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Optimizing Formulation and Economic Evaluation of Phosphate Solubilizing Bacteria for Enhanced Cauliflower Growth and Yield

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Abstract

A shortage of phosphorus (P), a necessary mineral ingredient for agriculture, may result in lower grain quality, productivity, and growth in cereal crops. Much of the phosphorus that is sprayed in agricultural contexts is immobilized in the soil, which limits the amount of phosphorus that is available to plants. This study focused on investigating the microbial communities in the rhizosphere of cauliflower crops from Kanpur, Unnao, and Lucknow districts in India, known for their fertile soils and favorable agricultural conditions. Soil samples were collected and screened for phosphate-solubilizing bacteria (PSB) and nitrogen-fixing bacteria. PSB was isolated using Pikovskaya's agar medium, and nitrogen-fixing bacteria were identified through nitrogen-free media supplemented with a bromothymol blue indicator. Morphological, biochemical, and molecular techniques were employed for characterization. The isolated strains were then tested for their impact on cauliflower growth and yield parameters under controlled conditions. Results showed significant enhancements in plant growth and yield parameters, suggesting potential applications in agricultural practices.

Keywords: Agricultural, Cauliflower Growth, Nitrogen-Fixing Bacteria, Phosphate-Solubilizing Bacteria, Rhizosphere.

Introduction

Phosphorus is not only a vital nutrient for plant growth and metabolism but also a limited natural resource, presenting a challenge to the sustainable development of the global economy. The readily accessible amount of phosphorus is insufficient to meet the growth demands of plants, particularly in the soils of subtropical forests, where severe phosphorus deficiency significantly hampers plant development and productivity (1,2). The phosphorus fertilizer recovery rate in soil is relatively low, ranging from 15 to 20%, with the rest becoming fixed in the soil. Globally, around 52.4 billion tons of phosphorus fertilizer are used annually to maintain soil fertility. Therefore, improving crops' capacity to efficiently absorb and utilize phosphorus is crucial from ecological and economic perspectives alike (3,4).

Recent studies have demonstrated that "phosphate-solubilizing bacteria" (PSB) play a beneficial role in enhancing plant growth. These microorganisms solubilize insoluble phosphate

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in the soil, which is essential for plant development, in addition to fixing nitrogen and releasing auxins. Research indicates that incorporating PSB into seeds or soil can enhance the solubilization of fixed soil phosphorus or applied phosphates, thereby promoting plant growth. For example, Hansen *et al.* demonstrated that inoculating *Bacillus simplex* significantly improved winter wheat plants, leading to increased phosphorus concentrations in root biomass and elevated levels of magnesium, manganese, and sulfur in shoot biomass (5,6). The efficiency of phosphorus-solubilizing microorganisms in soil may be affected by native microorganisms and soil conditions, which might make it difficult for them to establish sustained colonization. On the other hand, endophytes are essential to the plant's micro-ecosystem. They support overall plant development, improve plant tolerance to stresses, pests, and diseases, and aid in the fixation of nitrogen (7,8). Cauliflower (*Brassica oleracea* var. *botrytis*) is a prominent crop species in southern India, cultivated extensively for its economic importance. Despite its importance, the productivity of fir forests has declined in recent years due to intensive management practices and shorter rotation periods (9,10). Additionally, the soil in southern regions, characterized by high iron and aluminum content along with strong leaching, leads to phosphorus fixation and inactivation. This results in very low phosphorus utilization rates in the soil. This severely limits the sustainable development of *Brassica oleracea* var. *plantations*. Figure 1 shows the selection process of PSB and their growth-promoting mechanisms in potted *Brassica oleracea* var. *plants*. The figure highlights the steps involved in isolating and identifying effective PSB strains that enhance plant growth. It also details the various mechanisms through which these bacteria promote growth, such as nutrient solubilization and hormone production. Additionally, the figure demonstrates the significant impact of PSB application in wheat fields, showcasing improved growth and yield. This visual representation emphasizes the potential of PSB as a sustainable agricultural practice.

