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Plant growth promoting rhizobacteria combined with macronutrients treatments improve growth and market quality of cut sunflower (*Helianthus annuus* L.)

Usama Bin Arif[1]*, Tahir Saeed[1], Muhammad Ehetisham-Ul-Haq[2], Shabana Ehsan[3], Muhammad Amjad Qureshi[4], Saqib Ayyub[1, 5], Ahsan Akram[5], Ifra Saleem[6], Tanveer Ahmad[7], Iftikhar Ahmad[8], Muhammad Muzammil Ijaz[8] and Qaisar Abbas[9]

[1]Horticultural Research Sub-station Floriculture & Landscaping, Ayub Agricultural Research Institute, Faisalabad, Pakistan
[2]Oilseeds Research institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan
[3]Soil and Water Testing laboratory, Ayub Agricultural Research Institute, Faisalabad, Pakistan
[4]Department of Soil Bacteriology, Ayub Agricultural Research Institute, Faisalabad, Pakistan
[5]Institute of Horticultural Sciences, University of Agriculture, Faisalabad, Pakistan
[6]Soil Chemistry Section, Ayub Agricultural Research Institute, Faisalabad, Pakistan
[7]Department of Horticulture, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan
[8]Horticultural Research Sub-Station for Floriculture and Landscaping, Multan, Pakistan
[9]Regional Agricultural Research Institute, Bahawalpur, Pakistan

*Corresponding author: Usama Bin Arif (floriculturaari@gmail.com)

Abstract

Cut sunflower represents a significant cut crop within Pakistan's floriculture sector, benefiting from favourable agro-climatic conditions. However, the visual quality of ornamental plants has an essential association to a proper balance of nutrients. Qualitative aspects such as plant height, shape, and colouration are directly affected by mineral nutrition, along with various environmental factors. Recently plant growth promoting rhizobacteria (PGPR) combined with appropriate macro and micronutrients promising approach to enhance the growth and quality of ornamental plants. The significance of cut sunflower in the cut market is noteworthy. Therefore, this study was executed to improve the growth and maintain the market quality of cut sunflower cv. 'Vincent' by using various PGPR and macronutrients concentrations with control *viz*. T0: Control, T1: NPK (20: 20: 20), 60 g/m^2 bed, T2: *Bacillus* spp., T3: *Pseudomonas* spp., T4: PGPR injection, T5: *Bacillus* spp. + NPK (20: 20: 20), 60 g/m^2 bed, T6: *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m^2 bed, T7: PGPR injection + NPK (20: 20: 20), 60 g/m^2 bed. The application of *Bacillus* spp. + NPK (20: 20: 20), 60 g/m^2 bed, *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m^2 bed, PGPR injection + NPK (20: 20: 20), 60 g/m^2 bed resulted in higher flower visual quality, plant height, leaf area, stem diameter, flower diameter, blooming period, plant fresh and dry weight compared to control treatment. Among studied treatments *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m^2 bed exhibited higher plant nitrogen, phosphorous, potassium, organic matter and organic carbon contents. In conclusion, PGPR combined with macronutrients treatments effectively improves the growth attributes and maintains the market quality of cut sunflower cv. 'Vincent'.

Keywords: Biofertilizer, ornamental, plant quality, rhizobacteria, sustainable agriculture

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Introduction

The cut sunflower (*Helianthus annuus* L.) from the Asteraceae family is gaining popularity in the flower and decorative plant markets due to its attractive flowering and versatility for potted, cut flower and landscaping arrangements. The popularity of decorative sunflower farming derives from its easy method of production and marketing, rapid growing cycle, and adaptation to various environments (Baldotto & Baldotto, 2015). Sunflowers display two types of growth. The first kind emerges as a solitary stalk, yielding a large bloom at its apex. It is generally cultivated in gardens and landscapes and utilised as cut flowers (Puttha et al., 2023). The second form exhibits branching stems that yield shorter stems and a bush-like morphology, resulting in several miniature blooms on the sub-branches. This variety is frequently cultivated as a potted plant. cut sunflowers have a diverse array of petal shapes and hues, encompassing yellow, red, orange, and purple (Puttha et al., 2023).

Cut sunflowers are of commercial importance for many reasons, stemming from their popularity as a high demand cut flower, a key component in garden centre sales for bedding and landscaping, and a versatile element in the lucrative dried and value-added floral crafts market. The development of diverse cultivars, including pollenless varieties that extend vase life and offer a wide range of colours, sizes, and shapes, has been instrumental in expanding their year-round production and market appeal. This genetic and horticultural innovation, coupled with their

relatively low cultivation input requirements, solidifies the ornamental sunflower not merely as a seasonal novelty but as a major economic crop that contributes substantially to the diversity, profitability, and consumer reach of the modern floriculture sector (de Moura et al., 2022). Despite their commercial significance, the cultivation and postharvest management of ornamental sunflowers are constrained by several key challenges. A primary concern is their high susceptibility to fungal and bacterial pathogens, such as downy mildew and *Sclerotinia* stalk rot, which can cause severe crop losses, particularly in intensive production systems. Furthermore, their rapid post-harvest senescence, characterised by stem bending and head wilting, often leads to a compromised vase life that fails to meet consumer expectations (de Moura et al., 2022).

