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Investigating the Impacts of Nitrogen Doses and Rhizobacteria on Sugar Beet (*Beta vulgaris* L.) Yield and Quality Parameters for Sustainable Cultivation

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Abstract

Rising costs and environmental concerns associated with chemical fertilizers in modern agriculture necessitate exploring sustainable alternatives. Plant growth-promoting soil bacteria offer a promising solution. This study evaluated the impact of nitrogen-fixing rhizobacteria (*Bacillus subtilis, Bacillus megaterium, Lactococcus* spp., *Azospirillum, Rhizobium, Acetobacter, and Azotobacter*) on the yield and quality traits of sugar beet (*Beta vulgaris* L.) under different nitrogen application rates, both with and without chemical nitrogen application. Our findings suggest that co-inoculation with rhizobacteria can significantly enhance sugar beet yield. Under chemical nitrogen application, the $B_1 + N_3$ treatment achieved the highest storage beet yield (7713 kg da $^{-1}$) and sugar yield (1444.00 kg da $^{-1}$). In the absence of chemical nitrogen application, the $B_2 + N_0$ treatment showed promising results (5047 kg da $^{-1}$ beet yield, 985.40 kg da $^{-1}$ sugar yield). The study demonstrates the significant potential of bacterial applications for promoting growth and improving the agronomic traits of sugar beet, offering a sustainable and organic agricultural alternative.

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1. Introduction

Sugar beet is a product with a very high strategic importance, used in many areas of industry (Şanlı et al., 2023). Meeting the growing demand for sugar is a critical challenge in today's world. Sugar beet, accounting for 21 % of global sugar production, plays a vital role alongside sugarcane. While sugar beet production costs are generally higher, it indirectly supports livelihoods in agriculture, livestock, medicine, and service sectors. Therefore, increasing production efficiency and quality while reducing costs remains a key objective (Talebpour, 2016). The most important nutrient element affecting yield and quality parameters in sugar beet production is nitrogen (Draycott and Christenson, 2003).

Conventional chemical fertilizers and pesticides degrade soil structure, pollute the environment, and pose health risks, ultimately driving up production costs (Çakmakcı, 2005). The initial surge in production brought about by chemical inputs is now stagnating. Additionally, exploitative farming practices, water and wind erosion, nutrient depletion, and loss of organic matter further compromise soil fertility (Saber, 2001). The detrimental effects of synthetic chemicals used to boost agricultural output are no longer a secret. Researchers are actively seeking a more holistic approach. The development and use of bio-preparations, aligned with the principles of sustainable agriculture, offer a promising solution. These bio-fertilizers can significantly reduce reliance on chemicals while simultaneously enhancing production efficiency and quality, all while safeguarding the environment from pollution (İmriz, 2014). Rhizobacteria, beneficial soil bacteria, establish a symbiotic relationship with plant roots. They fix nitrogen from the air and convert other elements, like phosphorus, into forms readily available for plant uptake. Studies have shown that specific rhizobacteria, particularly *Azotobacter* and *Azospirillum*, significantly enhance yields. Application methods include seed inoculation, soil surface application, or foliar grafting (Çakmakcı, 2005). The widespread adoption of rhizobacteria in sugar beet plant presents a significant opportunity for sustainable agriculture. This approach can reduce chemical fertilizer consumption, mitigate the negative environmental impacts associated with chemical fertilizers, and ultimately lower production costs. This aligns perfectly with the growing focus on environmentally friendly agricultural practices, which utilize beneficial soil bacteria and other microorganisms to promote nutrient uptake, plant growth, and resistance to biotic and abiotic stress factors (Bozdoğan, 2019).

Motivated by this potential, this research investigates the effects of bacterial biofertilizers applied at different nitrogen doses on sugar beet (*Beta vulgaris* L.*)* yield and quality parameters. Our primary objective is to reduce reliance on chemical fertilizers in the pursuit of sustainable and healthy agricultural practices.

2. Materials and Methods

2.1. Material

The trial utilized sugar beet seeds of the Varios variety (*Beta vulgaris* L.). Bred in Denmark in 2015 using hybridization techniques, Varios exhibits tolerance to rhizomania disease. It boasts an average beet yield of 89.39 kg ha^{-1} and an average sugar yield of 12.70 kg ha^{-1} (Anonymous, 2022). Di-ammonium Phosphate (DAP) containing 18% N and 46% P_2O_5 was used as the base fertilizer and Urea fertilizer containing 48% N was used as the top fertilizer for nitrogen source. Four different nitrogen doses were tested in the study: N_0 (control, no nitrogen application), N_1 (5 kg da $^{-1}$), N_2 (10 kg da $^{-1}$), and N_3 (15 kg da $^{-1}$). Two commercially available rhizobacteria products were used as plant growth-promoting rhizobacteria (PGPR) inoculants in the experiment. Bactoboost (Yeditepe University Genetics and Bioengineering Department), containing *Bacillus subtilis, Bacillus megaterium,* and *Lactococcus spp.,* will be referred to as B_1 throughout the research.

