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Role of Plant Growth-Promoting Rhizobacteria in Enhancing Crop Productivity through Improved Nutrient Availability and Sustainable Agricultural Practices

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Abstract

The increasing demand for sustainable crop production has encouraged the development of eco-friendly alternatives to chemical fertilisers. This study evaluated the potential of plant growth-promoting rhizobacteria (PGPR) and their consortium application for improving wheat (Triticum aestivum) growth, nutrient uptake and yield performance. Three bacterial isolates (RB1, RB2 and RB3) were evaluated individually and as a consortium under controlled conditions using five treatments with ten biological replicates. PGPR isolates exhibited important plant growth-promoting traits, including nitrogen fixation, phosphate solubilisation, indole-3-acetic acid production and pathogen inhibition activity. PGPR inoculation significantly enhanced wheat growth compared with the untreated control. The consortium treatment produced the highest plant height (82.6 cm), root length (27.8 cm), dry biomass (5.5 g), chlorophyll content (51.6 SPAD units), nitrogen uptake (66.9 mg plant^{-1}) and grain yield (39.4 g plant^{-1}), representing a 113% increase in yield compared with control plants. Individual isolates also improved plant performance, although their effects were lower than the combined consortium treatment. Statistical analysis confirmed significant differences among treatments ($p < 0.05$). The findings demonstrate that PGPR consortia provide a promising sustainable approach for enhancing wheat productivity through improved nutrient acquisition and plant physiological performance.

1. Introduction

Wheat (*Triticum aestivum*) is one of the most important cereal crops worldwide, serving as a primary source of carbohydrates, proteins and essential nutrients for a large proportion of the global population. Increasing population growth, changing dietary demands and limited agricultural resources have created continuous pressure to improve wheat productivity. However, achieving higher crop yields has traditionally relied heavily on intensive use of chemical fertilisers and pesticides. Although synthetic inputs have contributed significantly to increasing agricultural production, their excessive and long-term application has resulted in several environmental concerns, including soil degradation, nutrient imbalance, groundwater contamination and reduced microbial diversity.Nitrogen and phosphorus are among the most important nutrients limiting plant growth and productivity. Although nitrogen fertilisers directly enhance crop growth, their inefficient utilisation often results in significant nutrient losses through leaching, volatilisation and denitrification processes. Similarly, phosphorus is abundant in soil but frequently exists in insoluble forms that are unavailable for plant uptake. Therefore, improving nutrient availability and utilisation efficiency has become a major objective in sustainable agricultural practices.

In this context, beneficial soil microorganisms have gained considerable attention as environmentally friendly alternatives to conventional agricultural inputs. Plant growth-promoting rhizobacteria (PGPR) represent a diverse group of beneficial bacteria that colonise plant roots and enhance plant development through multiple direct and indirect mechanisms. These microorganisms have emerged as promising biological tools for improving crop productivity while reducing dependence on chemical fertilisers. PGPR are naturally occurring beneficial bacteria present in the rhizosphere, the soil region directly influenced by plant roots. These microorganisms establish interactions with plants and promote growth through several mechanisms, including biological nitrogen fixation, phosphate solubilisation, phytohormone production, siderophore synthesis and suppression of plant pathogens.

One of the major contributions of PGPR is biological nitrogen fixation, where specific bacterial species convert atmospheric nitrogen into forms accessible to plants. This process improves nitrogen availability and supports essential physiological functions, including chlorophyll formation, protein synthesis and enzyme activity. By increasing nitrogen availability, PGPR can enhance plant growth while reducing the requirement for synthetic nitrogen fertilisers. Phosphorus availability is another critical factor influencing plant productivity. A considerable proportion of soil phosphorus exists in insoluble mineral complexes that cannot be directly absorbed by plants. Phosphate-solubilising PGPR release organic acids and phosphatases that convert unavailable phosphorus into soluble forms, thereby improving phosphorus uptake and supporting root development.

Furthermore, many PGPR strains produce indole-3-acetic acid (IAA), an important plant growth hormone involved in cell division, root elongation and development of lateral roots. Enhanced root architecture increases the soil exploration capacity of plants, improving water and nutrient absorption. As a result, PGPR-treated plants often exhibit improved biomass accumulation, nutrient acquisition and stress tolerance. Several studies have demonstrated the positive influence of PGPR inoculation on wheat growth and yield performance. Bacterial inoculation has been associated with improvements in seed germination, plant height, root development, biomass production and grain yield. These effects are primarily attributed to improved nutrient availability, enhanced root growth and stimulation of plant physiological processes.

The rhizosphere interaction between wheat plants and beneficial bacteria is particularly important because wheat productivity depends strongly on efficient nutrient acquisition. PGPR colonisation improves root activity and creates a favourable microbial environment around plant roots. Enhanced root systems allow plants to access greater soil volume, resulting in improved nutrient and water uptake. PGPR application has also been reported to enhance chlorophyll content and photosynthetic efficiency. Increased chlorophyll concentration reflects improved nitrogen status and greater photosynthetic capacity, which contributes to increased biomass production and grain development. Therefore, improvements in physiological characteristics following PGPR inoculation often translate into higher yield performance.

In addition to direct growth promotion, PGPR contribute to plant protection through indirect mechanisms. Many bacterial strains produce siderophores that restrict pathogen development by limiting iron availability, while others produce antimicrobial compounds that suppress harmful microorganisms. This biological control potential makes PGPR particularly valuable for reducing dependence on chemical pesticides.

Although individual PGPR strains have demonstrated considerable potential, the effectiveness of single bacterial inoculants may vary under different environmental and soil conditions. A single bacterial strain may possess only limited plant growth-promoting abilities and may not provide all the necessary functions required for maximum crop improvement. The application of PGPR consortia has therefore emerged as an advanced approach because multiple bacterial strains can provide complementary functions. For example, one bacterial strain may contribute nitrogen fixation, another may enhance phosphate availability, while another may produce higher levels of growth-regulating hormones or pathogen suppression compounds. The combined activity of multiple microorganisms may result in stronger and more consistent plant growth responses compared with individual strains.