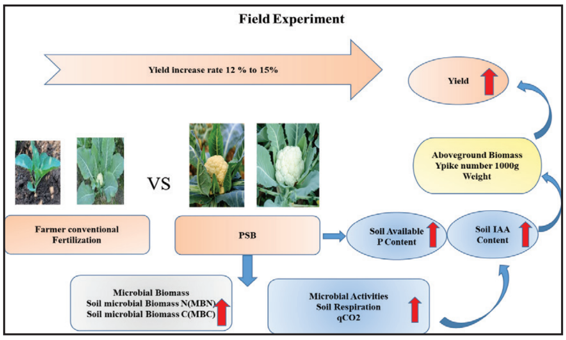

Figure 1: Detailed Selection and Impact Analysis of Phosphate-Solubilizing Bacteria (PSB) on *Brassica oleracea var*. and Wheat Cultivation.

Therefore, investigating the impact of PSB on the growth of *Brassica oleracea var.* is crucial for potential applications of PSB in forestry. Bioinoculant of rhizobia can effectively improve agricultural yield and productivity which indicates that Rhizobium is an effective Plant growth promoting microbe (11,12). In this study, PSB was isolated and screened from the stems, roots, as well as leaves of "*Brassica oleracea var*". The focus of the investigation was on traits that promote development, including siderophore generation, "indole-3-acetic acid" (IAA) synthesis, nitrogenase activity, and "1-Aminocyclopropane 1-Carboxylate" (ACC) deaminase activity (13,14). The study investigated the effects of PSB inoculation on plant growth, nitrogen absorption, and soil enzyme activity using "*Brassica oleracea var.*" as a model. These results are essential for producing useful understandings for creating and using PSB as biological fertilizer in forest applications.

Phosphorus is vital for plant growth, but its limited availability in soils poses a significant challenge for agriculture. Sustainable solutions, such as the use of phosphate-solubilizing bacteria (PSB), have shown promise in enhancing phosphorus availability. Research has demonstrated that various strains of PSB can significantly improve plant growth, soil health, and nutrient uptake. These beneficial microorganisms increase the bioavailability of phosphorus, promote root and shoot development, and reduce

Vol. 19(2) 2311-2321, April 2025, ISSN 0973-8916 (Print), 2230-7303 (Online)
DOI: 10.5530/ctbp.2025.2.18

the need for chemical fertilizers, thereby supporting sustainable agricultural practices and improving crop yields.

Z. Iqbal *et al.* (15) explored the phosphorus (P) is necessary for agriculture, its fixation in soils restricts plant accessibility, which affects grain output and growth. To increase P availability, this research looks at sustainable methods that use phosphate-solubilizing bacteria. *Bacillus subtilis* ZE15, *Bacillus megaterium* ZE32, *Bacillus megaterium* ZR3, and *Bacillus sp.* ZR19 were the four bacterial strains tested in Pikovskaya's broth, both with and without insoluble phosphorus (P). While organic acids were generated by all cultures, strain ZE15 showed the greatest capacity to solubilize phosphorus, reaching up to 130.00 µg mL−1. According to these results, Bacillus species may improve the solubilization or mineralization of the rhizosphere, which would increase phosphorus intake and facilitate future agricultural uses.

Z. Wang *et al.* (16) experimented to improve plant development and solubilizing phosphorus (P), PSB also helps to mitigate the negative effects of excessive agricultural fertilizers on soil health. This study identified *Pseudomonas moraviensis*, *Bacillus safensis*, as well as *Falsibacillus pallidus* as three effective PSB that can produce "indole-3-acetic acid" (IAA) and solubilize phosphate in sandy fluvo-aquic soils. Furthermore, the labile phosphorus percentage in the soil was dramatically enhanced by PSB by 122.05% ($P<0.05$), whereas the stable phosphorus fraction was significantly decreased by 46.80% ($P<0.05$). Moreover, PSB increased soil microorganism biomass and activity, indicating their potential to aid in the development of sustainable agriculture. These results highlight PSB as long-term sustainable resources that may improve soil health and agricultural output.

