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Effects of PGPR Usage on Yield and Quality of Different Head Lettuce (*Lactuca sativa* var. *capitata*)

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ABSTRACT

This study was conducted at Van Yuzuncu Yil University's Department of Horticulture to evaluate the effects of various PGPR (Plant Growth-Promoting Rhizobacteria) isolates on three lettuce varieties under field and greenhouse conditions. The varieties included Great, Kıvırcık, Iceberg for field conditions, and Chianti, Defne, Bombolo for greenhouse conditions. PGPR isolates used were Control, FZB42 (*Bacillus amyloliquefaciens*), CC44 (*Pseudomonas fluorescens*), and CC37/2 (*Pantoea agglomerans*). Field trials showed Iceberg had the largest head diameter (11.48 cm), and Great had the highest head weight (452.91 g). In greenhouse trials, Bombolo had the largest head diameter (10.91 cm), and CC44 led to the highest head weight (125.22 g). Kıvırcık yielded the highest leaf number in the field, while Bombolo excelled in greenhouse conditions. Although PGPR isolates had limited effects on leaf number, they significantly influenced head diameter and weight, especially in field trials. Variety differences were crucial, with PGPR effects varying based on environmental conditions. Additionally, pH levels were significantly impacted, with Great recording the highest leaf pH in the field and Chianti in the greenhouse. These findings suggest that selecting appropriate PGPR strains and optimizing environmental factors can enhance lettuce yield and quality. Future research should focus on broader field trials and the integration of PGPR with reduced chemical fertilizers for sustainable lettuce production.

Farklı Baş Salata (*Lactuca sativa* var. *capitata*) Çeşitlerinde PGPR Kullanımının Verim ve Kalite Üzerine Etkileri

Makale Bilgisi

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ÖZET

Bu çalışma, Van Yüzüncü Yıl Üniversitesi Bahçe Bitkileri Bölümü'nde, üç marul çeşidinin (Great, Kıvırcık, Iceberg tarla koşullarında; Chianti, Defne, Bombolo sera koşullarında) ve üç farklı PGPR izolatının (Kontrol, FZB42: *Bacillus amyloliquefaciens*, CC44: *Pseudomonas fluorescens*, CC37/2: *Pantoea agglomerans*) büyüme, verim ve kalite üzerindeki etkilerini değerlendirmiştir. Tarla denemelerinde Iceberg en büyük baş çapına (11,48 cm) ve Great en yüksek baş ağırlığına (452,91 g) ulaşmıştır. Sera denemelerinde Bombolo en büyük baş çapını (10,91 cm) ve CC44 en yüksek baş ağırlığını (125,22 g) sağlamıştır. Kıvırcık, tarla koşullarında en fazla yaprak sayısını üretirken, Bombolo sera koşullarında öne çıkmıştır. PGPR izolatları yaprak sayısını sınırlı şekilde etkilemiş, ancak baş çapı ve ağırlığını özellikle tarla koşullarında anlamlı şekilde etkilemiştir. Çeşit farklılıkları belirleyici olmuş, PGPR etkileri çevresel koşullara bağlı olarak değişmiştir. pH seviyeleri de önemli ölçüde etkilenmiş olup, tarla koşullarında Great ve sera koşullarında Chianti en yüksek pH'ı vermiştir. Sonuçlar, uygun PGPR suşlarının seçilmesi ve çevresel faktörlerin optimize edilmesinin verim ve kaliteyi artırabileceğini göstermektedir.

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INTRODUCTION

Lettuce has various types, such as leaf, cos, or head lettuce, and is among the important vegetables of the Compositae (Asteraceae) family. Its leaves are consumed fresh or cooked. In addition to lettuce, other species, such as artichoke and chicory, are also part of this family (Günay, 1981). Worldwide, lettuce is an annual cool-climate vegetable that can be grown in all seasons and has a wide consumer base. In Türkiye, especially head lettuce varieties have seen diversified production and consumption in recent years (Aybak, 2002). Lettuce possesses a deep and extensive root system, making it highly sensitive to soil structure and irrigation patterns. Proper fertilization and water management are crucial for optimizing the yield and quality of head lettuce (Eşiyok et al., 1996). Additionally, lettuce is sensitive to temperature fluctuations, with optimal growth occurring between 15.5 °C and 18.3 °C (Çivit and Akıncı, 2010). Due to favorable climatic conditions, lettuce can be cultivated year-round in various regions of Türkiye (Günay, 2005; Kabay et al., 2018; Küçük et al., 2024).