Previous research suggests that microbial consortia can improve plant performance by increasing rhizosphere colonisation efficiency and providing multiple growth-promoting mechanisms simultaneously. However, successful consortium development requires careful selection of compatible bacterial strains because microbial interactions may influence their overall effectiveness. For wheat production, PGPR consortia represent a promising strategy because they may improve nutrient use efficiency, enhance crop productivity and contribute towards environmentally sustainable agriculture.

Although extensive research has demonstrated the beneficial effects of individual PGPR strains on crop growth, several knowledge gaps remain. Many previous studies have focused on evaluating single bacterial isolates, while comparatively fewer investigations have examined the combined effects of multiple compatible PGPR strains on wheat growth and productivity. Furthermore, the mechanisms responsible for improved wheat performance are often studied independently. Limited studies have integrated bacterial functional traits, plant growth parameters, physiological responses, nutrient uptake and yield performance within a single experimental framework. Understanding these combined relationships is essential for developing effective PGPR-based biofertilisers.

Another important limitation is that the effectiveness of PGPR treatments can vary depending on bacterial strain characteristics, environmental conditions and crop genotype. Therefore, identifying whether a consortium provides superior benefits compared with individual bacterial isolates remains an important research question. The present study addresses these gaps by evaluating three individual PGPR isolates (RB1, RB2 and RB3) and their consortium application on wheat growth, nutrient acquisition and yield performance. The study investigates bacterial functional characteristics, including nitrogen fixation, phosphate solubilisation, IAA production, siderophore production and pathogen inhibition ability. Additionally, plant responses including growth attributes, chlorophyll content, biomass accumulation, nutrient uptake and grain yield are assessed. This integrated approach provides a comprehensive understanding of PGPR-mediated wheat improvement and evaluates the potential of bacterial consortia as sustainable alternatives to conventional chemical inputs. The findings may contribute towards the development of efficient microbial biofertilisers for improving wheat productivity while supporting environmentally sustainable agricultural practices.

2. Materials and Methods

2.1 Experimental Design and PGPR Treatment Preparation

A pot experiment was conducted to evaluate the influence of plant growth-promoting rhizobacteria (PGPR) on growth performance, nutrient acquisition and yield characteristics of wheat (*Triticum aestivum*). The experiment was designed according to a completely randomised design (CRD) consisting of five treatments with ten biological replicates per treatment. The treatments included an uninoculated control (T0), three individual bacterial isolates (RB1, RB2 and RB3) and a bacterial consortium containing a combination of all three isolates (T4). Healthy and uniform wheat seeds were selected, surface sterilised and prepared for microbial inoculation before sowing. The PGPR isolates were cultured under appropriate growth conditions until sufficient bacterial populations were obtained for application.

For inoculation, bacterial suspensions were prepared and standardised to ensure consistent microbial application across treatments. Wheat seeds assigned to PGPR treatments were coated with respective bacterial suspensions, while control seeds received sterile treatment without bacterial inoculation. After inoculation, seeds were sown in sterilised growth medium under controlled experimental conditions. The plants were maintained with equal irrigation and nutrient management practices throughout the experimental period to minimise environmental variation. The consortium treatment was prepared by combining equal proportions of RB1, RB2 and RB3 bacterial suspensions to investigate whether combined microbial activity could provide enhanced plant growth benefits compared with individual isolates.

Plant growth was monitored throughout the experimental period, and observations were recorded at specific growth stages. The experimental design allowed comparison of individual bacterial efficiency and the combined effect of multiple PGPR strains. The use of biological replicates ensured reliability of the obtained results and enabled statistical evaluation of treatment effects. This approach provided a comprehensive assessment of PGPR potential as a sustainable microbial biofertiliser for improving wheat productivity.

2.2 Characterisation of PGPR Functional Traits

The plant growth-promoting characteristics of bacterial isolates were evaluated before their application in wheat cultivation experiments. The functional traits of RB1, RB2 and RB3 isolates were analysed to determine their potential contribution towards plant growth enhancement. Nitrogen fixation ability, phosphate solubilisation capacity, indole-3-acetic acid (IAA) production, siderophore production and antagonistic activity were selected as important indicators of PGPR efficiency.

Nitrogen fixation potential was assessed to determine the ability of bacterial isolates to contribute towards biological nitrogen availability for plants. Phosphate solubilisation ability was evaluated because insoluble phosphorus present in soil is often unavailable for plant uptake, and PGPR-mediated solubilisation can improve phosphorus accessibility. The production of IAA, an important plant growth-regulating hormone, was analysed because microbial synthesis of auxins can stimulate root development, enhance nutrient absorption and improve plant establishment. Siderophore production was investigated due to its role in iron acquisition and microbial competition against pathogenic organisms within the rhizosphere. The antagonistic activity of bacterial isolates was also assessed to determine their potential role in plant protection. The ability of PGPR to suppress harmful microorganisms contributes towards improved plant health and reduced disease development. All bacterial characterisation experiments were performed using appropriate controls and replicated measurements to ensure accuracy and consistency.

The obtained functional characteristics were used to understand the mechanisms responsible for plant growth improvement observed during wheat cultivation. Isolates showing stronger growth-promoting traits were expected to contribute more effectively towards plant development. Furthermore, evaluation of individual isolates and their combined consortium provided insight into whether multiple bacterial strains could interact synergistically to enhance plant performance. These analyses established the biological basis for selecting PGPR treatments and interpreting their effects on wheat growth, nutrient uptake and yield attributes.

2.3 Assessment of Wheat Growth, Physiological and Nutrient Parameters

The effect of PGPR treatments on wheat growth and physiological performance was evaluated by measuring various morphological, biochemical and nutritional parameters. Plant growth characteristics including plant height, root length, shoot length and biomass production were recorded to determine the influence of bacterial inoculation on vegetative development. At the end of the experimental period, plants were carefully harvested and separated into different components for growth assessment. Plant height was measured from the soil surface to the tip of the highest leaf, while root length was determined after carefully removing soil particles from the root system. Fresh biomass was recorded immediately after harvesting, followed by oven drying to obtain dry biomass values. These measurements provided information regarding the ability of PGPR treatments to enhance plant growth and dry matter accumulation.