The quality of crops is primarily governed by genetic variables, while it is also affected by external influences, both natural and anthropogenic (Neto et al., 2015; Ali et al., 2025; Batool et al., 2025; Abdullah et al., 2025). Considering this scenario, the mineral nutrition of plants is crucial for achieving superior quality crops (Marschner, 2012). Plant quality is linked to physical properties that influence the visual characteristics of plants, as well as to chemical factors, including the appropriate balance of nutrients, necessary to meet commercialisation and usage requirements (Marschner, 2012; Baig et al., 2018; Abbas & Shafique, 2019). The visual quality of plants and their economic viability are crucial for ornamental species (Veatch-Blohm et al., 2012) and generally influence their market price.

Across mineral nutrients, nitrogen is the fundamental nutrient essential for plant growth, since it considerably influences photosynthesis and the generation of biomass, hence affecting plant quality (Azam et al., 2023; Arif & Ahmad, 2024). In addition to nitrogen, phosphorus is essential for plant development, as it regulates plant height, promotes root growth, boosts disease resistance, and ensures consistent crop maturity (Ahmad & Aslam, 2018; Arif & Ahmad, 2024). Potassium is an essential mineral vital for plant growth, as it enhances yield by augmenting leaf fresh weight and Vitamin C content, hence facilitating superior product (Arif & Ahmad, 2024). The cultivation of crops is significantly reliant on chemical fertilisers, which contribute to environmental degradation and impose financial burdens. This issue is effectively addressed by Plant growth promoting rhizobacteria (PGPR), which lowers the use of chemical fertilisers by providing supplementary nutrients (Adesemoye et al., 2009). Furthermore, currently public awareness and comprehension of sustainable agricultural advancements with floriculture plants are essential (Shafique et al., 2025).

Biofertilizers, formulations of beneficial living microorganisms, represent a pivotal sustainable agricultural technology designed to supplement chemical fertilisers by enhancing plant nutrient availability through natural processes (Shakeel et al., 2023). These microbes, including nitrogen-fixing bacteria, phosphate-solubilising bacteria, and mycorrhizal fungi, facilitate plant growth by converting essential elements like atmospheric nitrogen and soil-bound phosphorus into bioavailable forms, while also producing growth-promoting phytohormones. Their paramount importance lies in their dual role in promoting crop productivity and fostering soil health; they improve soil structure and long-term fertility without causing the detrimental environmental impacts associated with synthetic fertilisers, such as soil degradation and water eutrophication (Chaudhary et al., 2022). PGPR serves as a contemporary organic alternative, supplying nutrients to enhance plant development while also stimulating the synthesis of phytochemicals that protect against various diseases and promote plant health (Maciel-Rodriguez et al., 2025; Lawal & Babalola, 2014). Plants may encourage the populations of soil bacteria through the production of excrement from roots that are particular to the species cultivated. Microorganisms utilise these substances for multiplication and play a vital role in plant biology by producing compounds analogous to plant hormones that promote cell differentiation, root development, and alterations in root hair growth (Berg, 2009). Microbial colonisation of roots can trigger a symbiotic relationship that may lead to the onset of disease. The microbes that live in the roots are crucial for plant growth and protection. Rhizobacteria can be categorised into external organisms that predominantly inhabit the root's rhizosphere and intracellular species that colonise the inner layers of the root. Numerous PGPR may inhabit the soil, with the most significant being *Nitrobacter*, *Bacillus*, *Pseudomonas*, *Azospirillum*, *Agrobacterium*, *Caulobacter*, *Arthrobacter*, *Allorhizobium* and *Mesorhizobium* (Thomas & Singh, 2019).

Previously the combination of PGPR with inorganic fertilisers and vermicompost enhances the glucose, protein, and phenolic content of plants, hence promoting plant growth (Javed and Panwar, 2013). PGPR functions as a versatile additive. It enhances salt tolerance, improves water use efficiency under scarcity, inhibits excessive ethylene synthesis, and boosts the uptake of phosphorus and potassium (Mayak et al., 2004). PGPR strains enhance soil fertility when combined with inorganic fertilisers by facilitating the fixation and absorption of specific macronutrients, hence promoting healthy plant growth (Mia et al., 2005). The application of nitrogen 286 kg ha^{-1}, combined with 120 L ha^{-1} of Azospirillum brasilense suspension, resulted in optimal yield, growth, and NPK content in broccoli plants (Abou El-Magd et al., 2014). In one-month-old seedlings of cabbage crop treated with NK fertiliser, along with *Pseudomonas* fluorescens and humic acid, resulted in the highest non-wrapped leaf and maximum head yield of 54.38 t/ha (Verma et al., 2014). The collard plants treated with *Bacillus* cereus resulted in the highest plant height, plant fresh weight, leaf count and leaf area compared to non-treated plants (Helaly et al., 2018).

Conclusively, PGPR strains enhanced mineral concentrations in plants, highlighting the significant role of PGPR as a non-lethal and natural bioorganic resource for plant growth. The economic value of cut sunflowers is mostly assessed by plant height and the market quality of blooms. The growth and market quality are affected by various factors, such as soil and climatic conditions, mineral nutrition and irrigation water quality. In this context, the application of PGPR, which significantly affect the growth and development of decorative plants, may serve as an alternative to enhance the yield and quality of cut sunflowers. Considering the floriculture sector in Pakistan and the importance of cut sunflower as a novel cut flower, a study was executed to optimise its nutritional needs by the

application of PGPR and NPK alone or in combination to improve growth and maintain market quality.