Plant growth-promoting rhizobacteria (PGPR) colonize plant roots, enhancing seed germination, root development, and water uptake. PGPRs promote plant growth by producing growth hormones and modifying the microbial balance in the rhizosphere. They also protect plants against diseases by suppressing soil borne pathogens (Siddiqui, 2006; Bilge et al., 2019; Tunçtürk et al., 2019). Research conducted in Türkiye has shown that PGPRs positively impact head lettuce and general lettuce cultivation (Kıdoğlu et al., 2007; Akköprü et al., 2018). PGPR applications are particularly effective in supporting plant development in seedlings, leading to a higher success rate (Yan et al., 2003). Studies investigating the effects of PGPRs in organic lettuce production have demonstrated that these bacteria enhance root development and improve plant nutrient uptake. PGPR applications are highlighted as a promising alternative to chemical fertilizers, offering significant potential to support plant growth (Malkoçlu et al., 2016; Çiylez and Eşitken, 2018).

This study aimed to investigate the effects of three PGPR isolates (FZB42: *Bacillus amyloliquefaciens*, CC44: *Pseudomonas fluorescens*, and CC37/2: *Pantoea agglomerans*) on the growth, yield, and quality of head lettuce cultivars, including Great, Kıvırcık, and Iceberg in field conditions, and Chianti, Defne, and Bombolo in greenhouse conditions.

MATERIALS AND METHODS

Materials

The study was conducted in the greenhouses and application area of the Department of Horticulture, Faculty of Agriculture, Van Yuzuncu Yil University. Field and protected cultivation trials were carried out in 36 plots, using a randomized block design with 12 treatments and 3 replications. The experiment aimed to evaluate the effects of three head lettuce varieties and three different PGPR isolates on plant growth, yield, and quality.

The field trial started with seed sowing on April 14, 2016, and measurements were completed on August 12, 2016. In the field trial, plant varieties (Great, Curly, and Iceberg) were grown from seed. In the greenhouse trial, seedlings (Chianti, Laurel, and Bombolo) were purchased due to seed-related problems and time loss. Seedling planting started on October 2, 2016, and measurements were completed on December 15, 2016.

In both trials, beside to the control group 3 PGPR isolates (FZB42: *Bacillus amyloliquefaciens*, CC44: *Pseudomonas fluorescens*, CC37/2: *Pantoea agglomerans*) were applied to the head lettuce. PGPR applications were made to the root zone during seed sowing, seedling emergence and developmental stages in the field and before and after transplanting in the greenhouse.

The soil was cultivated at an appropriate depth and planting density was 40 cm between rows and was 30 cm in rows. There were 12 plants in the field plots and 24 plants in the greenhouse plots. Soil analysis was performed in both application periods and fertilization was carried out on June 7, 2016 in the field trial and on November 4, 2016 in the greenhouse trial at 15 kg da^{-1} (NPK 15-15-15).

Identification of appropriate bacterial isolates

The plant materials and PGPR isolates used in the experiment are shown in Table 1. To select the PGPR isolates for the study, three isolates available in the stocks of Van Yuzuncu Yil University, Faculty of Agriculture, Department of Plant Protection, and whose efficacy had been demonstrated in previous studies, were used.