J. Chen *et al.* (17)7 endophytic phosphate solubilizing bacteria were screened out from Chinese fir, and were characterized for plant growth-promoting traits. Based on morphological and 16S rRNA sequence analysis, the endophytes were distributed into 5 genera of which belong to Pseudomonas, Burkholderia, Paraburkholderia, Novosphingobium, and Ochrobactrum. HRP2, SSP2 and JRP22 were selected based on their plant growth-promoting traits for evaluation of Chinese fir growth enhancement. The growth parameters of Chinese fir seedlings after inoculation were significantly greater than those of the uninoculated control group. The results showed that PSBs HRP2, SSP2 and JRP22 increased plant height (up to 1.26 times analyzed the Chinese fir trees that were used to extract PSB, which were then tested for their capacity to stimulate plant development. In comparison to controls, three strains (SSP2, HRP2, and JRP22) considerably improved Chinese fir seedling growth characteristics including biomass, plant height, and stem diameter. Indicators of soil fertility, such as total nitrogen, potassium, phosphorus, and accessible nutrients, were also enhanced by these PSBs. According to the research, PSBs are useful biological agents for sustainable agroforestry that improve agricultural yields and environmental health without using chemical fertilizers as much.

S. Batool and A. Iqbal (18) discussed the PSB were isolated from rhizospheres of different plants to improve the nutrition and development of Triticum aestivum. Ten PSB strains were chosen from a group of thirty isolates based on their strong "phosphate solubilization" and PGP. Under ideal circumstances, these strains showed efficient phosphate solubilization and generated useful substances like hydrogen cyanide, ammonia, siderophores, and indole acetic acid. PSB injection dramatically increased root/shoot development (10% to 90%) and seed germination (50% to 80%) in laboratory testing. Improved seed germination (40%–80%) as well as increases in shoot length (5% to 34.8%) and seed weight (5% to 96%) were seen in field testing. According to the research, these PSB strains have promise as bio fertilizers that might eventually replace chemical fertilizers in sustainable *Triticum aestivum L.* production.

Vol. 19(2) 2311-2321, April 2025, ISSN 0973-8916 (Print), 2230-7303 (Online)
DOI: 10.5530/ctbp.2025.2.18

A. Nosheen *et al.* (19) investigated the use of biofertilizers on the Thori cultivar of Kasumbha has a positive impact, enhancing the quality of feedstock for biodiesel production. Biofertilizers improve soil fertility and nutrient availability, leading to healthier plant growth and higher yields. This, in turn, results in better-quality seeds with higher oil content, making them more suitable for efficient biodiesel production. The number of plant leaves, leaf area, and number of seeds per capitulum were all greatly enhanced by the administration of biofertilizer both alone and in conjunction with chemical fertilizer. Agronomic traits like plant height, branch number, and capitulum count were notably improved with biofertilizer alone compared to control. Seed yield and oil content, including beneficial seed phenolics, were enhanced by biofertilizer and chemical fertilizer treatments. Biofertilizer treatment alone yielded the highest biodiesel production, with optimal oleic acid content, while maintaining lower acid values and free fatty acids. This study supports biofertilizers as effective alternatives to chemical fertilizers, promoting sustainable and environmentally friendly agricultural practices.

S. B. Sharma *et al.* (20)in both organic and inorganic forms, its availability is restricted as it occurs mostly in insoluble forms. The P content in average soil is about 0.05 % (w/w developed that Phosphorus (P) is vital for plant growth but often limited in availability due to soil fixation and insolubility. Chemical P fertilizers are energy-intensive and environmentally harmful, prompting interest in phosphate-solubilizing microorganisms (PSM) as eco-friendly alternatives. PSM, including bacteria and fungi, enhances P availability through biological processes. However, their performance in field conditions varies, necessitating improvements like genetic modifications or co-inoculation techniques. This review discusses PSM diversity, solubilization mechanisms, phosphatase roles, influencing factors, and future applications for sustainable agriculture.

N. Kishore *et al.* (21)phosphorus (P discussed the essential elements required for plant growth include phosphorus (P), nitrogen (N), and potassium (K). Phosphorus is the most limiting nutrient after nitrogen. Even though there are several forms of P in soil, it is seldom available in a form that plants can use, which often calls for the use of expensive or harmful chemical fertilizers. When used in the rhizosphere, “phosphate solubilizing microorganisms” (PSMs) provide a sustainable substitute by increasing P availability in a variety of ways. Certain PSMs also function as biocontrol agents and PGPR, enhancing soil health and shielding plants from diseases. Thanks to technological developments, PSMs may be altered to improve their advantageous characteristics. Nonetheless, there are still problems and knowledge gaps, which are examined in this thorough analysis of PSMs.