Materials and Methods

Plant material and treatments

In the first week of February 2024 the seeds of cut sunflower cv. 'Vincent' (brown centre with deep orange colour petals, Sakata, Woodland, California, USA) were planted at the Floriculture Research Area, Horticultural Research Sub-Station Floriculture and Landscaping, Ayub Agricultural Research Institute, Faisalabad, Pakistan (Table 1 and 2). Before sowing seeds were split into four different groups equally and inoculated with respective PGPRs suspensions for 30 min. along with control. The treatment scheme was organised in a Randomised Complete Block Design (RCBD) with three replications and five plants considered as an experimental unit. Application of eight treatments *viz.* T0: Control, T1: NPK (20: 20: 20), 60 g/m2 bed, T2: *Bacillus* spp., T3: *Pseudomonas* spp., T4: PGPR injection, T5: *Bacillus* spp. + NPK (20: 20: 20), 60 g/m2 bed, T6: *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m2 bed, T7: PGPR injection + NPK (20: 20: 20), 60 g/m2 bed were applied at three intervals. The application of fertilisers and all other cultural practices remained consistent across all treatments.

Table 1 Research area soil properties (n = 4 samples)

Soil properties	Values
EC (mSm^{-1})	1.29
pH	8.81
Organic matter (%)	0.64
Phosphorous (mg Kg^{-1})	12.52
Potassium (mg Kg^{-1})	219.75
Saturation (%)	30.5
Texture	Loam

Table 2 Research area water properties (n = 4 samples)

Water properties	Values
EC ($uScm^{-1}$)	1057
Calcium (meq/L)	8.93
Sodium (meq/L)	1.64
Chloride (meq/L)	1.40
Bi-carbonate	9.10
Residual sodium carbonate (meq/L)	0.17
Sodium adsorption ratio (%)	0.78

Plant height, number of leaves and leaf area

Plant height was determined from five healthy plants from each treatment the soil base to the apex using a standard metre rod in the field and expressed as cm. From each replication, three plants were randomly chosen, and the aggregate number of leaves was recorded. The mean was recorded and analysed statistically. The leaf area was calculated by measuring the higher length and width from the leaf's centre by using scale and substituting these values into the calculation equation [Leaf Area (cm^2) = Length × Width × 0.68] and represented as cm^2 (Arif × Ahmad, 2024).

Stem diameter, blooming period and flower diameter

Stem diameter of plant was calculated with the help of vernier calliper and expressed as mm. The blooming period of flowers was recorded by monitoring the duration in days from emergence to the first flower to senescence. Flower diameter was calculated by measuring the length and width of flowers from centre using scale and stated as cm.

Plant fresh weight, plant dry weight, root fresh weight and root dry weight

The fresh weight of the plant and root was measured using a digital weighing scale (Setra, BL-4100S, USA) and expressed as g. The dry weight of the plant and root was determined after the specimens were thoroughly desiccated at 70°C for a duration of 72 h in an oven (USA), using a digital weighing scale and represented as g.

Plant biomass attributes

Plant nitrogen, phosphorous and potassium contents were determined by using digestion method as detailed by Arif & Ahmad (2024) and expressed as percentage. Sample digestion involved initially washing the leaves with detergent, followed by rinsing with tap water. Subsequently, the samples were dried for 48 h, followed by packing, labelling, and finally subjected to oven drying for 72 h in perforated bags. Dried leaves were subsequently ground into powder and stored in labelled bottles at room temperature.

Subsequently, for the determination of leaf nitrogen percentage, 0.1 g of the sample was utilised for the digestion method. The sample was placed in a conical flask, to which 10 mL of concentrated H2SO4 was added, and it was incubated overnight at room temperature. The incubated mixture was heated until fumes were emitted and then heated for an additional 30 minutes. The mixture was subsequently removed and allowed to cool. Subsequently, 4-5 mL of H2O2 was added to the mixture, and the conical flask was gently rotated. Once the mixture became

colourless, the volume was adjusted to 50 mL with distilled water. The extract was subsequently filtered and prepared for N % analysis. 10 mL of the sample and 10 mL of NaOH were added to the digestion tube. 5 mL of H3BO3 was added to a 50 mL volumetric flask. Distillate was collected in 30-35 mL of 4% H3BO3 solution in the receiver flask. The distillate was titrated with concentrated H2SO4 until a pink colour was observed.

For phosphorus and potassium analysis, 0.5 g of the sample was placed in a 100 mL conical flask, to which 10 mL of both nitric acid and hydrochloric acid were added. The mixture was permitted to stand overnight under a covered watch glass until all initial reactions had ceased. The mixture was subsequently heated gently until it became colourless, and the volume was reduced to 5 mL. The extract was subsequently cooled. Subsequently, distilled water was added to achieve a total volume of 100 mL.

Flower visual quality, plant organic matter and plant organic carbon

The flower visual quality was assessed by visual evaluation by three individuals, who graded them on a scale from 1 to 9 (1 = low quality flower; 5 = acceptable flower quality and 9 = fresh and high-quality flower.) Subsequently, the average was calculated in score (Arif and Ahmad, 2024). Organic matter and carbon in sunflower plants are typically measured using wet combustion method also known as Walkley and black method, which oxidizes carbon with chromic acid and quantifies it through titration, or dry combustion, which involves high-temperature thermal decomposition to produce and measure CO_2 (Loria et al., 2024).

Statistical analysis

The data evaluation was performed using Statistix 8.1 (Tallahassee, Florida, USA), employing Fisher's analysis of variance method. The mean differences of the treatments were evaluated by applying the least significant difference (LSD) at $P<0.05$. The Origin Pro 2021 program (Northampton, Massachusetts, USA) was used to ascertain a correlation across different variables.