Table 1

Plant Materials and Bacterial Isolates Used in the Study

Plant materials		**PGPR isolates**	
Field trial	**Greenhouse trial**	**Code**	**Species names**
Great	Chianti	FZB42	*Bacillus amyloliquefaciens*
Kıvırcık	Defne	CC44	*Pseudomonas fluorescens*
Iceberg	Bombolo	CC37/2	*Pantoea agglomerans*

Growing medium characteristics

In the experiment, peat-perlite mixture was used at a ratio of 3:1 and 72-vials were used as seedling growing medium. [Peat content: EC: 35 mS/m, pH: 5.5-6.5, Fertilizer content: 1.0 kg/m^3; Perlite content: SiO_2 (72.0 - 76.0 %), Al_2O_3 (11.0 - 17.0 %), K_2O (4.0 - 5.0 %), Na_2O (2.9 - 4.0 %), CaO (0.5 - 2.0 %), MgO (0. 1 - 0.5 %), Fe_2O_3 (0.5 - 1.5 %), TiO_2 (0.03 - 0.2 %), MnO_2 (0.03 - 0.1 %), SO_3 (0 - 0.2 %), H_2O (2 - 7 %).]

Location of the Research Site

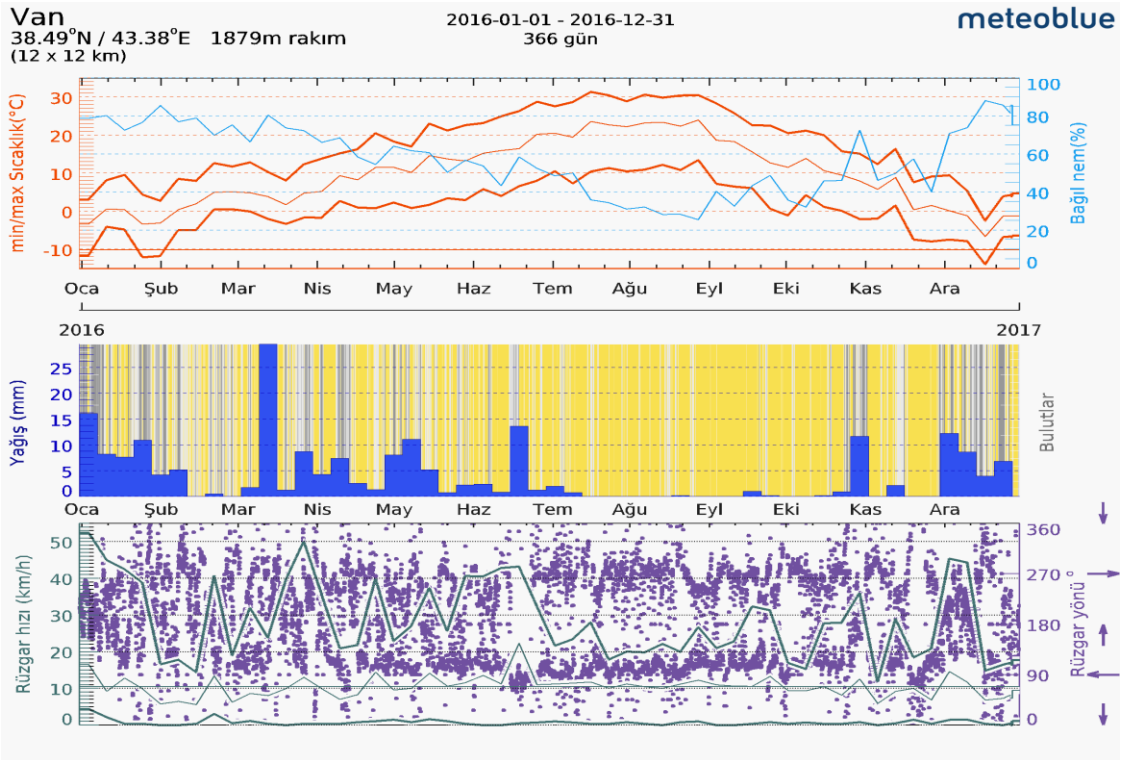
The research was conducted in the experimental field of Van Yuzuncu Yil University Research and Application Farm in 2016. The field trial was conducted between April 14 and August 12, and the greenhouse trial was conducted between October 2 and December 15. Van province is located in a basin surrounded by mountains to the west of Lake Van in the Eastern Anatolia Region, 1720 m above sea level and 38-25' north latitude and 43-21' east longitude. The trial area is located northeast of Lake Van, approximately 2 km from the lakeshore.