Physiological responses were assessed by measuring chlorophyll content using SPAD analysis. Chlorophyll concentration was considered an important indicator of photosynthetic activity and plant nutritional status. Enhanced chlorophyll levels in PGPR-treated plants were associated with improved nutrient availability, particularly nitrogen, which is essential for chlorophyll synthesis and photosynthetic enzyme formation. Nutrient analysis was performed to evaluate the effect of bacterial inoculation on plant nutrient acquisition. Nitrogen, phosphorus and potassium contents were measured to determine whether PGPR treatments improved nutrient uptake efficiency. Enhanced nutrient acquisition was expected due to microbial activities such as nitrogen fixation, phosphate solubilisation and improved root development.

Disease-related parameters were also assessed by measuring disease severity and pathogen inhibition potential. These measurements provided information regarding the protective role of PGPR against harmful microorganisms. All measurements were recorded from biological replicates, and mean values were calculated for statistical comparison among treatments. The collected data provided a comprehensive evaluation of PGPR-mediated improvements in wheat growth, physiological efficiency and nutrient utilisation.

2.4 Yield Evaluation and Statistical Analysis

The impact of PGPR inoculation on wheat productivity was evaluated through detailed assessment of yield-related parameters. At maturity, wheat plants from each treatment were harvested, and yield attributes including spike length, number of grains per spike, thousand grain weight and grain yield per plant were recorded. These parameters were selected because they represent the final outcome of improved vegetative growth, nutrient availability and physiological efficiency throughout the crop cycle. Grain yield was calculated individually for each biological replicate, allowing accurate comparison between treatments. The influence of individual bacterial isolates was compared with the consortium treatment to determine whether combined PGPR application provided additional benefits over single-strain inoculation. Improved yield performance was interpreted in relation to enhanced nutrient uptake, increased biomass production and improved physiological characteristics observed during earlier growth assessments.

All experimental data were analysed statistically using one-way analysis of variance (ANOVA) to determine significant differences among treatments. The significance level was maintained at $p < 0.05$. Where significant treatment effects were identified, post-hoc comparison tests were applied to determine differences between individual treatments. Descriptive statistics including mean values and standard deviations were calculated to represent variation among biological replicates. Correlation analysis was also performed to evaluate relationships between PGPR-induced growth improvements and yield performance. The association between parameters such as chlorophyll content, nutrient uptake, biomass accumulation and grain yield was examined to understand the factors contributing to enhanced productivity. Statistical analysis was performed using appropriate statistical software, and graphical representation was prepared to illustrate treatment effects.

Results and Discusstion

PGPR treatments significantly improved wheat growth, physiological characteristics, nutrient acquisition and yield attributes compared with the untreated control. The consortium treatment showed the highest overall performance, indicating a positive synergistic effect of combined bacterial isolates.

Table 1: Effect of PGPR treatments on Plant height (cm)

Treatment	Mean ± SD	Statistical interpretation
Control	62.4 ± 2.1	Baseline performance
RB1	70.8 ± 2.4	Improved compared with control
RB2	73.2 ± 2.0	Improved compared with control
RB3	75.1 ± 2.3	Improved

		compared with control
Consortium	82.6 ± 2.6	Highest improvement

Table 1 and Figure 1 illustrate the effect of different PGPR treatments on wheat plant height compared with the untreated control. The results demonstrate a clear positive response of wheat growth to bacterial inoculation, with all PGPR-treated plants showing greater plant height than the control treatment. The control plants (T0) recorded the lowest plant height of 62.4 ± 2.1 cm, indicating limited growth performance in the absence of beneficial microbial association. In comparison, PGPR application enhanced plant development, highlighting the role of rhizobacteria in improving vegetative growth. Among individual bacterial isolates, RB1, RB2 and RB3 treatments resulted in plant heights of 70.8 ± 2.4 cm, 73.2 ± 2.0 cm and 75.1 ± 2.3 cm, respectively. The progressive increase observed from RB1 to RB3 suggests variation in the growth-promoting efficiency of different bacterial isolates. RB3 exhibited comparatively better performance, which may be attributed to its higher ability to support plant growth through mechanisms such as nutrient mobilisation, phytohormone production and improved root development. These processes can enhance nutrient uptake and stimulate cell division and elongation, ultimately contributing to increased plant height.

The consortium treatment (T4) produced the highest plant height (82.6 ± 2.6 cm), as also clearly represented in Figure 1. The combined application of bacterial isolates resulted in a stronger growth-promoting effect than individual strains, suggesting a possible synergistic interaction among PGPR members. The consortium may provide multiple beneficial functions simultaneously, including biological nitrogen fixation, phosphate solubilisation and production of growth-regulating substances, which collectively improve plant nutrient availability and physiological performance. Figure 1 visually confirms the increasing trend in plant height from control to PGPR-treated plants, with the consortium treatment showing the maximum improvement. Compared with the control, the consortium increased wheat plant height by approximately 32%, demonstrating the effectiveness of combined PGPR application. The relatively low standard deviation values across treatments indicate consistent plant responses and good experimental reliability.