Prior studies and findings show that phosphate-solubilizing bacteria (PSB) offer a sustainable and effective solution to the challenge of phosphorus availability in agriculture. By enhancing phosphorus solubilization, promoting plant growth, and improving soil health, PSB reduce reliance on chemical fertilizers and contribute to more environmentally friendly farming practices. Continued research and application of PSB can play a crucial role in achieving higher agricultural productivity and sustainability.

Material And Methods

Research design

Soil samples were carefully collected from the rhizosphere regions of cauliflower crops grown in the districts of Kanpur, Unnao, and Lucknow, India. These regions are renowned for their fertile lands and conducive agricultural conditions, making them prime areas for cauliflower production in the country. The favorable climatic conditions and nutrient-rich soil composition in these districts greatly enhance the robust growth and high yield of cauliflower

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crops. The study aimed to comprehensively investigate the microbial populations in the rhizosphere of cauliflower crops by systematically collecting soil samples from these specific regions. By focusing on Kanpur, Unnao, and Lucknow, the study aimed to leverage the agricultural potential of these areas to explore the diversity and functionality of phosphate-solubilizing or nitrogen-fixing bacteria in cauliflower rhizospheres.

Sample

Using a nitrogen-free medium enhanced with a bromothymol blue indicator, soil samples taken from the cauliflower rhizosphere were examined for the presence of nitrogen-fixing bacteria. Nitrogen-fixing bacteria possess the enzymatic machinery to convert atmospheric nitrogen into ammonia, thereby contributing to soil fertility and plant nutrition. Colonies exhibiting a characteristic blue color change in the medium, indicative of nitrogen fixation activity, were selected for further identification and characterization. Identification methods similar to those described for PSB were employed for the nitrogen-fixing microbes isolated from the soil samples. Morphological, biochemical, and molecular techniques were utilized to characterize and classify the nitrogen-fixing bacterial strains at the genus and species levels. These methods yielded valuable insights into the taxonomic diversity and functional potential of the nitrogen-fixing microbial community associated with the cauliflower rhizosphere.

The isolation of PSB began with the serial dilution technique, a standard method for isolating microorganisms from environmental samples. One gram of soil from the cauliflower rhizosphere was weighed and suspended in 9 milliliters of sterile saline solution (0.85% NaCl) for thorough homogenization. Serial dilutions of the soil suspension were prepared, ranging from undiluted (10^{-1}) to 10^{-5}, with each step involving the transfer of an aliquot into a new saline solution volume. This process reduced microbial population density, enhancing the isolation of individual bacterial colonies. On Pikovskaya's agar medium, which is specific for PSB and uses "tricalcium phosphate" (TCP) as the phosphorus source, aliquots from these dilutions were spread out. The plates were incubated at 28°C for five to seven days to allow bacterial colonies to proliferate. Following incubation, the plates were inspected for morphologically distinct colonies exhibiting clear zones indicative of phosphate solubilization. These colonies were selected for further purification and characterization by subculturing onto fresh Pikovskaya's agar plates to ensure purity. This process of successive subculturing eliminated potential contaminants, resulting in pure cultures suitable for subsequent analyses and characterization.

Data collection

A soil auger, a specialized tool designed for efficient soil sampling, was employed to collect representative soil samples from the designated cauliflower rhizosphere regions. Sampling was conducted at a depth ranging from 0 to 20 centimeters beneath the soil surface, ensuring the inclusion of the rhizosphere zone where the majority of plant-microbe interactions occur. Careful attention was paid to avoid contamination and to maintain the integrity of the collected samples. For each experimental technique, three runs were conducted to guarantee the accuracy and consistency of the findings. To demonstrate the diversity within the dataset, the study's results were presented as mean values ± standard deviation. Statistical analyses were conducted using dedicated software packages like SPSS or R, following standard methodologies. Graphical representations, elucidating the trends and patterns observed in the data, were meticulously prepared using software tools like Graph Pad Prism or Microsoft Excel, facilitating a clear and concise presentation of the findings. An organized description of the steps required in isolating, characterizing, and characterizing PSB, particularly for cauliflower development is shown in Table 1, along with numerical results.