Climate Characteristics of the Research Site

Van has a continental climate with cold and snow-covered winters and cool and dry summers. Being located on the shores of Lake Van makes the climate of the province relatively mild. Monthly climate data for the periods of the study are presented in Figure 1. The rainfall during the growing season was 387.2 mm, the average temperature was 9.37 °C and the average relative humidity was 55.20%. In 2016, rainfall was 442.3 mm, average temperature was 9.85 °C and average relative humidity was 50.53% (Anonymous, 2018).

Figure 1

Some Climate Data for Van Province in 2016



Temperature was also measured inside and outside the greenhouse (°C), and the temperature inside the greenhouse varied ±8-13°C from the outdoor temperature.

Soil characteristics of the research site

Some physical and chemical analyses of the soil samples taken from 0-30 cm from the experimental area where the research was conducted were carried out in Van Commodity Exchange Laboratory and the results of the analysis are shown in Table 2.

Table 2

Field and Greenhouse Parcels' Soil Analysis Results

Field Soil Analyses	**Results**	**Status**
Potassium (K_2O)	131.7918	High
Phosphorus (P_2O_5)	6.6983	Medium
Lime (%)	7.3429	Moderately calcareous
Organic Matter (%)	0.5039	Very low
Total Salt (%)	0.0060	Salt-free
pH	7.16	Slightly alkaline
Saturation (%)	27	Sandy
Greenhouse Soil Analyses	**Results**	**Status**
Potassium (K_2O)	265.4233	High
Phosphorus (P_2O_5)	6.4258	Medium
Lime (%)	8.9274	Moderately calcareous
Organic Matter (%)	2.1639	Medium
Total Salt (%)	0.0045	Salt-free
pH	7.44	Neutral
Saturation (%)	33	Loamy

Methods

Plant cultivation

For the field trial, 4 varieties of head lettuce and 3 different PGPR isolates were planted in 72-well vials with 3 replicates (April 14, 2016). The field trial was conducted between April 14 and August 12, and the greenhouse trial was conducted between October 2 and December 15, determined as 110-120 days after sowing and 90-100 days after transplanting. The greenhouse trial determined this period as 70-80 days from seedling planting.

PGPR Applications

Each root bacterial isolate was grown in KB medium for 48 hours at 24°C. Bacterial cultures were suspended with 1.5% CMC. PGPR treatments were performed one week apart, starting at seedling emergence. At seedling emergence, a concentration of 10^9 cfu/ml was applied to the roots by inoculation.

Determination of Seedling Development Parameters

Determination of the number of head lettuce leaves: Determined by counting at the end of the experiment.

Head lettuce diameter and height measurements (cm): The head diameter and height were measured with a ruler.

Determination of head weight (g): Head lettuce weights were measured with a precision balance (±1g).

Determination of TSS content (°Brix): The total soluble solid content in the juice obtained from lettuce plants was measured using a hand refractometer.

Determination of leaf pH: The sap obtained by crushing the plant leaves in a ceramic mortar was measured with a pH meter.

Statistical analysis

The data obtained were analyzed using analysis of variance (one-way ANOVA) within the SPSS software package (IBM SPSS Statistics 21.0) according to the randomized block experimental design. The means were separated by "Duncan Multiple Comparison Test".

RESULTS AND DISCUSSION

Field Trial

Effect of PGPR Applications on Leaf Number

In the present study, the effects of PGPR on leaf number of different head lettuce (*Lactuca sativa* var. *capitata*) cultivars were investigated (Table 3). Significant differences ($P \leq 0.001$) were found among the cultivars. The cv. Kıvırcık gave the highest value with an average number of 25.88 leaves. It was followed by cv. Great (15.83 leaves) and Iceberg (15.21 leaves) varieties, respectively. In terms of PGPR treatments, the highest average number of leaves was found in CC37/2 isolate (20.55). No statistically significant difference was observed in the cultivar x PGPR interaction. Karagöz and Kotan (2010) reported that although PGPR isolates had positive effects on some parameters such as leaf number, these increases were not significant.