Results and Discussion

Plant height, number of leaves and leaf area

Results showed regarding plant height no significant difference among treatments; however, cut sunflower cv. 'Vincent' plants treated with *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m² bed treatment, had about 2.24-fold the highest plant height compared to all other treatments (Table 3). The higher number of leaves about 1.15-fold, was recorded in *Bacillus* spp. + NPK (20: 20: 20), 60 g/m^2 bed treatment, while the lowest number of leaves was observed in untreated control plants (Table 3). Among applied treatments NPK (20: 20: 20) 60 g/m^2 bed treatment showed about 1.26-fold higher leaf area compared to control treatments. However, non-significant differences were observed in the number of leaves and leaf area among treatments (Table 3). PGPR consists of microorganisms that are typically sourced from plant roots and their surrounding zones. Previous study indicates that they can enhance plant growth by as much as 40% through colonisation of the rhizome or plant roots, thereby promoting the emergence of seeds and the growth of plants. Microorganisms enhance soil health and crop yield by breaking down soil nutrients, thereby increasing their availability to plant roots (Prisa & Benati, 2021). In this study PGPR combined with macronutrient treatments effectively enhanced the growth and quality-related attributes of cut sunflower cv. 'Vincent' as compared to the control. The application of PGPR resulted in increased plant growth, likely attributable to various direct and indirect processes, including enhanced nutrient availability, phytohormone synthesis, and inhibition of detrimental microbes in the root zone (Saharan & Nehra, 2011). Similar results regarding higher plant spread and plant height were observed in ornamental kale (Arif & Ahmad, 2024), chrysanthemum (Kumari et al., 2016) and Narcissus (Prisa & Benati, 2021) plants treated with PGPR.

Table 3 Influence of PGPR and macronutrient treatments on various growth metrics of cut sunflower cv. 'Vincent'

Treatments	PH	NL	LA	PFW	PDW	RFW
Control	126.0 a	18.5 a	114.8 ab	361.1 a	173.9 bc	33.2 a
NPK (20: 20: 20), 60 g/m^2 bed	130.3 a	19.4 a	145.6 a	511.1 a	246.3 a	36.6 a
Bacillus spp.	136.8 a	19.3 a	102.8 ab	394.4 a	178.7 bc	25.7 a
Pseudomonas spp.	132.0 a	18.6 a	99.9 ab	400.0 a	204.3 a-c	36.3 a
PGPR injection	147.5 a	21.2 a	85.4 b	473.3 a	237.5 ab	45.5 a
Bacillus spp. + NPK (20: 20: 20), 60 g/m^2 bed	144.8 a	21.4 a	86.1 b	393.8 a	161.7 c	35.4 a
Pseudomonas spp. + NPK (20: 20: 20), 60 g/m^2 bed	283.3 a	20.7 a	108.6 ab	441.6 a	200.7 a-c	44.1 a
PGPR injection + NPK (20: 20: 20), 60 g/m^2 bed	129.4 a	21.1 a	106.5 ab	436.1 a	167.5 c	39.1 a
LSD = $P \leq 0.05$	162.8	3.2	49.0	170.2	64.8	21.6

PH = Plant height (cm); NL = Number of leaves; LA = Leaf area (cm^2); PFW = Plant fresh weight (g); PDW = Plant dry weight (g); RFW = Root fresh weight (g); The tabular data demonstrated as a means of three replicates and dissimilar letters indicate significant variations by LSD test ($P \leq 0.05$).

Table 4 Influence of PGPR and macronutrient treatments on various flower metrics of cut sunflower cv. 'Vincent'

Treatments	Blooming period (days)	Flower diameter (cm)
Control	20.3 b	17.8 a
NPK (20: 20: 20), 60 g/m^2 bed	22.8 ab	19.3 a
Bacillus spp.	22.1 ab	19.4 a
Pseudomonas spp.	20.7 ab	16.9 a
PGPR injection	23.2 a	19.0 a
Bacillus spp. + NPK (20: 20: 20), 60 g/m^2 bed	23.5 a	19.1 a
Pseudomonas spp. + NPK (20: 20: 20), 60 g/m^2 bed	23.1 ab	31.0 a
PGPR injection + NPK (20: 20: 20), 60 g/m^2 bed	23.4 a	19.7 a
LSD = $P \leq 0.05$	2.8	14.8

The tabular data demonstrated as a means of three replicates and dissimilar letters indicate significant variations by LSD test ($P \leq 0.05$).

Stem diameter, blooming period and flower diameter

The maximum about 2.53-fold higher stem diameter was recorded in *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m^2 bed treatment, while the minimum stem diameter was observed in untreated control plants (Fig. 1B). Across studied treatments *Bacillus* spp. + NPK (20: 20: 20), 60 g/m^2 bed treatment exhibited about 1.15-fold higher blooming period compared to control treatments (Table 4). Outcomes regarding flower diameter no significant difference among treatments; nevertheless, cut sunflower cv. 'Vincent' plants treated with *Bacillus* spp. + NPK (20: 20: 20), 60 g/m^2 bed treatment had about 1.74-fold the highest flower diameter compared to untreated control treatment plants (Table 4). In current work 'Vincent' plants treated with PGPR and macronutrients relatively higher number of leaves, leaf area, flower diameter, stem diameter blooming period than control treatment. The continuous maintenance of adequate nitrogen and phosphorus supports vegetative growth in plants, which enhances the photosynthetic area and subsequently increases the formation of assimilates, facilitating the portion of to developing flower buds. The current results of our study align with the findings of Kumari et al. (2016); Arif & Ahmad (2024), who reported that seed inoculation of ornamental kale and chrysanthemum with rhizobacterial or a combination of bioformulations led to a higher number of buds/leaves per plant compared to non-inoculated seeds. Facilitated absorption of nutrients and concurrent transport of growth-promoting substances, such as cytokinins, to the axillary buds, leading to the disruption of apical dominance (Moghadam & Shoor, 2013). Eventually, they led to improved sink efficiency for accelerated mobilisation of photosynthates and the prompt transition of plant components from the vegetative to reproductive phase (Salma et al., 2013). Similarly, the extended flowering duration may be linked to the improved nutrient status associated with these PGPR treatments combinations. Comparable outcomes with higher stem diameter, flower diameter and blooming period were noted in chrysanthemum (Kumari et al., 2016) and Narcissus (Prisa & Benati, 2021) specimens subjected to PGPR treatment.