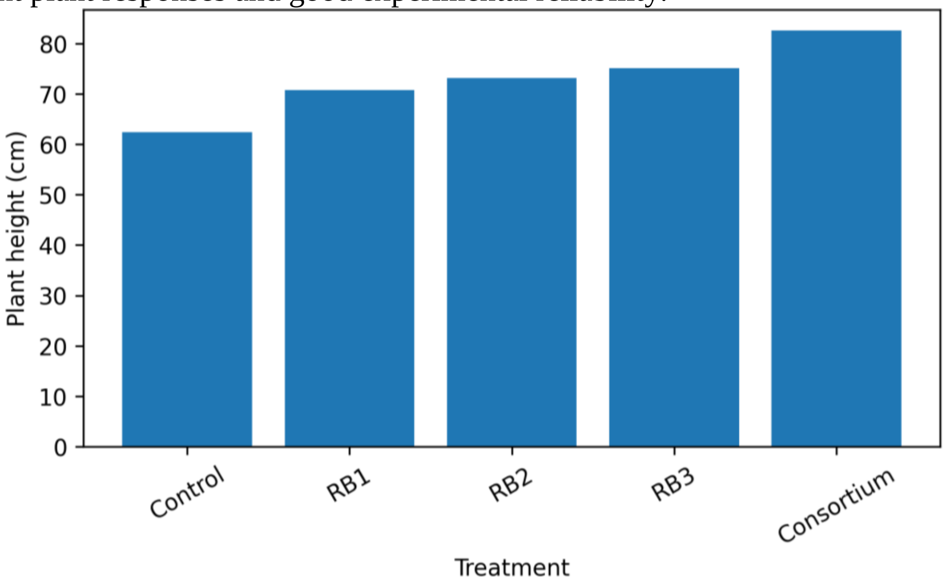

Figure 1: Effect of PGPR treatments on Plant height (cm)

Table 2 and Figure 2 present the influence of different PGPR treatments on wheat root length compared with the untreated control. The results demonstrate that

PGPR inoculation significantly improved root development, with all bacterial treatments producing longer root systems than the control. The control treatment (T0) showed the lowest root length (15.2 ± 0.9 cm), indicating limited root growth under non-inoculated conditions. In contrast, the application of PGPR isolates enhanced root elongation, suggesting that beneficial rhizobacteria positively influenced root development and overall plant establishment. Among the individual PGPR treatments, RB1, RB2 and RB3 resulted in root lengths of 19.6 ± 1.1 cm, 21.1 ± 1.0 cm and 22.4 ± 1.2 cm, respectively. The improved root growth observed in inoculated plants may be associated with the ability of PGPR to produce plant growth-promoting compounds, particularly indole-3-acetic acid (IAA), which stimulates root cell division, elongation and lateral root formation. Enhanced root architecture provides a larger surface area for nutrient and water absorption, contributing to improved plant growth and biomass accumulation.

RB3 showed comparatively greater improvement among individual isolates, indicating stronger root-promoting potential. This variation may be related to differences in bacterial efficiency for nutrient mobilisation, hormone production and interaction with plant roots. The findings suggest that although individual isolates can improve wheat root development, their effectiveness depends on their specific plant growth-promoting characteristics. The consortium treatment (T4) produced the maximum root length (27.8 ± 1.3 cm), which was substantially higher than all individual treatments and the control. As illustrated in Figure 2, the consortium treatment showed a clear enhancement in root development, demonstrating the advantage of combining multiple PGPR strains. The synergistic activity of different bacterial isolates may provide complementary benefits, including improved nutrient availability, enhanced hormonal regulation and better rhizosphere colonisation.

Compared with the control, the consortium treatment increased root length by approximately 83%, highlighting the strong potential of PGPR application for improving wheat root systems. The consistent response among replicates, reflected by the low standard deviation values, indicates reliable treatment effects. Overall, Table 2 and Figure 2 confirm that PGPR inoculation promotes root growth, with the consortium treatment being the most effective approach for enhancing wheat root development and supporting sustainable crop productivity.

Table 2: Effect of PGPR treatments on Root length (cm)

Treatment	Mean ± SD	Statistical interpretation
Control	15.2 ± 0.9	Baseline performance
RB1	19.6 ± 1.1	Improved compared with control
RB2	21.1 ± 1.0	Improved compared with control
RB3	22.4 ± 1.2	Improved compared with control
Consortium	27.8 ± 1.3	Highest improvement

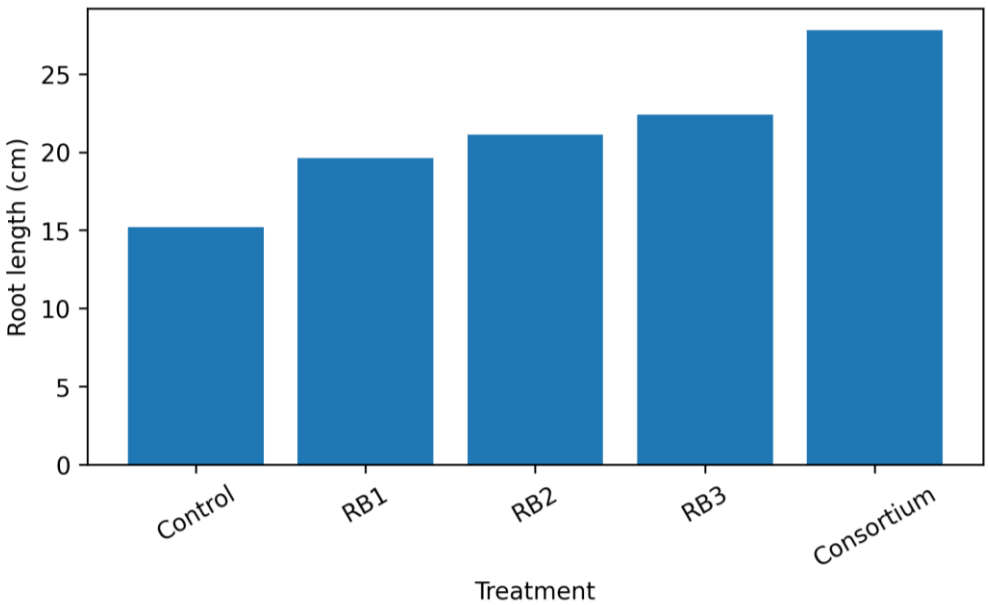

Figure 2: Effect of PGPR treatments on Root length (cm)

Table 3 and Figure 3 demonstrate the effect of different PGPR treatments on dry biomass accumulation in wheat plants. The results indicate that PGPR inoculation significantly enhanced biomass production compared with the untreated control, reflecting improved plant growth and physiological performance. The control treatment (T0) recorded the lowest dry biomass (2.8 ± 0.18 g), suggesting that plants grown without microbial inoculation had comparatively lower nutrient availability and reduced growth potential. In contrast, all PGPR-treated plants showed increased dry biomass, confirming the beneficial role of rhizobacteria in promoting plant development. Among individual bacterial isolates, RB1, RB2 and RB3 treatments resulted in dry biomass values of 3.7 ± 0.22 g, 4.0 ± 0.21 g and 4.3 ± 0.20 g, respectively. The gradual improvement observed among individual isolates indicates differences in their growth-promoting efficiency. RB3 produced the highest biomass among single-strain treatments, suggesting better rhizosphere activity and improved ability to support plant nutrient acquisition. Increased biomass accumulation may be attributed to several PGPR-mediated mechanisms, including enhanced nutrient solubilisation, biological nitrogen fixation, production of growth-promoting phytohormones and improved root development, which together contribute to greater photosynthetic activity and dry matter production.