Table 3

Effects of PGPR Treatments on the Average Leaf Number of Different Head Lettuce Cultivars under Field Conditions

	CULTIVARS			
PGPR	**GREAT**	**KIVIRCIK**	**ICEBERG**	**MEAN**
CONTROL	14.17 ^{ns}	26.67	14.50	18.44 ^{ns}
CC37/2	17.33	**29.00**	15.33	20.55
CC44	**13.67**	27.17	14.50	18.44
FZB42	18.17	20.67	16.50	18.44
MEAN	15.83 B***	25.88 A	15.21 B	

***: Significant at P≤0.001 level

$^{ns:}$ not significant, there is no statistical difference between means.

Effect of PGPR Treatments on Head Diameter

The effects of PGPR treatments on head diameter in different head lettuce cultivars are presented in Table 4. Among PGPR isolates, CC37/2 isolate gave the highest value with 12.16 cm (P≤0.05). Iceberg variety had the highest head diameter with an average of 11.48 cm. No significant difference was found in the cultivar x PGPR interaction. Kesimci (2013) and Kıdoğlu *et al*. (2007) reported that the effects of PGPR and plant activators on head diameter were generally insignificant.

Table 4

Effects of PGPR Treatments on Average Head Diameter of Different Head Lettuce Cultivars under Field Conditions (cm)

	CULTIVARS			
PGPR	**GREAT**	**KIVIRCIK**	**ICEBERG**	**MEAN**
CONTROL	11.11 ^{ns}	**9.89**	10.15	10.38B*
CC37/2	12.69	10.21	**13.59**	12.16A
CC44	11.05	10.05	12.16	11.09AB
FZB42	11.64	10.10	10.00	10.58AB
MEAN	10.46 ^{ns}	10.06	11.48	

*: Significant at P≤0.05 level.

$^{ns:}$ not significant, there is no statistical difference between means.

Effect of PGPR Applications on Head Height

The effects of PGPR treatments on head height of head lettuce cultivars are given in Table 5. Among the varieties, cv. Kıvırcık had the highest head height with 14.00 cm (P≤0.001). Among PGPR isolates, CC37/2 isolate showed the highest value with 12.05 cm. No significant difference was found in the cultivar x PGPR interaction. Malkoçlu (2016) and Sadak *et al*. (2021) reported that the effect of PGPR applications on plant height was generally statistically insignificant in similar studies.

Table 5

Effects of PGPR Treatments on Average Head Height of Different Head Lettuce Cultivars under Field Conditions (cm)

	CULTIVARS			
PGPR	**GREAT**	**KIVIRCIK**	**ICEBERG**	**MEAN**
CONTROL	10.50 ^{ns}	13.50	10.00	11.33 ^{ns}
CC37/2	10.50	**14.83**	10.83	12.05
CC44	**9.67**	15.50	10.33	11.83
FZB42	10.33	12.17	11.00	11.17
MEAN	10.25 B***	14.00 A	10.54 B	

***: Significant at P≤0.001 level.

$^{ns:}$ not significant, there is no statistical difference between means.

Effect of PGPR Treatments on Head Weight

The effects of PGPR treatments on head weight of lettuce cultivars are shown in Table 6. Among PGPR isolates, CC37/2 isolate gave the highest result with 405.55 g (P≤0.05). The cv. Great had the highest head weight with 452.91 g (P≤0.001). No significant difference was found in the cultivar x PGPR interaction. Merdin (2009) and Malkoçlu *et al*. (2016) emphasized that the effects of PGPR on head weight were generally insignificant.

Table 6

Effects of PGPR Treatments on Average Head Weight of Different Head Lettuce Cultivars under Field Conditions (g)

	CULTIVARS			
PGPR	**GREAT**	**KIVIRCIK**	**ICEBERG**	**MEAN**
CONTROL	400.00 ^{ns}	**226.00**	299.33	308.44AB*
CC37/2	**570.00**	244.33	402.33	405.55A
CC44	342.33	265.00	284.68	297.33B
FZB42	499.33	232.00	257.00	329.44AB
MEAN	452.91 A***	241.83 B	310.83 B	

*: Significant at P≤0.05 level.

***: Significant at P≤0.001 level.

$^{ns:}$ not significant, there is no statistical difference between means.