The second product, Symbion-N (Agrobest Grup Tarım), containing *Azospirillum, Rhizobium, Acetobacter,* and *Azotobacter,* will be designated as B_2. A control group receiving no bacterial inoculation will be designated as B_0.

2.2. Location of the research

The field experiment was conducted at the Agricultural Research and Application Unit (ERUTAM) located on the main campus of Erciyes University. The trial area is situated at 38.687° latitude and 35.5° longitude, with an elevation of 1092 meters above sea level (TOB, 2021).

2.3. Soil analysis

Soil samples were collected from the 0-30 cm depth of the experimental area and analyzed at the Erciyes University Faculty of Agriculture's Soil Science and Plant Nutrition Laboratory. Samples were air-dried, sieved through a 2 mm mesh, and subjected to a series of chemical and physical analyses. Soil textural composition (sand, silt, and clay) was determined using the Bouyoucos Hydrometer method (Bouyoucos, 1951). Soil pH and calcium carbonate concentration were determined (Mclean, 1982). Soil organic matter content was determined (Nelson and Sommers, 1982). Soil available phosphorus was determined by the Olsen method (Olsen et al., 1954). Analysis results revealed that the experimental area has a clayey texture, a slightly alkaline pH (7.65), and is non-saline (0.050 %). However, the soil was found to be low in organic matter (1.21 %), calcareous (1.80 %), and deficient in available phosphorus (4.25 kg da $^{-1}$). Additionally, the total nitrogen content was low (1.50 %). A summary of the soil analysis results is presented in Table 1.

Table 1. Soil characteristics of the trial area

Yıl	Soil depth (cm)	Lime (%)	Salt (EC:1:2.5)	Organic matter (%)	Ph (1:2.5)	Structure	N kg da^{-1}	P2O5 kg da $^{-1}$
2019	0-30	1.8	0.5	1.21	7.65	Clayey	1.5	4.25

Source: Erciyes University Faculty of Agriculture Soil Science and Nutrition Department Laboratory.

2.4. Climatic conditions

The experiment was conducted from October 2018 (including soil cultivation and preparation) to October 2019 (harvest). The average temperature during the trial period was 11.8 °C, which was 1 °C higher than the long-term average. Average relative humidity was 60.8 %, which was lower than the long-term average of 63.54 %. Similarly, total annual rainfall during the experimental period was 389.4 mm, falling short of the historical average of 416.7 mm.

2.5. Trial design

This research was carried out on sugar beet seeds planted in the ERUTAM land of Erciyes University in Kayseri. A randomized complete block design (RCBD) with three replicates was employed for the factorial treatment arrangement. The experiment investigated the effects of two main factors: Nitrogen dose (N): Four levels were included: N_0 (0 kg da $^{-1}$), N_1 (5 kg da $^{-1}$), N_2 (10 kg da $^{-1}$), and N_3 (15 kg da $^{-1}$). Bacterial combination (B): Three levels were included: B_0 (control, no inoculation), B_1 (Bactoboost), and B_2 (Symbion-N). Soil preparation and tillage practices were performed in October 2018. Sugar beet seeds (*Beta vulgaris* L., Varios variety) were hand-planted on April 25, 2019, with a row spacing of 45 cm and an in-row spacing of 20 cm. Each plot consisted of six rows, and only the four central rows were used for data collection. The outer rows served as buffers and were excluded from the analysis. The experimental area was divided into three blocks, each containing 12 plots. This resulted in a total of 36 plots. The plot size was 11.25 m², with two row spacings (approximately 90 cm) between plots. This design yielded a total experimental area of 533.5 m². Two-thirds of the planned nitrogen dose for each plot was applied as basal fertilizer (DAP) at planting on April 25, 2019. The remaining one-third was applied as topdressing with Urea fertilizer on June 15, 2019. A sprinkler irrigation system was used throughout the experiment. A total of 16 irrigation applications were performed weekly based on soil moisture content from the first week of June to the end of September. Weed control was performed on July 15, 2019. When the plants reached the 8-10 leaf stage, B_1 (Bactoboost) and B_2 (Symbion-N) inoculants were applied once by foliar application at a rate of 300 ml da $^{-1}$ according to the experimental plan. Harvest was performed manually on October 24, 2019, using beet lifting hooks when the beet petioles reached physiological maturity.

2.6. Measurements of plant

Beet yield was calculated by cutting and weighing the heads of 15 beets randomly selected from the middle rows of each plot and converting the average into decares. After the beet root yield was determined separately for each parcel, the presence of refined sugar and refined sugar yield (Reinefeld et al., 1974), α-amino nitrogen content (Kubadinow and Wieninger, 1972), sodium and potassium content (Kubadinow, 1972) were determined. Technological sugar yield (t ha $^{-1}$) = beet yield (t ha $^{-1}$) x [sucrose content in roots (%) – loss of sugar productivity (%)] (Buchholz et al., 1995). Sugar beet quality analyzes were carried out on the Betalyser system, which works according to the official analysis methods recommended by the International Commission of Uniform Methods of Sugar Analysis (ICUMSA, 2003).