Plant fresh weight, plant dry weight, root fresh weight and root dry weight

Across studied treatments NPK (20: 20: 20) 60 g/m^2 bed treatment exhibited about 1.41- and 1.40-fold higher plant fresh weight and plant dry weight compared to control treatments. Nevertheless, there was no significant variations in plant fresh weight among various treatments (Table 3). The higher root fresh weight and root dry weight about 1.37- and 1.61-fold, was recorded in PGPR injection treatment, while the lowest number of leaves were observed in untreated control plants (Table 3; Fig. 1C). Nonetheless, no significant variations in root fresh weight were observed among the different treatments. Concerning the attributes of plant fresh weight, plant dry weight, root fresh weight, and root dry weight, cut sunflower cv. 'Vincent' treatment using PGPR combined with macronutrients demonstrated higher levels relative to the control group. This may be attributed to the capacity of biofertilizers to generate growth-promoting substances, including IAA and gibberellin-like compounds, as well as vitamins and riboflavin, which could have contributed to enhanced plant growth. Prisa and Benati (2021) proposed that crop growth and produce quality can be enhanced through the production of plant hormones and the solubilisation of nutritive elements via biological processes. The augmentation of root dry weight may be ascribed to the activities of free-living *Bacillus* megatherium bacteria present in the rhizosphere, which function as phosphate-solubilizing agents, so conserving the readily accessible phosphate in plants (Habib & Zaghloul, 2012). Earlier findings regarding higher fresh weight, dry weight, root fresh weight and dry weight were noted in PGPR treated ornamental kale (Arif & Ahmad, 2024; Kordatzaki et al., 2022), chrysanthemum (Prisa & Benati, 2021; Prasad et al., 2012), greenhouse-grown petunias (Kaylee et al., 2021) and African marigold (Hashemabadi et al., 2012) plants.