Effect of PGPR Applications on Leaf pH

The effects of PGPR treatments on leaf pH are presented in Table 7. The cv. Great had the highest pH value with 6.49 (P≤0.001). FZB42 isolate gave the highest result with a pH value of 6.43 (P≤0.05). No significant difference was found in the cultivar x PGPR interaction. Kesimci (2013) reached similar results and reported that PGPR treatments had no significant effect on pH.

Table 7

Mean Leaf pH Values of PGPR Treatments in Different Head Lettuce Cultivars under Field Conditions

	CULTIVARS			
PGPR	**GREAT**	**KIVIRCIK**	**ICEBERG**	**MEAN**
CONTROL	6.43 ns	6.20	6.33	6.32 B*
CC37/2	6.53	6.17	6.47	6.39 AB
CC44	6.40	**6.13**	6.43	6.32 B
FZB42	**6.57**	6.17	**6.57**	6.43 A
MEAN	6.49 A***	6.17 B	6.45 A	

*: Significant at P≤0.05 level.

***: Significant at P≤0.001 level.

ns: not significant, there is no statistical difference between means.

Effect of PGPR Treatments on TSS content

The effects of PGPR treatments on the TSS content of head lettuce cultivars are given in Table 8. The cv. Kıvırcık had the highest TSS value with 5.00 °Brix. However, no significant difference was found between PGPR treatments. There was also no significant difference in the cultivar x PGPR interaction.

Table 8

The Effects of PGPR Treatments on the Average TSS Content of Different Head Lettuce Cultivars under Field Conditions (°Brix)

	CULTIVARS			
PGPR	**GREAT**	**KIVIRCIK**	**ICEBERG**	**MEAN**
CONTROL	4.33 ns	**5.00**	**5.00**	4.78 ns
CC37/2	4.67	4.33	4.33	4.44
CC44	4.00	**5.00**	4.00	4.33
FZB42	**3.33**	5.67	4.33	4.44
MEAN	4.08 ns	5.00	4.41	

ns: not significant, there is no statistical difference between means.

These results indicate that PGPR applications have various effects on plant growth, but these effects vary depending on the cultivar and isolates applied.

Protected cultivation (Greenhouse) trial

Effects of PGPR on the Number of Leaves in Different Head Lettuce Cultivars

PGPR treatments caused significant differences in the number of leaves in head lettuce cultivars (Table 9). Bombolo cultivar had the highest number of leaves with an average of 18.00 leaves, while cv. Chianti showed the lowest number of leaves. Significant differences in the number of leaves were also observed among PGPR isolates. Especially CC44 isolate formed significantly more leaves than the others. In the control treatment, the number of leaves remained lower. Similarly, Sadak *et al*. (2021) reported that the effect of PGPR on leaf number in pepper seedlings was insignificant, while Çiylez and Eşitken (2018) reported that some PGPR treatments were effective in strawberries. Our findings, as in these studies, show that PGPR has variety and isolate independent effects on plant growth.

Table 9

Effects of PGPR Treatments on The Average Number of Leaves of Different Head Lettuce Cultivars under Greenhouse Conditions

	CULTIVARS			
PGPR	**CHIANTI**	**DEFNE**	**BOMBOLO**	**MEAN**
CONTROL	**12.67** ns	15.83	**18.67**	15.72AB*
CC37/2	14.67	14.33	16.67	15.22B
CC44	15.17	18.17	**18.67**	17.33A
FZB42	13.17	16.00	18.00	15.72AB
MEAN	13.91 C***	16.09 B	18.00 A	

*: Significant at P≤0.05 level.

***: Significant at P≤0.001 level.

ns: not significant, there is no statistical difference between means.

Effects of PGPR on Head Diameter in Different Head Lettuce Varieties

In head diameter measurements, cv. Bombolo had the largest head diameter, while no significant difference was observed between the other cultivars (Table 10). Among PGPR treatments, CC44 isolate provided the largest head diameter. Studies such as Sadak *et al*. (2021) and Ekici *et al*. (2015) indicated that PGPR treatments can positively affect head diameter. However, in this study, the effect of PGPR on head diameter did not differ among varieties.