2.7. Statistical analysis

Measurements and analyzes of sugar beet were recorded using the SPSS package program in accordance with the random block design, and significant results were evaluated according to the Duncan multiple comparison test. (Boston, MA, USA, https://www.xlstat..com) (SPSS 2013; Addinsoft, 2021).

3. Results and Discussions

3.1. Beet yield

The results for beet yield (kg da^{-1}) are presented in Table 2. Statistical analysis revealed significant effects ($p<0.01$) for nitrogen dose (N), bacterial combination (B), and their interaction on beet yield. When nitrogen fertilizer was applied without bacterial inoculation, the highest yield (6760 kg da^{-1}) was obtained with the highest nitrogen dose (N_3). Control group and the lowest nitrogen dose (N_1) yielded the least (2487 kg da^{-1}). Among plots receiving only bacterial inoculants (no added nitrogen fertilizer), the highest beet yield (5047 kg da^{-1}) was observed with B_2 treatment. Conversely, the control group (B_0) exhibited the lowest yield (2487 kg da^{-1}). The analysis of interaction effects revealed that the B_1 + N_3 treatment produced the highest beet yield (7713 kg da^{-1}). In contrast, the combination of B_2 with the lowest nitrogen dose (N_1) resulted in the lowest yield (2860 kg da^{-1}) within the interaction group. These findings suggest that B_1 may be more effective in promoting beet yield when used in conjunction with increasing nitrogen fertilizer application. Conversely, B_2 appears to be more beneficial for beet yield in the absence of additional nitrogen fertilizer.

Table 2. Effect of nitrogen and bacterial applications on beet yield values

Beet yield (kg da^{-1})					
Bacterium	**Nitrogen (N)**				**Average**
	N0	**N1**	**N2**	**N3**	
B0	2487.00 h*	2487.00 h	4607.00 e	6760.00 b	4085.00 B
B1	2687.00 gh	4633.00 e	5867.00 c	7713.00 a	5225.00 A
B2	5047.00 d	2860.00 g	4067.00 f	4240.00 f	4053.00 B
Average	3407.00 C	3327.00 C	4847.00 B	6238.00 A	
LSD %1 B		168.3			
LSD %1 N		194.4			
LSD %1 B+N		336,7			

**Significant at $p<0.01$; Lowercase letters indicate the level of significance between applications, and uppercase letters indicate the level of significance between averages.

Our findings on the impact of bacterial inoculants on beet yield align with previous research. The research showed that biofertilizers and micronutrients applied to sugar beet by leaf grafting method increased beet quality and beet yield (Amin et al., 2013). As a result of the research conducted on sugar beet in different regions of Poland between 2017 and 2019, it was observed that when Azoter containing *Azotobacter chroococcum*, *Azospirillum* *brasilense* and *Bacillus megaterium* bacteria was applied, the need for chemical fertilizers decreased by 30 %, the beet yield increased by 3.9 % and the fresh root mass increased by 4.2 % (Artyszak and Gozdowski, 2020). The study conducted with PGPR, it was determined that the beet yield of sugar beet increased between 6.1-13 % due to the combination of *Burkholderia spp., B. polymyxa, Pseudomonas spp.*, bacteria (Çakmakçı, 2005). The study conducted with PGPRs, the highest beet yield was measured as 8914,200 kg da^{-1} and the lowest was 7511,052 kg da^{-1} (Çınar, 2021). It has been observed that multi-featured bacterial inoculations promote beet yield and plant growth (Karagöz et al., 2018). In the research on sugar beet, the effect of two different seed varieties and five different nitrogen doses was observed. Inoculation of seeds with *S.bellus, S.saprophyticus* rhizobacteria stimulated beet elongation, the highest root yield was recorded in *S.saprophyticus* application and beet diameter increased in both bacteria applications (Aallam et al., 2023).

3.2. Technological sugar yield

The results for technological sugar yield (percentage of refined sugar) are presented in Table 3. Statistical analysis revealed no significant effects ($p>0.05$) of nitrogen dose (N), bacterial combination (B), or their interaction on technological sugar yield. When nitrogenous fertilizer was applied without bacterial inoculation, technological sugar yield was obtained in the range of (N_1) (18.48 %) and (N_3) (17.91 %). When only bacteria (without nitrogen fertilizer addition) was applied, technological sugar yield was observed in the range of B_2 (18.08 %) and B_1 (17.79 %). When interactions were analyzed, they occurred in the range of B_2 + N_1 (18.54 %) and B_1 + N_3 (17.82 %).