Vol. 19(2) 2311-2321, April 2025, ISSN 0973-8916 (Print), 2230-7303 (Online)
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Table 1: Quantitative Analysis of Isolation, Identification, and Characterization Processes of PSB for Enhancing Cauliflower Growth.

S.No.	Step	Numeric Value
1.	Soil Sample Collection	20 soil samples collected
2.	Sampling Depth	0-20 cm depth
3.	Preparation of Soil Suspension	1 gram of soil sample suspended in 9 ml of saline solution
4.	Serial Dilution	Dilutions prepared from 10^{-1} to 10^{-5}
5.	Spread Plating	Aliquots plated onto Pikovskaya's agar medium
6.	Incubation Period	5-7 days at 28°C
7.	Colony Selection	Morphologically distinct colonies with clear zones selected
8.	Purification of Selected Colonies	Subcultured onto fresh Pikovskaya's agar plates
9.	Morphological Characterization	Colony morphology observed
10.	Gram Staining	Gram staining performed for classification
11.	Biochemical Tests	Catalase, oxidase, and sugar fermentation tests conducted
12.	Molecular Identification	16S rRNA gene sequencing performed for precise identification
13.	Phosphate Solubilization Efficiency Assessment	NBRIP broth method used
14.	Organic Acid Production	High-performance liquid chromatography (HPLC) or colorimetric assays performed
14.	Plant Growth-Promoting Substances" Assessment	Indole acetic acid" (IAA) and siderophore production assessed

Data analysis

Pure cultures of the isolated PSB underwent a thorough morphological examination to identify key characteristics indicative of bacterial taxonomy and classification. Colony morphology, including features such as size, shape, color, elevation, and texture, was carefully observed and documented. Additionally, cellular morphology, including cell shape, arrangement, and motility, was assessed through microscopic examination of bacterial smears prepared from pure cultures. Gram staining, a crucial differential staining technique, was used to classify bacterial isolates as either Gram-positive or Gram-negative based on the makeup of their cell walls. Subsequently, comprehensive biochemical tests were carried out to enhance the biochemical characteristics of the separated PSB strains. A variety of metabolic activities and enzymatic reactions characteristic of bacterial physiology were covered in these experiments. In particular, the enzyme catalase, which catalyzes the breakdown of hydrogen peroxide into oxygen along with water, was found using the catalase test. The oxidase test was used to measure cytochrome c oxidase activity, which helped distinguish various bacterial species according to their capacity for respiration. To evaluate the bacterial isolates' capacity to metabolize different sugars as carbon sources and get insight into their metabolic flexibility and substrate usage patterns, experiments on sugar fermentation were also conducted.

In parallel with morphological and biochemical characterization, molecular identification techniques were employed to achieve a comprehensive and precise taxonomic classification of the isolated PSB strains. Table 2, shows the biochemical and microbial activity in soil samples from varied locations and depths

Vol. 19(2) 2311-2321, April 2025, ISSN 0973-8916 (Print), 2230-7303 (Online)
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across Kanpur, Unnao, and Lucknow. The highly conserved 16S ribosomal RNA (rRNA) gene, a ubiquitous molecular marker prevalent across bacterial taxa, was targeted for amplification and sequencing. The "Polymerase Chain Reaction" (PCR) was used to amplify the 16S rRNA gene with universal primers, followed by sequencing of the resulting DNA fragments. Phylogenetic analysis followed by comparison of these sequences with reference databases enabled precise taxonomic identification and classification of the isolated PSB strains at both the genus and species levels (22). In addition to offering a reliable method of species identification, this molecular technique also gave insightful information on the genetic diversity and evolutionary relationships within the isolated bacterial community. The National Botanical Research Institute's Phosphate (NBRIP) broth technique was one of the standard tests used to quantitatively evaluate the isolated PSB strains' phosphate solubilization efficiency. This study assessed PSB's capacity to solubilize phosphate in its insoluble forms, including tricalcium phosphate (TCP). Under ideal circumstances, the PSB isolates were inoculated into NBRIP broth that had been supplemented with insoluble phosphate sources. Using established techniques, the broth's soluble phosphate content and pH variations were recorded regularly throughout the incubation period. The degree of phosphate solubilization shown by every strain was measured by measuring the gradual rise in soluble phosphate concentration and the corresponding decrease in pH. The comparison between the control group and the plants infected with PSB Isolates 1, 2, and 3 is shown in Table 3, which also includes the shoot length (cm), root length (cm), fresh weight (g), as well as dry weight (g). In comparison to the control group, Table 4 displays the quantity of curds, curd weight (g), and curd diameter (cm) of cauliflower plants infected with PSB Isolates 1, 2, and 3.