Table 10

Effects of PGPR Treatments on Average Head Diameter of Different Head Lettuce Cultivars Under Greenhouse Conditions (cm)

	CULTIVARS			
PGPR	**CHIANTI**	**DEFNE**	**BOMBOLO**	**MEAN**
CONTROL	9.73 ns	**9.46**	10.89	10.03 ns
CC37/2	9.68	9.57	10.21	9.82
CC44	10.26	11.16	10.95	10.79
FZB42	9.52	10.10	**11.59**	10.40
MEAN	9.80 ns	10.07	10.91	

ns: not significant, there is no statistical difference between means.

Effects of PGPR on Head Height in Different Head Lettuce Varieties

In the head height results, cv. Bombolo reached the highest plant height, while the head height of the control group was the highest among PGPR treatments (Table 11). Kesimci (2013) and other studies reported that the effects of bacterial treatments on head height were generally limited, and our findings showed similar results.

Table 11

Mean Head Height (cm) of Different Lettuce Cultivars of PGPR Treatments under Greenhouse Conditions

	CULTIVARS			
PGPR	**CHIANTI**	**DEFNE**	**BOMBOLO**	**MEAN**
CONTROL	13.83 ^{ns}	14.33	**14.50**	14.22 ^{ns}
CC37/2	13.50	**10.33**	13.17	12.33
CC44	11.50	15.33	14.00	13.61
FZB42	13.33	11.17	13.83	12.78
MEAN	13.04 ^{ns}	12.80	13.88	

$^{ns:}$ not significant, there is no statistical difference between means

Effects of PGPR on Head Weight in Different Head Lettuce Varieties

In head weight measurements, cv. Defne had the highest average head weight, while CC44 isolate provided the highest head weight among PGPR isolates (Table 12). Similarly, Moustaine *et al*. (2017) and Güneş (2018) reported that PGPR applications can positively affect head weight. Our findings show that some PGPR isolates can increase head weight in accordance with this literature.

Table 12

Effects of PGPR Treatments on Average Head Weight of Different Head Lettuce Cultivars under Greenhouse Conditions (g)

	CULTIVARS			
PGPR	**CHIANTI**	**DEFNE**	**BOMBOLO**	**MEAN**
CONTROL	89.00 ^{ns}	103.33	137.33	109.89
CC37/2	94.00	106.67	112.00	104.22
CC44	110.33	139.00	126.33	125.22
FZB42	**91.33**	106.33	**142.00**	113.22
MEAN	96.17 B*	113.83 AB	129.41 A	

*: Significant at P≤0.05 level.

$^{ns:}$ not significant, there is no statistical difference between means.

Effects of PGPR on pH in Different Head Lettuce Varieties

Among the PGPR isolates, CC44 isolate provided the highest pH (P≤0.05); the highest pH among the varieties was measured in cv. Chianti (Table 13). Öztekin *et al*. (2015) obtained similar results in pH values in tomato, and our findings showed that the differences in pH varied depending on specific isolates.

Table 13
Mean Leaf pH Values of PGPR Treatments in Different Head Lettuce Cultivars under Greenhouse Conditions

	CULTIVARS			
PGPR	**CHIANTI**	**DEFNE**	**BOMBOLO**	**MEAN**
CONTROL	6.47 ns	6.40	**6.27**	6.38 AB*
CC37/2	**6.27**	6.33	6.37	6.32 B
CC44	**6.60**	6.43	6.40	6.48 A
FZB42	6.40	6.37	6.40	6.39 AB
MEAN	6.43 ns	6.39	6.35	

*: Significant at P≤0.05 level.

ns: not significant, there is no statistical difference between means.

Effects of PGPR on TSS in Different Head Lettuce Cultivars

Chianti cultivar obtained the highest average TSS values, while FZB42 isolate provided the highest average TSS in PGPR treatments (Table 14). Studies such as Kesimci (2013) and Gök and Onaç (1995) have reported that the effects of PGPR on TSS may vary depending on cultivar and conditions. Our findings also support these variations.