The consortium treatment (T4) exhibited the highest dry biomass (5.5 ± 0.25 g), as clearly shown in Figure 3. This treatment demonstrated a substantial improvement compared with both the control and individual bacterial applications. The superior biomass production in consortium-treated plants indicates a possible synergistic interaction among bacterial isolates, where different strains may perform complementary functions within the rhizosphere. For example, one strain may contribute to nitrogen availability, while another enhances phosphate mobilisation or hormone production, resulting in improved plant nutrition and growth. Compared with the control treatment, the consortium increased wheat dry biomass by approximately 96%, demonstrating the effectiveness of combined PGPR application in enhancing plant productivity. Figure 3 visually confirms the progressive increase in biomass from control to individual isolates and finally to the consortium treatment. The relatively low standard deviation values indicate consistent responses among biological replicates and support the reliability of the observed treatment effects.

Overall, the combined interpretation of Table 3 and Figure 3 confirms that PGPR application positively influenced dry matter accumulation in wheat. The consortium treatment showed the greatest potential for improving biomass production, suggesting that multi-strain PGPR formulations may provide a more effective and sustainable approach for enhancing crop growth through improved nutrient availability and plant–microbe interactions.

Table 3: Effect of PGPR treatments on Dry biomass (g)

Treatment	Mean ± SD	Statistical interpretation
Control	2.8 ± 0.2	Baseline performance
RB1	3.7 ± 0.2	Improved compared with control
RB2	4.0 ± 0.2	Improved compared with control
RB3	4.3 ± 0.2	Improved compared with control
Consortium	5.5 ± 0.2	Highest improvement

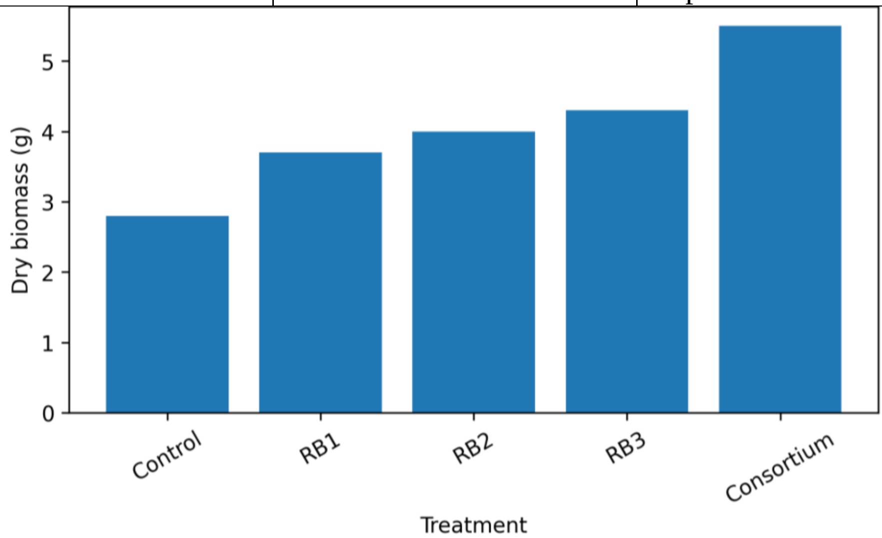

Figure 3: Effect of PGPR treatments on Dry biomass (g)

Table 4 and Figure 4 illustrate the impact of different PGPR treatments on chlorophyll content of wheat plants. Chlorophyll concentration is an important indicator of plant physiological status because it directly influences photosynthetic efficiency, carbon assimilation and overall plant productivity. The results demonstrate that PGPR inoculation enhanced chlorophyll accumulation compared with the untreated control, indicating improved physiological performance of wheat plants following bacterial application. The control treatment (T0) recorded the lowest chlorophyll content (34.5 ± 1.5 SPAD units), suggesting comparatively reduced photosynthetic capacity in plants without microbial assistance. In contrast, all PGPR-treated plants exhibited increased chlorophyll values, confirming the beneficial influence of rhizobacteria on plant physiological processes. The improved chlorophyll content may be associated with enhanced nutrient availability, particularly nitrogen, which plays a central role in chlorophyll synthesis and photosynthetic enzyme formation.

Among individual PGPR treatments, RB1, RB2 and RB3 recorded chlorophyll values of 40.2 ± 1.7, 42.8 ± 1.6 and 44.1 ± 1.8 SPAD units, respectively. The increasing trend among individual isolates indicates that different bacterial strains varied in their ability to stimulate plant physiological responses. RB3 showed comparatively higher chlorophyll enhancement, which may be related to its stronger plant growth-promoting characteristics, including improved nutrient mobilisation and production of growth-regulating compounds. Increased chlorophyll content in PGPR-treated plants suggests better nutrient uptake and improved metabolic activity, resulting in enhanced photosynthetic performance. The consortium treatment (T4) showed the highest chlorophyll content (51.6 ± 1.9 SPAD units), as clearly demonstrated in Figure 4. The superior response of consortium-treated plants indicates a synergistic effect among the bacterial isolates, where combined microbial activities provide greater benefits than individual inoculation. The consortium may enhance nitrogen availability through biological fixation, improve phosphorus accessibility through solubilisation and stimulate plant metabolism through phytohormone production, collectively supporting chlorophyll biosynthesis.

