6- T1 + Consortium	642.7	665.8	654	654.17	32430	32405	32405	70697	73238	71940	38267	40833	39535	2.18	2.26	2.22
T7- T1 + Consortium + 2 % KCl spray	655.3	669.0	662	662.10	32470	32420	32510	72083	73590	72820	39613	41170	40310	2.22	2.27	2.24
T8- T1 + Consortium + PPFM spray	673.3	682.8	678	678.03	32625	32655	32710	74063	75108	74580	41438	42453	41870	2.27	2.30	2.28
T9 - T1 + Consortium + 2 % KCl spray + PPFM spray	704.7	720.5	713	712.73	32710	32750	32815	77517	79255	78430	44807	46505	45615	2.37	2.42	2.39
SEd	20.06	43.1	17.8		-	-	-	-	-	-	-	-	-	-	-	-
CD (P=0.05)	42.16	91.4	37.7		-	-	-	-	-	-	-	-	-	-	-	-

-plant yield and grain yield per hectare. Specifically, when the bioinoculant consortium was applied in conjunction with NPK, along with 2% KCl and PPFM foliar spray, good results were observed (Table 2 and 4). These treatments resulted in 110.6 capsules per plant (Table 2), a significantly higher single-plant yield of 9.37 g per plant (Fig. 1) and an impressive mean grain yield of 712.7 kg per hectare (Fig. 2). Application of individual bioinoculants with inorganic fertilizers and KCL and PPFM spray produced 101.0 capsules and resulted in 669.9 kg mean grain yield per ha. Application of consortium with PPFM and KCl spray had significant plant growth and the grain yield was 8.86 percent increase over inorganic fertilizer application alone. These increased yields underscore the effectiveness of the bacterial consortium throughout the various growth stages of the crop, including critical stages *viz*., flowering and capsule formation and also associated physiological activities. The application of phosphobacteria, potassium-releasing bacteria and nitrogen-fixing bacteria had a profound influence on seed quality and quantity, stimulating growth and yield. Additionally, phosphorous supplementation positively affected photosynthesis, carbohydrate metabolism (14, 34), flower production per plant and capsule setting percentage (13), subsequently increasing metabolite production in sesame plants.

In this study, potassium was applied in three different forms: through inorganic nutrition, foliar spraying and biological sources. This combined approach likely contributed to the results observed. Split applications of potassium are associated with the production of a high-quality product, characterized by elevated protein and oil content. Application of potash-releasing bacteria leads to earlier flowering and maturity (35), while the foliar potassium nutrition increases the yield parameters (36, 37). Positive responses to potassium application is well-established and are in confirmity with our findings(32, 38).

Seed quality

Comprehensive analysis of the three years data reveals a clear and consistent correlation between yield and quality parameters, such as seed oil content and protein percentage, in sesame (Table 2). These correlations were statistically significant in the bioinoculant-applied treatments compared to the other treatments. Seeds that received bioinoculant consortium and NPK in addition with 2% KCl and PPFM spray had the highest nutrient content at 3.47% nitrogen, 0.57% P, 2.35% K and 0.42% sulphur. In addition, this treatment had recorded the highest protein content at 21.8% with an oil content of 47.2%. The seeds from plants treated with inorganic fertilizers registered 3.22% nitrogen, 0.46% P, 1.93% K and 0.34% sulphur, with 18.2% protein and 42.0% oil.

Consistent trends were observed across these nutrient -related parameters such as plant uptake, soil nutrient status, seed quality and nutrient content. Notably, plants that received the bioinoculant consortium in combination with NPK, 2 % KCl and PPFM foliar spray exhibited higher nutrient uptake and improved soil nutrient status compared to those in the other treatment groups. This treatment resulted in the highest content of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K) and sulfur (S), in the seed analysis. In addition, the protein and oil content was elevated. These findings indicate the positive correlation between seed nutrient content and seed quality (39).

Nutrient analysis

The extensive nutrient analysis, including assessments of plant uptake, soil nutrient status, seed quality and nutrient content, is outlined in Table 2. Consistent trends were observed across these nutrient-related parameters. Notably, plants treated with the bio-inoculant consortium with NPK along with 2% KCl foliar and PPFM spray exhibited higher nutrient uptake and improved soil nutrient status compared to those in the other treatment groups. Nutrient uptake was assessed in plant samples and significant differences were observed and supportted by previous studies on other oilseed crops (40 , 41). These observations were similar to those of the biometrics and yield parameters. The highest nutrient uptake in terms of N (1.74%), P (0.39%), K (1.48%) and S (0.17%) was recorded in plants inoculated with the bio inoculant consortium and the recommended fertilizer dose along with both sprays. This was followed by plants which received consortia with fertilizers and PPFM spray alone. These results indicate a synergistic effect on the nutrient acquisition pattern.

Survivability studies further supported these results, by demonstrating that these bioagents persisted in the crop rhizosphere until the harvest stage. Their presence likely contributed to strengthening the soil microbial population and enhancing nutrient cycling processes. The application of bioinoculants, including *Azospirillum*, phosphobacteria, potash-releasing bacteria, along with pink-pigmented methylotrophs, demonstrated compatibility and exhibited an additive effect. This synergy was particularly evident in biometric observations and yield parameters and it was further enhanced when combined with KCl spraying.

Economics

Combined bioinoculant application is a promising alternative to traditional inorganic fertilizers in boosting yields and increasing the gross income with a good cost benefit ratio and a reduced input cost with high returns. (Table 4). Significant grain yield was recorded in the treatment with bioinoculant consortium in combination with NPK, 2 % KCl and PPFM spray for all the years. Among the three years, a notable increase in yield was observed in 2020 (720.5 kg ha^{-1}) in the treatment with consortium, NPK and PPFM sprayed plants; the gross income was 79255/- INR with the highest BC ratio of 2.42. Treatments with 100% inorganic constituents resulted in a gross income of 71610/- INR and a BC ratio of 2.20. Significantly lower BC ratio (1.48) was observed in plants treated with only the bioinoculant in comparison to that in the other treatments. These results are parallel to the research work with *Azotobacter* and phosphobacteria where the yield and economics were higher (8).

Combined bioinoculant application as a consortium formulation is an alternative to traditional inorganic fertilizers. These microorganisms, once established in the rhizosphere, provide essential nutrients and growth-promoting substances, eventually boosting yields with a favourable cost-benefit ratio of 2.39. This cost-benefit ratio is especially beneficial for the small and marginal farmers practicing rainfed farming in their small holdings.

Conclusion

This study highlights effective bacterization methods for improving crop yields, particularly in drought-prone areas. The application of a liquid bacterial consortium significantly enhanced plant growth, seed quality and nutrient uptake. Optimized use of inorganic fertilizers and bioinoculants in nutrient-deficient soils proved is crucial to boost productivity in sesame cultivation. The synergistic effects of these bacterial combinations improved the yield and economic returns. This approach holds potential for other oilseed crops like groundnut and castor, promoting sustainable

Acknowledgements

We gratefully acknowledge Tamil Nadu Agricultural University for providing the financial support, laboratory facilities and equipment that made this research possible.

Authors' contributions

RB and KP carried out the field experiment and laid out the experimental calendar, GG participated in microbiological work, CT conducted the physiological activity, SHH and MY contributed for statistical analysis and economic analysis, VV contributed for seed quality works in the study, ST and CH contributed for analysis of data obtained, KS contributed for field data measurement and analysis.

Compliance with ethical standards

Conflict of interest: We declare that there are no competing interests related to this work

Ethical issues: None

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