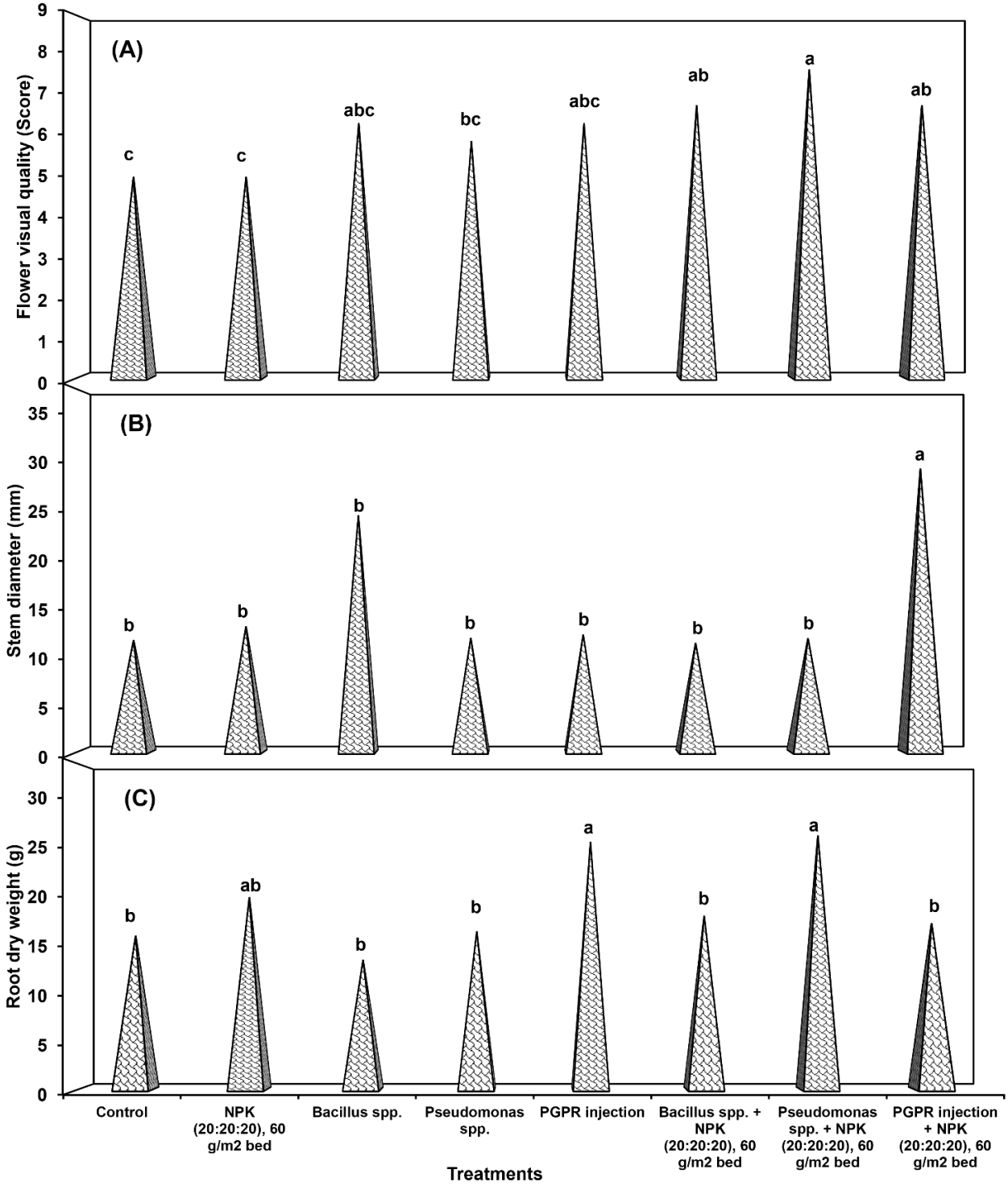

Fig. 1 Influence of PGPR and macronutrient treatments on flower visual quality (A) stem diameter (B) and root dry weight (C) contents of cut sunflower cv. 'Vincent'. n = 3 replicates

Plant biomass attributes

Results regarding plant nitrogen showed significant difference among treatments; nevertheless, *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m^2 bed treatment had about 1.30-fold the highest nitrogen in plant, followed by NPK (20: 20: 20) 60 g/m^2 bed (1-fold) compared to all other treatments (Fig. 2A). Similarly, in the examined treatments, *Pseudomonas* spp. combined with NPK (20: 20: 20) at a dosage of 60 g/m^2 demonstrated about 1.78- and 1.25-fold increases in phosphorus and potassium levels in plants relative to the control treatments. Furthermore, statistically notable variations in phosphorus and potassium levels in plants were observed among the different treatments (Fig. 2B and C). The plant macronutrient contents increased substantially due to PGPR, resulting in highest macronutrient balance. This occurred due to the influence of macronutrients on enhancing plant quality and yield. Kader (2008) asserts that PGPR provide vital macronutrients to plants, which subsequently contribute to plant dry matter (Abou El-Magd et al., 2014). PGPR and essential macronutrients improve flower quality by making

them grow stronger by making phytohormones and fixing nitrogen, making nutrients more available by dissolving phosphorus and other minerals, and making flowers healthier by protecting them from pathogens and abiotic stress. Macronutrients are the basic building blocks of plant structures and energy. PGPR helps plants take in and utilise these nutrients, which improves the overall quality of the plants, such as their colours, size of blossoms, and vase life (Emmanuel & Babalola, 2020; Kordatzaki et al., 2022). Comparable outcomes regarding enhanced visual quality of flowers and foliage were noted in ornamental kale (Kordatzaki et al., 2022; Arif & Ahmad, 2024). The quantities of leaf macronutrients substantially raised due to PGPR, resulting in highest macronutrient balance (Arif & Ahmad, 2024). This occurred due to the influence of macronutrients on enhancing plant quality and yield. Kader (2008) states that PGPR provide important macronutrients to plants, which subsequently contribute to plant dry matter (Abou El-Magd et al., 2014). Similar results of improved nitrogen, phosphorous and potassium contents in leaf were seen in ornamental kale (Arif & Ahmad, 2024; Kordatzaki et al., 2022).