Table 2: Biochemical and Microbial Activity of Soil Samples from Different Locations and Depths in Kanpur, Unnao, and Lucknow.

Sample ID	Location	Soil Depth (cm)	Nitrogenase Activity	ACC Deaminase Activity	IAA Production	Siderophore Production	PSB Isolation (CFU/g)
1	Kanpur	0-20	3.5 U/mg	1.2 U/mg	15 µg/mL	+	$1.5x10^6$
2	Unnao	0-20	3.7 U/mg	1.1 U/mg	13 µg/mL	++	$1.7x10^6$
3	Lucknow	0-20	3.2 U/mg	1.3 U/mg	14 µg/mL	+	$1.6x10^6$

CFU/g: "Colony-Forming Units" per gram of soil.

- U/mg: Enzyme activity units per milligram of protein.
- +: Presence of activity.
- ++: Higher presence of activity.

Table 3: Growth Parameters of Plants Inoculated with PSB Isolates and Control.

Growth Parameter	PSB Isolate 1	PSB Isolate 2	PSB Isolate 3	Control
Shoot Length (cm)	30.2	31.5	29.8	25.4
Root Length (cm)	15.1	15.8	14.9	12.3
Fresh Weight (g)	350	360	340	280
Dry Weight (g)	50	52	48	40

Current Trends in Biotechnology and Pharmacy
Vol. 19(2) 2311-2321, April 2025, ISSN 0973-8916 (Print), 2230-7303 (Online)
DOI: 10.5530/ctbp.2025.2.18

Table 4: Yield Parameters of Cauliflower Plants Inoculated with Phosphate-Solubilizing Bacteria (PSB) Isolates and Control

Yield Parameter	PSB Isolate 1	PSB Isolate 2	PSB Isolate 3	Control
Number of Cards	12	13	11	8
Curd Weight (g)	600	620	590	500
Curd Diameter (cm)	20	21	19	16

Result and Discussion

Selected strains of Phosphate-Solubilizing Bacteria (PSB) and nitrogen-fixing microbes, either isolated individually or in combination, underwent comprehensive growth assays to assess their synergistic impacts on cauliflower growth and yield. Surface-sterilized cauliflower seeds were inoculated with these selected bacterial strains to establish microbial associations prior to planting. Sterilized soil, mimicking natural rhizosphere conditions, was filled in pots, and the inoculated seeds were sown under controlled environmental conditions.

Growth parameter measurements

Plant growth parameters, such as fresh weight, shoot length, root length, and dry weight, were carefully measured at designated intervals throughout the growth period. Additionally, yield parameters such as the number of curds, curd weight, and curd diameter were recorded at harvest to assess the impact of microbial inoculation on cauliflower productivity. To clarify any noteworthy variations between treatment groups and to speculate about possible synergistic effects of PSB as well as nitrogen-fixing microorganisms on cauliflower growth and yield, statistical studies were carried out. Figure 2 illustrates the impact of various PSB isolates on plant development metrics, including shoot length, root length, fresh weight, and dry weight. The most significant improvement in plant development is shown in PSB Isolate 2, which reached the maximum shoot length of 31.5 cm, root length of 15.8 cm, fresh weight of 360 grams, and dry weight of 52 grams. With shoot lengths of 30.2 cm or 29.8 cm, root lengths of 15.1 cm as well as 14.9 cm, fresh weights of 350 grams and 340 grams, as well as dry weights of 50 grams and 48 grams, respectively, PSB Isolates 1 and 3 also exhibit notable advantages over the control group. The control group, on the other hand, had the lowest values for all parameters shoot length of 25.4 cm, fresh weight of 280 grams, root length of 12.3 cm, and dry weight of 40 grams because they did not get PSB therapy. This information demonstrates how well PSB isolates work to encourage plant development, with PSB Isolate 2 being especially helpful.