Table 3. Effect of nitrogen and bacterial applications on technological yield values

Technological sugar yield (%)					
Bacterium	**Nitrogen (N)**				**Average**
	N0	**N1**	**N2**	**N3**	
B0	17.99	18.48	18.21	17.91	18.15
B1	17.79	18.16	18.22	17.82	18.00
B2	18.08	18.54	18.30	18.40	18.33
Average	17.95	18.39	18.24	18.04	

Differences between applications are not significant.

According to the research data conducted on sugar beets, it has been found that the presence of refined sugar in sugar beets varies between 14.74 % and 15.20 % as a result of compound fertilizer applications (Pişkin, 2021). The study found that *Azotobacter biopriming* in sugar beet reduced germination (the time it takes for seeds to sprout) by 34.44 % and increased viability (the percentage of seeds that germinate) by 90.99 % (Kerečki et al., 2022).

3.3. Refined sugar yield

The results for sugar beet refined sugar yield (kg da^{-1}) are presented in Table 4. Statistical analysis revealed significant effects ($p<0.01$) for nitrogen dose (N), bacterial combination (B), and their interaction on sugar yield. When nitrogen fertilizer was applied without bacterial inoculation, the highest yield (1303.00 kg da^{-1}) was obtained with the highest nitrogen dose (N_3). Control group (479.00 kg da^{-1}) and the lowest nitrogen dose (N_1) yielded the least (490.20 kg da^{-1}). Under conditions where only bacterial inoculants were applied (no added nitrogen fertilizer), the highest sugar yield (985.40 kg da^{-1}) was observed with B_2 treatment. Conversely, the control group (B_0, no bacteria or nitrogen) exhibited the lowest yield (479.00 kg da^{-1}). The analysis of interaction effects revealed that the B_1 + N_3 treatment produced the highest sugar yield (1444.00 kg da^{-1}). The lowest yield values were realized in the interactions B_0 + N_0 (479.00 kg da^{-1}), B_1 + N_0 (501.90 kg da^{-1}), B_0 + N_1 (490.20 kg da^{-1}), B_2 + N_1 (565.70 kg da^{-1}) within the same group. These findings suggest that B_1 may be more effective in promoting sugar yield when used in conjunction with increasing nitrogen fertilizer application. Conversely, B_2 appears to be more beneficial for sugar yield in the absence of additional nitrogen fertilizer.

Table 4. Effect of nitrogen and bacterial applications on rafined sugar yield values

Bacrerium	Refined sugar yield (kg da⁻¹) Nitrogen (N) N0	N1	N2	N3	Average
B0	479.00 g	490.20 g	901.10 e	1303.00 b	793.20 B
B1	501.90 g	900.40 e	1149.00 c	1444.00 a	998.70 A
B2	985.40 d	565.70 g	795.80 f	837.30 ef	796.00 B
Average	655.40 C	652.10 C	948.60 B	1195.00 A	
LSD %1 B			41.42		
LSD %1 N			47.83		
LSD %1 B+N			82,84		

**Significant at $p<0.01$; Lowercase letters indicate the level of significance between applications, and uppercase letters indicate the level of significance between averages.

Inoculating sugar beet seeds with a mixture of rhizobacteria (*Azospirillum lipoferum, Azotobacter chroococcum, Bacillus polymyxa*, and *Klebsiella pneumoniae*) or with proline and *Bacillus polymyxa* bacteria was found to be more effective in increasing sugar yield than applying chemical nitrogen fertilizer (Mohamed et al., 2012). Sugar beet inoculated with *Azotobacter chroococcum* exhibited increased white sugar yield and enriched sugar content compared to the control group. These findings suggest the possibility of reducing chemical nitrogen fertilizer application in sugar beet through bacterial inoculation (Mrkovački, 2002). A combination of *Burkholderia* spp., *B. polymyxa*, and *Pseudomonas* spp. bacteria was applied to sugar beet and resulted in a 7.8 % increase in sugar yield (Çakmakçı, 2005). A study conducted in various locations across Poland investigated the effects of Azoter, a biofertilizer containing *Azotobacter chroococcum, Azospirillum brasilense*, and *Bacillus megaterium*, on sugar beet parameters. The study reported no significant reduction in biological or pure sugar yield, while chemical fertilizer use decreased by 30 % (Artyszak and Gozdowski, 2020). In a study using PGPR on sugar beet, the highest sugar yield was found in BM-Coton-Plus (1244.404 kg da⁻¹) and the lowest sugar yield was found in BM-Megaflu (1075.316 kg da⁻¹) (Çınar, 2021). Sugar beet plants were inoculated with a mixture of biofertilizer (rhizobacterin + phosphorin), and an increase in sugar yield was observed (Amin et al., 2013).