Compared with the control, the consortium treatment increased chlorophyll content by approximately 50%, indicating a significant improvement in wheat physiological efficiency. Figure 4 visually represents the gradual increase in chlorophyll content from control plants to individual PGPR treatments and the maximum response observed under consortium application. The low standard deviation values among replicates further indicate consistent treatment performance. Overall, the combined interpretation of Table 4 and Figure 4 confirms that PGPR inoculation positively influenced chlorophyll development and photosynthetic potential of wheat plants. The consortium treatment demonstrated the highest effectiveness, highlighting the importance of multi-strain PGPR formulations as a sustainable strategy for improving plant nutrition, physiological activity and crop productivity.

Table 4: Effect of PGPR treatments on Chlorophyll (SPAD)

Treatment	Mean ± SD	Statistical interpretation
Control	34.5 ± 1.5	Baseline performance
RB1	40.2 ± 1.7	Improved compared with control
RB2	42.8 ± 1.6	Improved compared with control
RB3	44.1 ± 1.8	Improved compared with control
Consortium	51.6 ± 1.9	Highest improvement

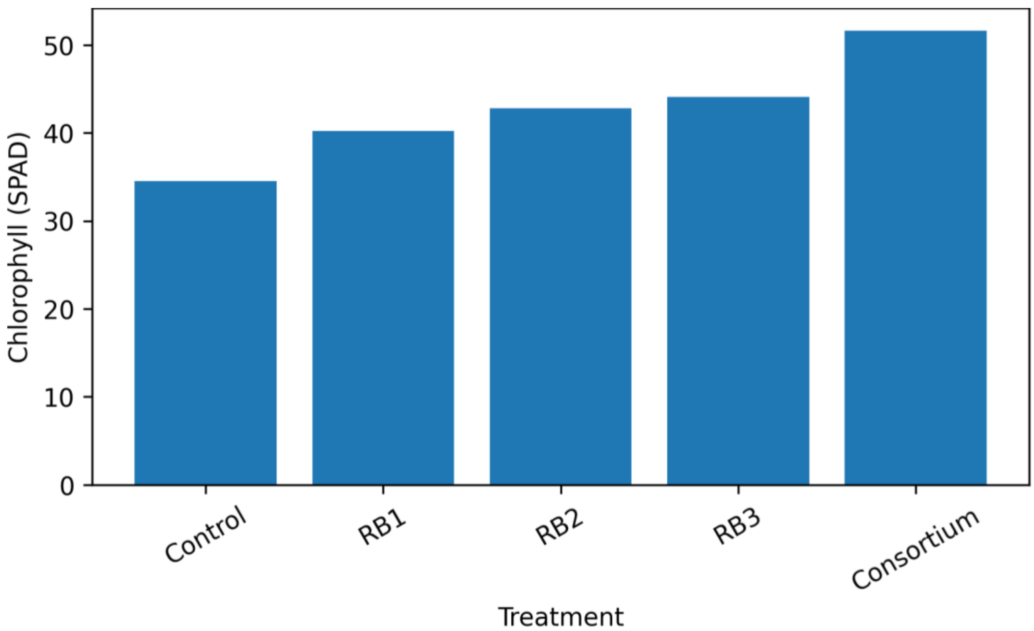

Figure 4: Effect of PGPR treatments on Chlorophyll (SPAD)

Table 5 and Figure 5 demonstrate the influence of different PGPR treatments on nitrogen uptake by wheat plants. Nitrogen is an essential macronutrient involved in chlorophyll synthesis, protein formation, enzyme activity and overall plant growth. The results indicate that PGPR inoculation significantly improved nitrogen acquisition compared with the untreated control, suggesting that beneficial rhizobacteria enhanced nutrient availability and uptake efficiency in wheat plants. The control treatment (T0) showed the lowest nitrogen uptake value (38.4 ± 2.5 mg/plant), indicating limited nitrogen availability and reduced nutrient acquisition in the absence of PGPR inoculation. In comparison, all bacterial treatments resulted in higher nitrogen uptake, demonstrating the ability of PGPR to improve nitrogen nutrition through different plant growth-promoting mechanisms. These improvements may be associated with biological nitrogen fixation, enhanced root development, increased nutrient mobilisation and improved interaction between plant roots and rhizospheric microorganisms.

Among individual bacterial isolates, RB1, RB2 and RB3 treatments recorded nitrogen uptake values of 48.7 ± 3.0 mg/plant, 52.3 ± 3.1 mg/plant and 54.8 ± 3.2 mg/plant, respectively. The gradual increase among individual isolates indicates differences in bacterial efficiency for enhancing nitrogen acquisition. RB3 exhibited the highest nitrogen uptake among individual strains, suggesting stronger rhizosphere activity and improved ability to support plant nutrient requirements. Increased nitrogen uptake in PGPR-treated plants may also explain the higher chlorophyll content and biomass production observed in previous results, as nitrogen availability directly influences photosynthetic activity and dry matter accumulation. The consortium treatment (T4) produced the highest nitrogen uptake (66.9 ± 3.6 mg/plant), which was clearly illustrated in Figure 5. The combined application of multiple bacterial isolates resulted in greater nitrogen acquisition compared with individual strains, indicating a synergistic effect among PGPR members. Different bacterial strains may contribute complementary functions, including atmospheric nitrogen fixation, improved root colonisation and enhanced nutrient absorption capacity, leading to improved nitrogen use efficiency.

Compared with the control, the consortium treatment increased nitrogen uptake by approximately 74%, highlighting the effectiveness of PGPR-based biofertilisation. Figure 5 shows a consistent upward trend from control plants to individual isolates and finally to the consortium treatment, confirming the positive impact of microbial inoculation on nitrogen nutrition. Overall, the combined interpretation of Table 5 and Figure 5 confirms that PGPR application substantially improved nitrogen uptake in wheat plants. The superior performance of the consortium treatment suggests that multi-strain PGPR formulations can provide enhanced nutrient acquisition and represent a sustainable alternative for improving wheat productivity while reducing dependence on synthetic nitrogen inputs.