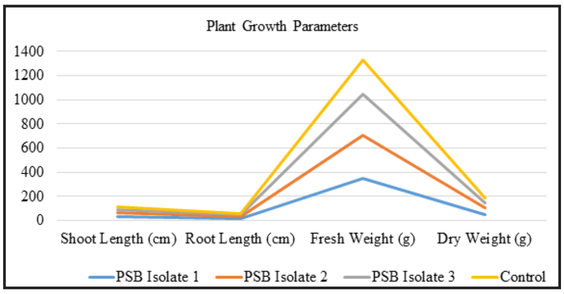

Figure 2: The Graph Shows the Plant Growth Parameter.

To establish a baseline for comparison, control pots devoid of bacterial inoculation were meticulously maintained under identical environmental conditions throughout the experiment. These control pots were used as reference points to evaluate the effects of microbial inoculation on cauliflower growth and yield parameters. By eliminating the confounding influence of microbial treatments, the control group facilitated the accurate evaluation of the specific effects attributable to the introduced bacterial strains.

Evaluation of yield parameters

At harvest, yield parameters crucial for assessing cauliflower productivity were systematically recorded. These parameters included the number of curds, curd weight, and curd diameter, which collectively reflect the quality and quantity of cauliflower produced. The harvest data offered valuable insights into the efficacy of microbial inoculation in enhancing cauliflower yield and marketable quality compared to the control group. Figure 3 compares the growth metrics of cauliflower treated with different phosphate-solubilizing bacteria (PSB) isolates against a control group. The metrics assessed include the number of curds, curd weight, and curd diameter. PSB Isolate 1 resulted in 12 curds with an average weight of 600 grams and a diameter of 20 cm. PSB Isolate 2 showed the best performance, producing 13 curds with an average weight of 620 grams and a diameter of 21 cm. PSB Isolate 3 resulted in 11 curds, each averaging 590 grams and 19 cm in diameter. In contrast, the control group, which did not receive PSB treatment, had the lowest values, with only 8 curds averaging 500 grams in weight and 16 cm in diameter. These results indicate that PSB isolates significantly enhance cauliflower growth, evidenced by increased curd number, weight, and diameter compared to the control.

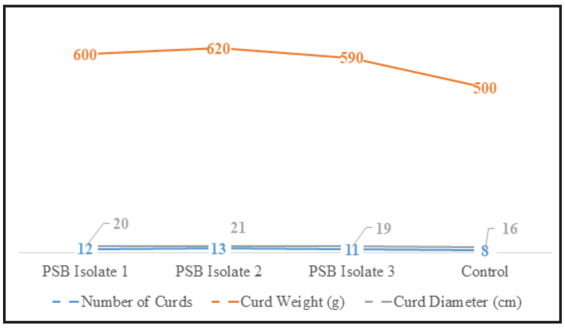

Figure 3: The graph shows the Yield Parameters.

To identify meaningful distinctions between the treatment groups and the control, rigorous statistical analyses were conducted using established methods such as “Analysis of Variance” (ANOVA), followed by post hoc tests like Tukey’s “honestly significant difference” (HSD) test. These analytical approaches allowed for a comprehensive assessment of treatment effects on diverse growth and yield parameters, ensuring robust interpretation of the results with a high level of confidence. Statistical significance was defined at $p < 0.05$ to uphold the reliability and validity of the findings.

Conclusion

This research showed that phosphate-solubilizing or nitrogen-fixing bacteria were present and active in the rhizosphere of cauliflower crops grown in the districts of Kanpur, Unnao, and Lucknow. The isolated bacterial strains exhibited promising effects on cauliflower growth and yield, underscoring their potential as biofertilizers in sustainable agriculture. Further research could explore optimizing bacterial inoculants for broader agricultural applications, enhancing crop productivity and soil health management strategies. These findings highlight the promise of PSB as sustainable alternatives to chemical fertilizers, offering potential benefits for agricultural practices aiming at improved crop productivity and soil health. Future research directions could explore optimizing PSB inoculation strategies and their broader applications across different agricultural contexts.

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Conflict of interest

The authors declare that they have no conflict of interest.

Vol. 19(2) 2311-2321, April 2025, ISSN 0973-8916 (Print), 2230-7303 (Online)
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