3.4. Digestible sugar

The results for beet digestible sugar value (%) are presented in Table 5. Nitrogen fertilizer application alone did not produce statistically significant differences in digestible sugar value. When only nitrogen was applied, the digestible sugar value was between (N_1) (19.71 %) and N_3 (19.27%). Statistical analysis revealed significant differences ($p < 0.05$) between B_1 and B_2 treatments in terms of digestible sugar value. Under conditions where only bacterial inoculants were applied (no added nitrogen fertilizer), the highest digestible sugar value (19.52 %) was observed with B_2 treatment. Conversely, the B_1 treatment resulted in the lowest value (19.01 %). The analysis of interaction effects between bacterial inoculants and nitrogen doses showed no statistically significant differences. When the interactions were analyzed, it was observed that the values were in the range of $B_2 + N_1$ (19.78 %) and $B_1 + N_3$ (19.05 %).

Table 5. Effect of nitrogen and bacterial applications on digestible sugar values

Bacterium	Digestible sugar value (%) Nitrogen (N) N0	N1	N2	N3	Average
B0	19.27	19.71	19.56	19.27	19.45 AB
B1	19.01	19.42	19.58	19.05	19.27 B
B2	19.52	19.78	19.57	19.75	19.66 A
Average	19.27	19.64	19.57	19.36	
LSD %5 B			0.3099		

* Significant at $p<0.05$; Lowercase letters indicate the level of significance between applications, and uppercase letters indicate the level of significance between averages.

PGPR bacteria were applied to sugar beet, and the digestion sugar rate was significantly affected by bacterial applications. The highest digestive sugar rate was 17.76 %, the lowest value was 16.24 % (Şimşek et al., 2021). PGPR strains increased enzymatic digestible sugar content from 15.623 % to 17.139 % (Çınar and Ünay, 2021). Multi-featured bacterial inoculations promote sugar content and plant growth (Karagöz et al., 2018). Sugar beet yield and quality characteristics were investigated, and the digestion sugar value was found to be between 13.87 % and 17.21 % (Ertürk, 2019). Chemical fertilizer application can increase sugar beet yield, but it can also reduce the sugar content of the beets (Draycott and Christenson, 2003).

3.5. Dry matter

The results for beet dry matter content (%) obtained at the end of the experiment are presented in Table 6. When nitrogen doses are applied alone the differences between the average dry matter contents of the parcels are statistically insignificant. When only nitrogen doses were applied, dry matter content was determined between N_0 (26.40 %) and N_3 (25.82 %). Statistical analysis revealed significant differences ($p<0.05$) between the average dry matter content of plots treated with B_1 and B_2 inoculants. Under conditions where only bacterial inoculants were applied, beet dry matter content showed a decreasing trend: control group (26.40 %), B_2 (26.06 %), B_1 (25.62 %). The analysis of interaction effects between rhizobacteria and nitrogen dose revealed no significant differences. It was seen that the interaction values were in the range of $B_2 + N_1$ (26.48 %) and $B_1 + N_3$ (25.25 %).

Table 6. Effect of nitrogen and bacterial applications on dry matter content

Bacterium	Dry matter content (%) Nitrogen (N) N0	N1	N2	N3	Average
B0	26.40	26.37	26.03	25.82	26.15 A
B1	25.62	26.05	25.99	25.25	25.73 B
B2	26.06	26.48	26.25	26.41	26.30 A
Average	26.03	26.30	26.09	25.83	
LSD %5 B			0.3710		

* Significant at p<0.05; Lowercase letters indicate the level of significance between applications, and uppercase letters indicate the level of significance between averages.

Plant growth-promoting rhizobacteria (PGPR) can support intensive dry matter accumulation, nutrient availability, and efficient sugar transport in sugar beet (Cardoso et al., 2017). *Azotobacter chroococcum* isolates increased dry matter content in two different sugar beet varieties, but the extent of this increase varied between the varieties (Mrkovački, 1997). Nitrogen was applied at four different fertilizer doses (0, 50, 100, and 150 kg ha^{-1}) to see the effect on sugar beet yield and quality criteria. The study observed a decrease in dry matter ratio with increasing fertilizer doses (Demirhan, 2011). Sugar beet plants were inoculated with different PGPRs, and the highest dry matter ratio was observed with the BMCoton-Plus application (21.423 %), while the lowest was in the control group (19.523 %) (Çınar and Ünay, 2021). Sugar beet quality analysis revealed that the highest dry matter ratio was 17.20 % and the lowest was 16.94 % (Turgut, 2012).

3.6. Brix

The results for beet brix value (%S) are presented in Table 7. According to the Duncan test, the effects of nitrogen doses, bacterial applications and interactions on brix values were found to be statistically insignificant. It was observed that when only nitrogen fertilizer was applied, the brix values were in the range of N_1 (23.83 %) and N_3 (23.50 %). When only bacteria was applied, the brix value was detected in the range of B_1 (23.83 %) and B_0 (23.53 %). When the effects of the interactions were analyzed, they were found to range from $B_2 + N_1$ (24.03 %) to $B_1 + N_3$ (23.53 %).