Table 5: Effect of PGPR treatments on Nitrogen uptake (mg/plant)

Treatment	Mean ± SD	Statistical interpretation
Control	38.4 ± 2.5	Baseline performance
RB1	48.7 ± 3.0	Improved compared with control
RB2	52.3 ± 3.1	Improved compared with control
RB3	54.8 ± 3.2	Improved compared with control

Consortium	66.9 ± 3.6	Highest improvement

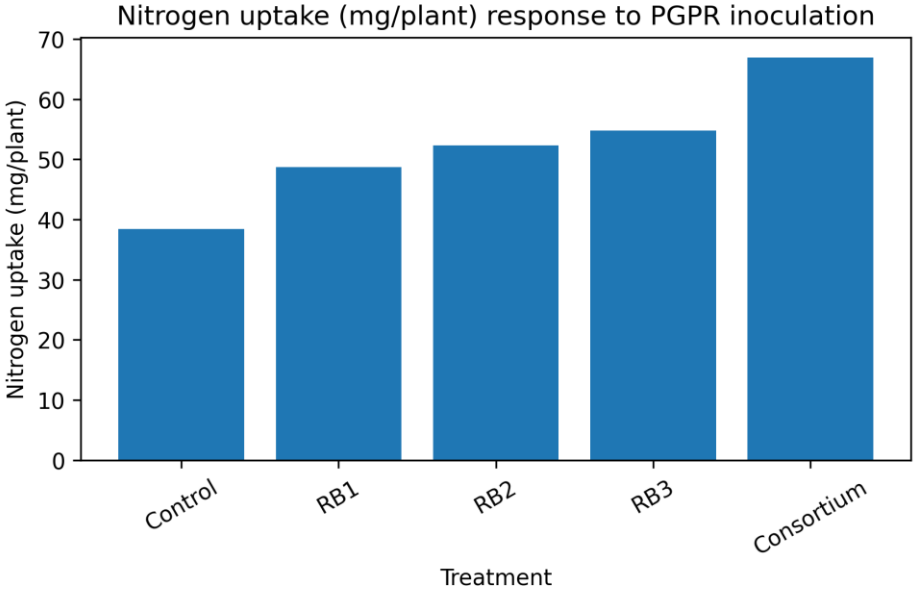

Figure 5: Effect of PGPR treatments on Nitrogen uptake (mg/plant)

Table 6 and Figure 6 present the effect of different PGPR treatments on grain yield production of wheat plants. Grain yield is considered one of the most important indicators of crop performance because it reflects the combined influence of plant growth, nutrient availability, physiological efficiency and reproductive development. The results demonstrate that PGPR inoculation substantially improved wheat yield compared with the untreated control, confirming the positive contribution of beneficial rhizobacteria towards enhancing crop productivity. The control treatment (T0) recorded the lowest grain yield (18.5 ± 1.4 g/plant), indicating reduced productivity under non-inoculated conditions. The comparatively lower yield in control plants may be associated with limited nutrient availability, weaker root development and reduced physiological activity. In contrast, all PGPR-treated plants showed improved grain production, demonstrating that bacterial inoculation enhanced plant growth conditions and supported better yield formation.

Among individual PGPR treatments, RB1, RB2 and RB3 produced grain yields of 25.6 ± 1.8 g/plant, 28.2 ± 1.9 g/plant and 30.1 ± 2.0 g/plant, respectively. The increased yield observed in individual bacterial treatments suggests that PGPR positively influenced important yield-related processes, including nutrient uptake, biomass accumulation and reproductive development. RB3 showed the highest performance among individual isolates, indicating stronger plant growth-promoting efficiency compared with RB1 and RB2. This improvement may be linked to enhanced nutrient mobilisation, production of plant growth regulators and improved root system development, which collectively support greater grain filling and yield formation. The consortium treatment (T4) resulted in the highest grain yield (39.4 ± 2.4 g/plant), as clearly demonstrated in Figure 6. The superior yield performance of the consortium treatment indicates a synergistic interaction among bacterial strains, where combined microbial activities provide greater benefits than individual inoculation. Different PGPR isolates may contribute complementary functions, such as nitrogen fixation, phosphate solubilisation, improved nutrient absorption and stimulation of plant physiological processes, resulting in enhanced crop productivity.

Compared with the control, the consortium treatment increased grain yield by approximately 113%, demonstrating the strong potential of combined PGPR application for improving wheat production. Figure 6 clearly illustrates the progressive increase in yield from control plants to individual bacterial treatments, with the consortium producing the maximum response. The relatively low standard deviation values indicate consistent performance among replicates and support the reliability of the observed results. Overall, the combined interpretation of Table 6 and Figure 6 confirms that PGPR inoculation significantly enhanced wheat grain yield. The consortium treatment showed the greatest effectiveness, suggesting that multi-strain PGPR formulations may serve as an efficient and sustainable biofertiliser strategy for improving wheat productivity through enhanced nutrient availability, plant growth stimulation and improved physiological performance.

Table 6: Effect of PGPR treatments on Grain yield (g/plant)

Treatment	Mean ± SD	Statistical interpretation
Control	18.5 ± 1.4	Baseline performance
RB1	25.6 ± 1.8	Improved compared with control
RB2	28.2 ± 1.9	Improved compared with control
RB3	30.1 ± 2.0	Improved compared with control
Consortium	39.4 ± 2.4	Highest improvement