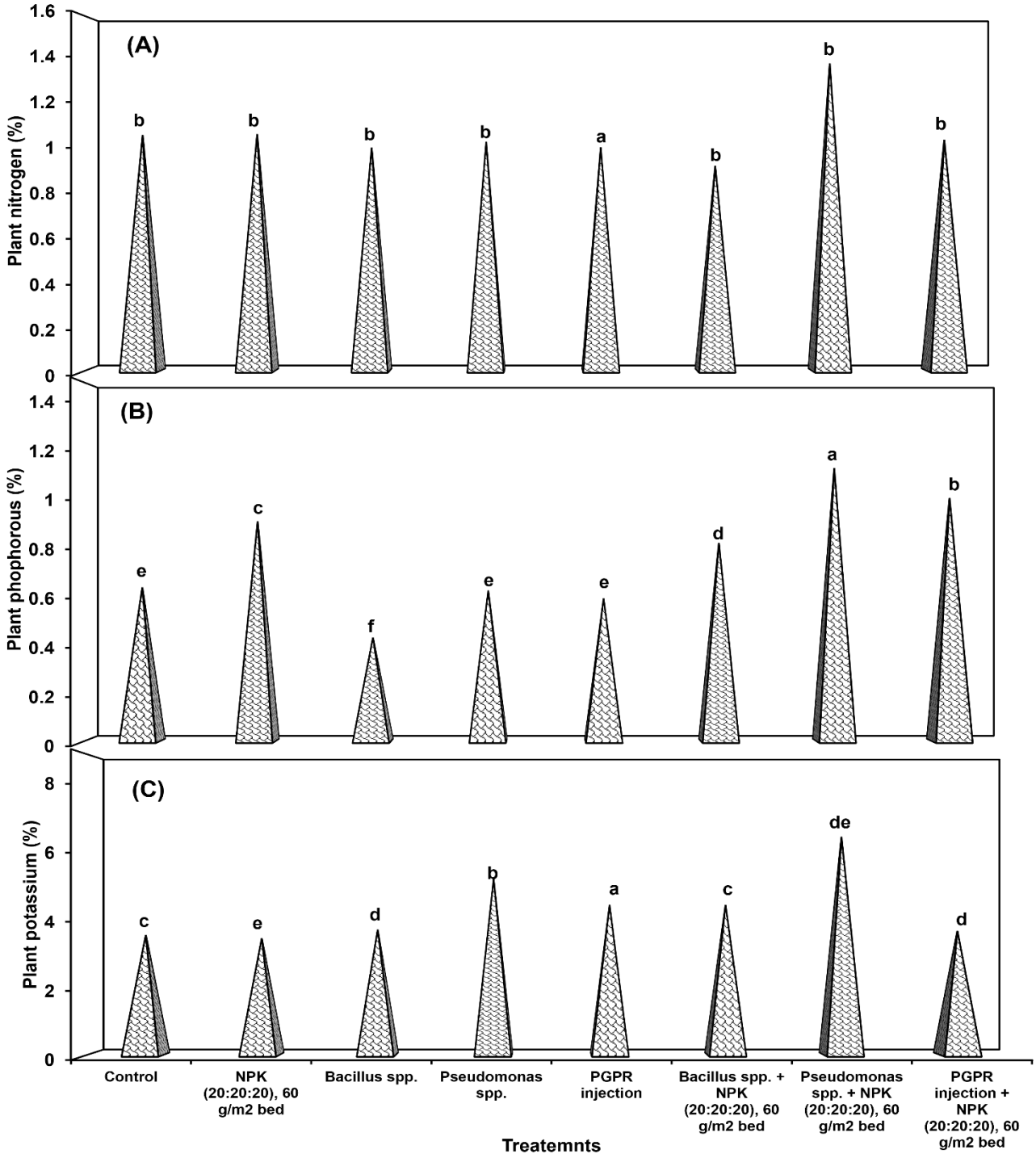

Fig. 2 Influence of PGPR and macronutrient treatments on plant nitrogen (A), plant phosphorus (B) and plant potassium (C) contents of cut sunflower cv. 'Vincent'. n = 3 replicates

Flower visual quality, plant organic matter and plant organic carbon

The maximum about 1.53-fold higher flower visual quality was recorded in *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m^2 bed treatment, while the minimum stem diameter was observed in untreated control plants (Fig. 1A). The maximum about 1.03- and 1.10-fold higher organic matter and organic carbon was recorded in *Pseudomonas* spp. + NPK (20: 20: 20), 60 g/m^2 bed while the minimum organic matter and organic carbon was observed in untreated control plants (Fig. 3A and B). PGPR help plants develop by making nutrients more available, stimulating root growth via phytohormones, and increasing total plant productivity and biomass (Cig et al., 2021). Plants need macro-nutrients like nitrogen, phosphorus, and potassium for photosynthesis and their general structure. PGPB helps plants take in these nutrients, which makes them grow stronger and leads to more organic matter and carbon being stored in the soil (Ruiz & Sanjuan, 2022). Furthermore, plants accumulate more carbon from the air into their tissues as they become bigger and more productive owing to better nutrition and growth stimulation from PGPR (Numan et al., 2018). Increased biomass and enhanced root systems result in more organic carbon transfer to the soil through root exudates (Maciel-Rodriguez et al., 2025).