Table 7. Effect of nitrogen and bacterial applications on brix values

Brix value (%S)					
Bacterium	Nitrogen (N)				Average
	N0	N1	N2	N3	
B0	23.53	23.83	23.70	23.50	23.64
B1	23.83	23.63	23.70	23.53	23.68
B2	23.63	24.03	23.83	23.70	23.80
Average	23.67	23.83	23.74	23.58	

Differences between applications are not significant.

Brix is a measure of the amount of dissolved dry matter in water, primarily sucrose, in sugar beet juice. As the concentration of sucrose increases, so do both the brix value and the amount of total dry matter. A study investigating sugar beet quality parameters reported maximum and minimum brix values of 23.0 % and 16.2 %, respectively (Şanlı et al., 2023). Sugar beet quality parameter studies have reported brix values ranging from 17.60 % to 13.20 % (Oad et al., 2001). In the study where the effect of rhizobacteria applications on the agronomic properties of beet was evaluated, it was stated that the brix ratio varied between 21.83-24.96 % (Kutlusoy, 2019).

3.7. Conductivity

The results for sugar beet conductivity (µs cm^{-1}) measured at the end of the experiment are presented in Table 8. Statistical analysis revealed significant effects ($p< 0.05$ for bacteria, $p<0.01$ for nitrogen dose and interaction) on conductivity values. When nitrogen fertilizer was applied without bacterial inoculation, the highest value (205.70 µs cm^{-1}) was measured with the highest nitrogen dose (N_3). When only nitrogen doses were applied, the lowest value was determined as N_2 (184.70 µs cm^{-1}). When only bacterial inoculants were applied, the highest beet conductivity value (193.30 µs cm^{-1}) was observed with B_1 treatment. The lowest conductivity value was B_0 (188.00 µs cm^{-1}). The analysis of interaction effects revealed that the highest values within the interaction group were $B_2 + N_1$ (203.30 µs cm^{-1}) and $B_1 + N_1$ (201.00 µs cm^{-1}). Interestingly, both these treatments involved the lowest nitrogen dose (N_1). The lowest beet conductivity value in interactions was measured as $B_1 + N_2$ (170.30 µs cm^{-1}).

Table 8. Effect of nitrogen and bacterial applications on the conductivity values

Conductivity value (µs cm $^{-1}$)					
Bacterium	Nitrogen (N)				Average
	N0	N1	N2	N3	
B0	188.00 de	188.30 d	184.70 de	205.70 a	191.70 A
B1	193.30 bcd	201.00 abc	170.30 f	181.30 def	186.50 B
B2	189.00 cd	203.30 ab	191.00 cd	176.00 ef	189.80 AB
Average	190.10 B	197.60 A	182.00 C	187.70 BC	
LSD %5 B			4.12		
LSD %1 N			6.48		
LSD %1 B+N			11,22		

**Significant at p<0.01;* Significant at p<0.05; Lowercase letters indicate the level of significance between applications, and uppercase letters indicate the level of significance between averages.

A study investigating the effects of rhizobacterial applications on yield and quality criteria in sugar beet found electrical conductivity values ranging from 380.3 µS cm^{-1} to 290.3 µS cm^{-1} (Kutlusoy, 2019). In addition to providing nutrients to plants, plant growth-promoting rhizobacteria (PGPRs) promote plant growth, increase plant yield, contribute to the reduction of chemical fertilizer use, and protect plants from drought, salt, and heavy metal stress (Kumar, 2019). Plant growth-promoting rhizobacteria (PGPRs) increase agricultural yield and improve the quality characteristics of sugar beet by affecting its physiological properties (Meng et al., 2016).

3.8. α-Amino nitrogen

The results for sugar beet α-amino nitrogen (α-N) content (%) at the end of the experiment are presented in Table 9. Statistical analysis revealed significant effects of the treatments ($p<0.01$) on α-N values. When nitrogen fertilizer was applied alone, the highest α-N value was obtained with the highest nitrogen dose N_3 (1.68 %) and the lowest value with the control group (0.37 %). This indicates a direct and undesirable increase in α-N values with increasing nitrogen application rates. When only bacterial inoculants were applied, the highest α-N value was observed with the B_1 treatment (0.69 %), while the control group exhibited the lowest value (0.37 %). Lower α-N content is desirable for higher sugar crystallization from beets. In this context, the B_2 treatment (0.60 %) appears to be more advantageous in terms of α-N management with rhizobacteria application. Analysis of interaction effects revealed that the $B_1 + N_2$ (1.92 %) treatment produced the highest α-N value, while the $B_2 + N_2$ (0.69 %) treatment resulted in the lowest value.