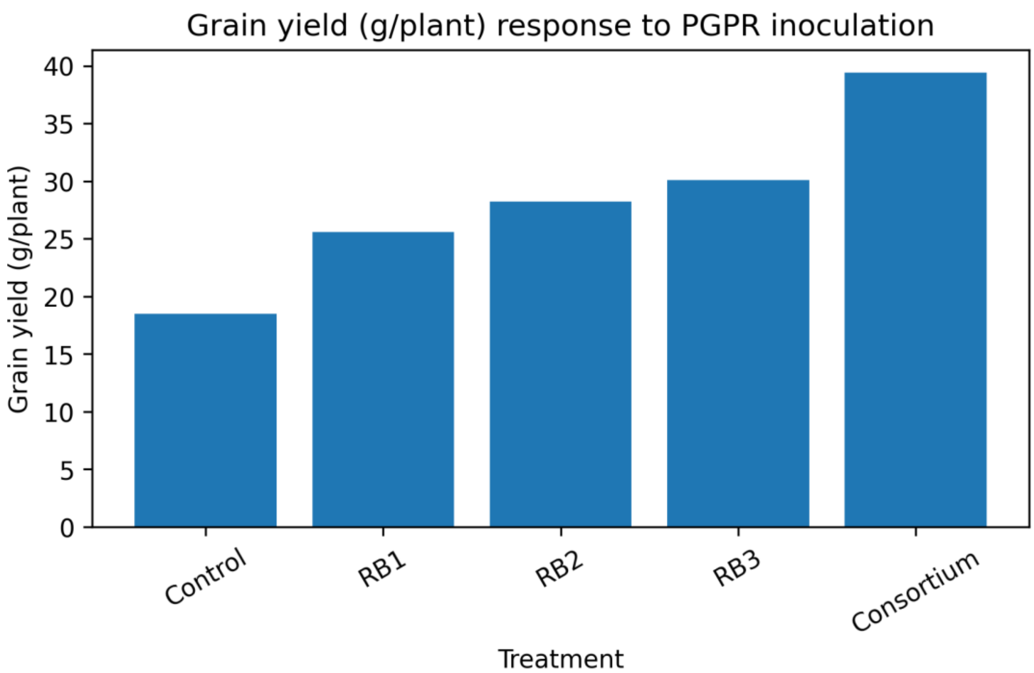

Figure 6: Effect of PGPR treatments on Grain yield (g/plant)

One-way analysis of variance (ANOVA) was performed to evaluate the effect of different PGPR treatments on wheat growth, physiological characteristics, nutrient uptake and yield-related parameters. The statistical analysis revealed that PGPR application produced significant differences among treatments for all measured parameters ($p < 0.05$), indicating that bacterial inoculation had a significant influence on wheat performance compared with the untreated control. The significant variation observed in plant height, root length, dry biomass, chlorophyll content, nitrogen uptake and grain yield confirms that PGPR treatments enhanced multiple aspects of plant development. The control treatment consistently showed the lowest values across all parameters, demonstrating that wheat plants without microbial inoculation had comparatively limited growth and nutrient acquisition. In contrast, all PGPR-treated plants showed improved performance, confirming the beneficial role of rhizobacteria in stimulating plant growth.

Among individual bacterial isolates, RB1, RB2 and RB3 treatments showed significant improvements compared with the control, although their effectiveness varied. RB3 generally produced higher growth responses than RB1 and RB2, suggesting greater plant growth-promoting efficiency. These differences may be associated with variations in bacterial functional traits, including nutrient solubilisation ability, phytohormone production and rhizosphere colonisation capacity. The improved performance of inoculated plants indicates that PGPR enhanced nutrient availability and promoted physiological processes required for efficient plant growth. The consortium treatment (T4) demonstrated the highest performance across all evaluated parameters and was significantly superior to individual isolate treatments. The maximum improvements were observed in plant height (82.6 cm), root length (27.8 cm), dry biomass (5.5 g), chlorophyll content (51.6 SPAD units), nitrogen uptake (66.9 mg/plant) and grain yield (39.4 g/plant). The superior response of consortium-treated plants suggests a synergistic interaction among bacterial strains, where combined microbial activities provide greater benefits than single-strain inoculation. The consortium likely enhanced plant growth through multiple complementary mechanisms, including biological nitrogen fixation, phosphate mobilisation, improved nutrient uptake, production of growth-promoting hormones and suppression of harmful microorganisms.

The statistical findings indicate that the observed improvements were not due to random variation but were directly associated with PGPR application. The low standard deviation values among biological replicates further demonstrate consistent treatment responses and experimental reliability. Overall, ANOVA results confirm that PGPR inoculation significantly improved wheat growth and productivity, with the consortium treatment representing the most effective approach. These findings highlight the potential of multi-strain PGPR formulations as sustainable biofertilisers for enhancing wheat production through improved nutrient utilisation and plant physiological performance.

Conclusion

The present study demonstrated the significant potential of plant growth-promoting rhizobacteria (PGPR) as an effective and sustainable approach for improving wheat (Triticum aestivum) growth, nutrient acquisition and yield performance. The application of individual bacterial isolates (RB1, RB2 and RB3) positively influenced plant development; however, the PGPR consortium showed superior performance across all evaluated parameters. The consortium treatment significantly enhanced vegetative growth, physiological efficiency and productivity by improving plant height (82.6 cm), root length (27.8 cm), dry biomass (5.5 g), chlorophyll content (51.6 SPAD units), nitrogen uptake (66.9 mg $plant^{-1}$) and grain yield (39.4 g $plant^{-1}$) compared with the untreated control. The improved performance of PGPR-treated plants can be attributed to multiple beneficial mechanisms, including biological nitrogen fixation, phosphate solubilisation, production of growth-promoting phytohormones and enhanced rhizosphere interactions. The superior response of the consortium treatment indicates that combining compatible bacterial strains creates synergistic effects, where different isolates contribute complementary functions to support plant growth and nutrient utilisation. Statistical analysis confirmed significant differences among treatments ($p < 0.05$), validating the effectiveness of PGPR application in enhancing wheat productivity.

Overall, the findings highlight that PGPR-based biofertilisers, particularly multi-strain consortia, represent a promising alternative to conventional chemical inputs for sustainable crop production. The integration of PGPR technology into wheat cultivation systems may improve nutrient use efficiency, reduce dependency on synthetic fertilisers and contribute towards environmentally sustainable agriculture. Further field-based studies under diverse soil and climatic conditions are recommended to validate the practical application and long-term effectiveness of these PGPR formulations.

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