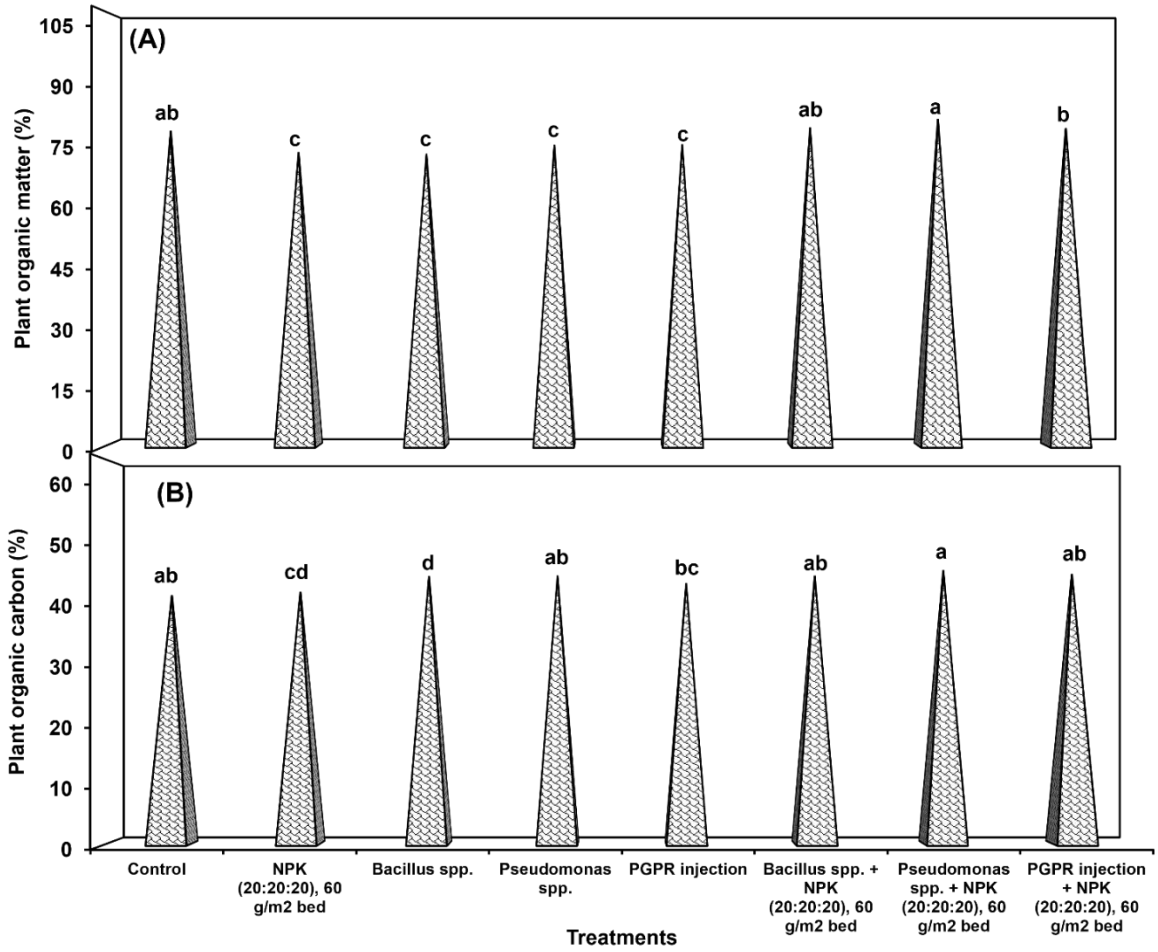

Fig. 3 Influence of PGPR and macronutrient treatments on plant organic matter (A) and plant organic carbon (B) contents of cut sunflower cv. 'Vincent'. n = 3 replicates

Correlation analysis

The correlation matrix indicates that the use of PGPR combined with macronutrients significantly promotes plant growth and quality by enhancing the favourable relationships among morphological, biomass, and nutritional characteristics. PH, NOL, SD, and biomass metrics (PFW, PDW, RFW and RDW) exhibited positive association, signifying that PGPR combined with macronutrients enhances robust vegetative development and improves biomass accumulation (Fig. 4). Furthermore, nutrients contents in plant (N, P, K, OM and OC) exhibited positive relationship with quality traits, such as VQ, indicating that enhanced nutrient availability through PGPR + NPK not only promotes growth but also elevates the nutritional quality of the plant (Fig. 4). Negative associations are infrequent and less robust, as demonstrated by LA exhibiting a marginal negative association with certain traits (Fig. 4).

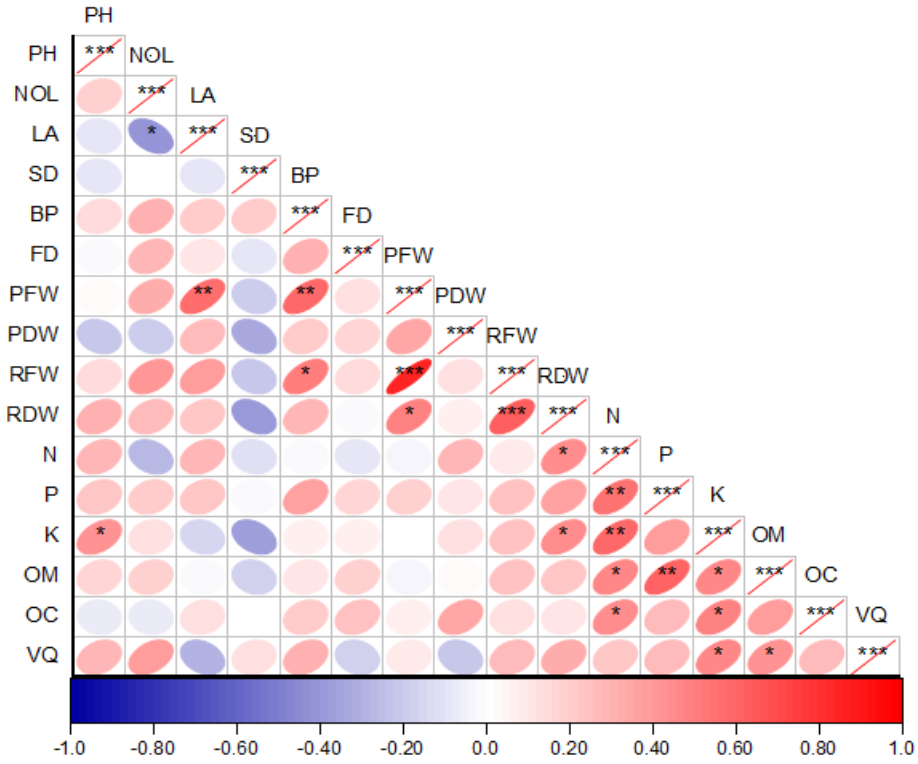

Fig. 4 The correlation coefficients among various plant growth and quality characteristics cut sunflower cv. 'Vincent'. PH = Plant height, NOL = Number of leaves, SD = Stem diameter, PFW = plant fresh weight, PDW = plant dry weight, RFW = root fresh weight, RDW = Root dry weight, N = Nitrogen, P = Phosphorous, K = Potassium, OM = Organic matter, OC = Organic carbon, VQ = Visual quality, LA = Leaf area

Conclusion

The use of PGPR, including Bacillus spp. and Pseudomonas spp., in combination with NPK (20: 20: 20) at a rate of 60 g/m2, proved to be more effective in several growth and quality parameters of cut sunflower cv. 'Vincent'. The correlation analysis findings indicate that the synergistic interaction between PGPR and NPK fertilisation enhances plant nutrient dynamics, leading to better plant growth and market quality. Further investigation is required in this domain to examine the molecular and postharvest longevity and quality attributes of ornamental plants, as well as to enhance their quality and resilience against biotic and abiotic challenges.

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