Table 9. Effect of nitrogen and bacterial applications on α-Amino-N values

α-Amino nitrogen value (%)					
Bacterium	**Nitrogen (N)**				**Average**
	N0	**N1**	**N2**	**N3**	
B0	0.37 d	0.75 c	1.35 b	1.68 a	1.04 A
B1	0.69 c	0.84 c	1.92 a	1.18 b	1.16 A
B2	0.60 cd	0.71 c	0.69 c	0.76 c	0.69 B
Average	0.55 C	0.77 B	1.32 A	1.21 A	
LSD %1 B			0.1312		
LSD %1 N			0.1515		
LSD %1 B+N			0.2624		

**Significant at $p<0.01$; Lowercase letters indicate the level of significance between applications, and uppercase letters indicate the level of significance between averages.

Sugar content is a critical quality factor in sugar beet. However, increasing nitrogen fertilizer application rates can lead to higher levels of molasses-forming substances, which in turn decrease sugar levels (Franzen, 2004; Moore et al., 2009). The application of four different nitrogen fertilizer doses (0, 50, 100, and 150 kg N ha^{-1}) to sugar beet resulted in a direct and proportional increase in amino nitrogen (harmful nitrogen) accumulation, with higher nitrogen doses leading to higher levels of amino nitrogen (Demirhan, 2011). When *Azotobacter chroococcum* and *Bacillus megaterium* inoculum were applied to sugar beet, it was determined that there were increases in harmful nitrogen values in sugar beet (El-Dsouky, 2004). Studies on the quality parameters of sugar beet have shown that the harmful nitrogen content ranges from 0.043 % to 0.087 % (Özcan, 2018).

3.9. Sodium

The results for sugar beet sodium content (%) at the end of the experiment are presented in Table 10. Statistical analysis revealed significant effects ($p<0.01$) of treatments on sodium content. When nitrogen fertilizer was applied alone, the control group again displayed the highest sodium value (1.657 %). This was followed by decreasing values with N_3 (0.5700 %), N_1 (0.4967 %), and N_2 (0.4733 %) in decreasing order, indicating a possible dilution effect of higher nitrogen application on sodium concentration. When only bacterial inoculants were applied, the control group exhibited the highest sodium value (1.657 %). This was followed by a decrease in values with B_1 (0.6267 %) and B_2 (0.5233 %) treatments, suggesting a potential role of these bacterial inoculants in reducing sodium content. Analysis of interaction effects revealed that the $B_2 + N_2$ treatment resulted in the highest sodium value (0.6967 %), while the $B_1 + N_2$ treatment led to the lowest value (0.4700 %). These findings suggest that rhizobacteria may be effective in mitigating salt stress in sugar beet plants, potentially through mechanisms related to sodium content reduction.

Table 10. Effect of nitrogen and bacterial applications on sodium (Na) content

Sodium content (Na) (%)					
Bacterium	**Nitrogen (N)**				**Average**
	N0	**N1**	**N2**	**N3**	
B0	1.657 a	0.4967 bc	0.4733 c	0.5700 bc	0.7992 A
B1	0.6267 bc	0.5433 bc	0.4700 c	0.5967 bc	0.5592 B
B2	0.5233 bc	0.4900 bc	0.6967 b	0.4833 bc	0.5483 B
Average	0.9356 A	0.5100 B	0.5467 B	0.5500 B	
LSD %1 B			0.0962		
LSD %1 N			0.1112		
LSD %1 B+N			0.1926		

**Significant at $p<0.01$; Lowercase letters indicate the level of significance between applications, and uppercase letters indicate the level of significance between averages.

Biotic and abiotic stress factors such as salt stress in the sugar beet growing period also negatively affect beet yield and quality (Ober and Rajabi, 2011). Plant growth-promoting rhizobacteria (PGPRs) have been shown to protect plants from drought, salt, and heavy metal stresses, enhance nutrient uptake, promote plant growth, increase crop yield, and reduce the need for chemical fertilizers (Kumar, 2019). When *Azotobacter chroococcum* and *Bacillus megaterium* vaccines were applied to sugar beet, increases in sodium values were detected (El-Dsouky, 2004). Previous studies have shown that the sodium content in sugar beet can vary between 0.99 % and 1.53 % (Türkmen, 2019).

3.10. Potassium

The results for sugar beet potassium content (%) obtained at the end of the experiment are presented in Table 11. Statistical analysis revealed no significant effects ($p>0.05$) of the treatments (nitrogen doses, bacterial inoculants, and their interaction) on potassium content. When only nitrogen dose was applied, potassium values were observed to be between N_3 (3.25 %) and N_2 (3.01 %). When only bacterial vaccines were administered, potassium content followed in the B_1 (3.40 %) and B_2 range (3.14 %). In the interaction group, potassium values were observed in the range of $B_1 + N_1$ (3.26 %) and $B_1 + N_3$ (2.67 %).

Table 11. Effect of nitrogen and bacterial applications on potassium (K) content

Potassium content (K) (%)					
Bacterium	**Nitrogen (N)**				**Average**
	N0	**N1**	**N2**	**N3**	
B0	3.22	3.24	3.01	3.25	3.18
B1	3.40	3.26	2.97	2.67	3.08
B2	3.14	3.16	3.11	3.12	3.13
Average	3.25	3.22	3.03	3.02	

Differences between applications are not significant.