Table 14
The Effects of PGPR Treatments on the Average TSS of Different Head Lettuce Cultivars under Greenhouse Conditions (°Brix)

	CULTIVARS			
PGPR	**CHIANTI**	**DEFNE**	**BOMBOLO**	**MEAN**
CONTROL	**6.93**ns	**5.13**	5.47	5.84 ns
CC37/2	6.40	6.27	6.43	6.37
CC44	6.07	6.07	6.70	6.28
FZB42	6.67	6.53	6.00	6.40
MEAN	6.51 ns	6.00	6.15	

ns: not significant, there is no statistical difference between means

Shao *et al*. (2023) studied different strains of PGPRs on lettuce and highlighted the role of specific bacterial strains in promoting lettuce growth and yield. The strains used in their study, such as *Bacillus velezensis* and *Bacillus amyloliquefaciens*, showed improvements in head diameter, plant height, and fresh weight, aligning with our findings on PGPR effects. Shao *et al*. (2023) also emphasized how lettuce variety impacts the effectiveness of microbial applications; discussed how benefits observed in pot trials do not always translate to field conditions; and stating that there was a lack of PGPR effectiveness across different environments.

Demir *et al*. (2023) studied biofertilizer (BM-MegaFlu®) comprised *Bacillus megaterium*, *Pseudomonas fluorescens*, and *Pantoea agglomerans* bacteria on lettuce and brokoli, and they found when combining these bacteria with reduced doses of chemical fertilizers aligns with our findings about the benefits of specific PGPR strains like *Pseudomonas fluorescens* (CC44) and *Pantoea agglomerans* (CC37/2) on lettuce growth and yield. Their study emphasizes how combining biofertilizers with lower doses of chemical fertilizers can achieve comparable or even superior yields to full chemical treatments.

CONCLUSION

This study investigated the effects of different PGPR isolates on head lettuce under both field and greenhouse conditions. The results demonstrated that the impact of PGPR treatments on lettuce growth and yield varied significantly depending on plant variety, isolate type, and environmental factors such as climate and growing conditions. The findings indicate that specific bacterial strains can effectively promote lettuce growth, but their effectiveness may vary across different environments and cultivation methods.

In our study, the Kıvırcık variety yielded the highest number of leaves under field conditions, while the Bombolo variety excelled in greenhouse conditions. Although PGPR isolates had limited effects on leaf number, their impact on head diameter was notable, particularly in the field. The Iceberg variety exhibited the largest head diameter under field conditions, and Bombolo performed best in the greenhouse. Regarding head weight, the Great variety led in field trials, while the Defne variety excelled in greenhouse conditions. PGPR isolates significantly influenced head weight in field conditions, though their effect was more limited in greenhouse trials. In terms of pH, the Great and Chianti varieties recorded the highest leaf pH under field and greenhouse conditions, respectively, with PGPR isolates having a statistically significant impact across both environments.

The study suggests that selecting compatible PGPR strains for specific lettuce varieties is key to optimizing growth. Additionally, environmental factors in greenhouse conditions, like soil and moisture, should be carefully managed to enhance PGPR effectiveness. Combining PGPR isolates with reduced chemical fertilizers could be an effective strategy for sustainable lettuce production. Future research should focus on conducting broader field trials across diverse regions to validate and refine these approaches.

In conclusion, while this study confirms the potential of PGPR isolates to enhance lettuce yield and quality, the outcomes are highly dependent on plant variety, environmental conditions, and isolate type. Continued research is needed to refine these treatments and fully integrate them into sustainable agricultural practices.

Ethical Statement

The article is adapted from the first author's M.Sc. thesis. The authors would like to thank Dr. A. Akkopru, Van Yüzüncü Yıl University, Faculty of Agriculture, Department of Plant Protection, for the PGPR supply.

Author Contributions

Research Design (CRediT 1) Author 1 (%50) – Author 2 (%50)

Data Collection (CRediT 2) Author 1 (%70) – Author 2 (%30)

Research - Data Analysis - Validation (CRediT 3-4-6-11) Author 1 (%50) – Author 2 (%50)

Writing the Article (CRediT 12-13) Author 1 (%60) – Author 2 (%40)

Revision and Improvement of the Text (CRediT 14) Author 1 (%20) – Author 2 (%80)

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Sustainable Development Goals (SDG)

12 Responsible Production and Consumption

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