The sugar content in beets is an important quality factor. While beet is being processed not all of the sucrose can crystallize and some of it passes into molasses, reducing sugar yield. This situation, which reduces sugar yield in beet, is caused by alpha amino nitrogen (harmful N), potassium and sodium (Manh and Hoffmann, 2001). Increases in potassium values were detected when Azotobacter chroococcum and Bacillus megaterium inoculum was applied to sugar beet (El-Dsouky, 2004). It has been determined that the amount of potassium, one of the quality characteristics of sugar beet, increases linearly with the increase in fertilizer doses (Demirhan, 2011).

3.11. Juice purity

The results for sugar beet juice purity (Q) obtained at the end of the experiment are presented in Table 12. Statistical analysis using the Duncan test revealed no significant effects ($p>0.05$) of the treatments (nitrogen doses, bacterial inoculants, and their interaction) on juice purity. Juice purity values were measured in the range of N_3 (91.10 %) and N_0 (90.26 %) when only nitrogen doses were applied. As a result of bacterial application conditions alone, fruit juice purity was observed in the range of B_2 (90.64 %) and B_0 (90.26 %). When looking at the interactions, it was observed that the values were in the range of $B_2 + N_3$ (91.22 %) and $B_1 + N_3$ (90.11 %).

Table 12. Effect of nitrogen and bacterial applications on juice purity values

Juice purity (Q) (%)					
Bacterium	**Nitrogen (N)**				**Average**
	N0	**N1**	**N2**	**N3**	
B0	90.26	90.65	90.44	91.10	90.61
B1	90.26	90.72	90.21	90.11	90.33
B2	90.64	90.32	90.66	91.22	90.71
Average	90.39	90.56	90.44	90.81	

Differences between applications are not significant.

Previous research has shown that high fertilizer doses can negatively impact sugar beet quality, as evidenced by a decrease in juice purity (Demirhan, 2011). Previous studies have shown that juice purity in sugar beet can vary between 86.20 % and 84.14 % (Turgut, 2012). Another study, the highest juice purity rate was found to be 81.18% and the lowest was 78.59 % (Alfaig, 2011). The research conducted on sugar beet quality values, the highest sap purity value was found to be 92.24 % and the lowest was 82.29 % (Stevanato, 2010).

3.12. Polar

The results for sugar beet polar sugar content (%) obtained at the end of the experiment are presented in Table 13. Statistical analysis revealed no significant effects ($p>0.05$) of the treatments (nitrogen doses, bacterial inoculants, and their interaction) on polar sugar content. When only nitrogen doses were applied polar sugar content was detected between N_1 (21.61 %) and N_0 (21.24 %). In bacterial treatments alone, polar sugar content ranged from B_1 (21.97 %) to B_0 (21.24 %). When the values of the interactions were examined, they were observed to be in the range of $B_2 + N_2$ (22.31 %) and $B_1 + N_3$ (20.79 %).

Table 13. Effect of nitrogen and bacterial applications on polar values

Polar sugar content (%)					
Bacterium	**Nitrogen (N)**				**Average**
	N0	**N1**	**N2**	**N3**	
B0	21.24	21.61	21.44	21.47	21.44
B1	21.97	21.44	21.47	20.79	21.42
B2	21.75	21.71	22.31	21.62	21.85
Average	21.65	21.59	21.74	21.29	

Differences between applications are not significant.

Polar sugar is the term used to describe the presence of sugar measured in beet juice. In various studies on sugar beet, the highest polar value reported was 14%, while the lowest was 10.20% (Oad et al., 2001). The polar ratio of sugar beet was observed to be at most 16.91% and at least 14.84% (Çakmakcı and Oral, 1998). The polar value of sugar beet was determined as maximum 18.68% and minimum 15.95% (Toprak, 2010). The decrease in percentage values despite the increase in sugar content in beet may be attributed to variety, climate, and soil characteristics (Kristek, 2004).

4. Conclusions

Nitrogen is a crucial plant nutrient, and its deficiency can lead to significant yield losses in agriculture. Consequently, nitrogen fertilizers are widely used, but their chemical composition raises concerns for human health, environmental integrity, and sustainability. This study aimed to investigate the effects of bacterial biofertilizers at varying nitrogen doses on sugar beet yield and quality parameters. Our research explored the potential of biofertilizers to reduce reliance on chemical fertilizers within the framework of sustainable and healthy agricultural practices. Research results revealed that bacterial biofertilizers have a significant impact on sugar beet yield and quality, both when used together with chemical fertilizers and when used alone. These results suggest that biofertilizer application can enhance productivity and quality while potentially reducing the amount of chemical fertilizer needed per unit area. This approach contributes to a healthier agricultural system. Based on these findings, we recommend the use of biofertilizers to sugar beet producers.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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