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Research Article

Effects of *Bacillus mojavensis* on Growth and Nutrient Responses of Arugula (*Eruca vesicaria*)

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Abstract: The present research aims to assess the biochemical characteristics and environmental stress adaptation of the *Bacillus mojavensis* AOB29 strain, along with its influence on the growth and nutrient uptake of arugula (*Eruca vesicaria*). The *B. mojavensis* AOB29 strain used in this study was isolated from soil samples collected from an agricultural field. The morphological, physiological, metabolic, and environmental characteristics of the isolate were evaluated through Gram staining, spore staining, motility assessment, various enzyme activity tests, BIOLOG GEN III analysis, antibiotic susceptibility testing, and tolerance assays under different salt, heavy metal, and pH conditions. In addition, its effect on plant growth was investigated through pot experiments. Pot experiments demonstrated that the application of *B. mojavensis* AOB29 resulted in significant improvements in plant growth compared to the control group. In particular, the treatment led to a 57.8% increase in dry biomass and a 40.9% increase in fresh biomass relative to the control. Nutrient analyses revealed increases in potassium, magnesium, phosphorus, zinc, and manganese levels, while decreases in calcium, iron, and copper levels were detected. In conclusion, the *B. mojavensis* AOB29 strain was found to possess the potential to promote plant growth, enhance nutrient uptake, and improve tolerance to environmental stress conditions. These findings indicate that this strain may be considered for use as a biofertilizer or biocontrol agent in agricultural applications.

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1. Introduction

The rapid growth of the global population, together with increasing concerns regarding environmental sustainability and soil degradation, has intensified the demand for agricultural practices that maintain high productivity while minimizing ecological impacts. Conventional farming systems

relying heavily on chemical fertilizers and pesticides have been associated with soil quality deterioration, disruption of beneficial microbial communities, and environmental contamination, thereby threatening long-term agricultural sustainability (Rouphael and Colla, 2020). As a result, biologically based strategies have gained considerable attention as environmentally friendly alternatives for sustainable crop production.

Among these strategies, plant growth-promoting bacteria (PGPB) play a pivotal role due to their ability to enhance plant growth and resilience through multiple direct and indirect mechanisms. These mechanisms include phytohormone production, nutrient mobilization and solubilization, siderophore-mediated micronutrient acquisition, and mitigation of abiotic stresses such as salinity and nutrient deficiency (Backer et al., 2018; Kumar et al., 2020). Within this framework, bacteria belonging to the genus *Bacillus* are widely recognized as highly effective PGPB owing to their capacity for endospore formation, broad environmental adaptability, and strong rhizosphere colonization ability, which collectively ensure functional stability under diverse soil and climatic conditions (Fira et al., 2018).

Recent research has highlighted the importance of potassium-solubilizing bacteria in sustainable agriculture, as potassium is a key macronutrient involved in enzyme activation, osmoregulation, photosynthesis, and stress tolerance in plants. Despite its abundance in soils, a substantial proportion of potassium exists in insoluble mineral forms that limit its availability to plants. Potassium-solubilizing *Bacillus* spp. overcome this limitation by secreting organic acids and protons that mobilize potassium from mineral matrices, thereby increasing potassium bioavailability in the rhizosphere (Etesami et al., 2017; Sattar et al., 2019). Nevertheless, the functional performance of potassium-solubilizing *Bacillus* strains under crop-specific production systems remains insufficiently characterized, particularly for leafy vegetable crops.

Arugula (*E. vesicaria*), a fast-growing leafy vegetable of the Brassicaceae family, is widely consumed due to its short cultivation cycle and high nutritional value. Efficient nutrient acquisition is essential for maximizing yield and quality in arugula production, especially under controlled cultivation conditions. While recent studies have demonstrated that PGPB significantly enhance plant biomass accumulation and nutrient uptake in various crops, information regarding the application of *B. mojavensis* in arugula cultivation remains limited (Backer et al., 2018; Kumar et al., 2020).

In this context, the present study aimed to evaluate the plant growth-promoting potential of the *B. mojavensis* AOB29 strain under controlled pot conditions. The effects of bacterial inoculation on fresh and dry biomass production, tissue-specific growth responses, and macro- and micronutrient uptake in arugula plants were systematically investigated. By integrating growth-related and nutritional parameters, this study provides new insights into the functional role of *B. mojavensis* as a promising bioinoculant for sustainable vegetable production.

2. Materials and Methods

Soil samples were collected from a depth of 20 cm at the location Kahramanmaraş Province, Onikisubat/Kılavuzlu (WGS 84 ×373759 Y 364841 Z 579), brought to the laboratory, and air-dried in the shade. For potassium solubilization tests, Aleksandrov agar and Aleksandrov broth supplemented with mica were used as growth media. The plates were incubated at 35 ± 2 °C for 48 hours, and the resulting colonies were transferred to appropriate media and stored at 4 °C for subsequent analyzes (Akkaya et al., 2025).

2.1. Morphological and biochemical characterization

The bacterial strain used in this study (*B. mojavensis* AOB29) was selected from strains obtained under the Scientific Research Project No. 2022/10 2S at Kahramanmaraş Sutcu Imam University. For the identification of the selected bacterial isolates, microscopic tests such as Gram staining, motility, and spore formation, as well as examination of culture morphology, were performed (Akkaya et al., 2025). The biochemical and metabolic characteristics of the bacterial strains were determined using the MicroStation™/MicroLog (Biolog) system (Luo et al., 2016; Hemdan et al., 2019).

2.2. Determination of selected enzymatic activities

The enzymatic potential of the selected strain was assessed using selective media specific to the target enzymes. All analyses were performed after overnight incubation at 35 ± 2 °C and evaluated using appropriate staining or observation methods. Amylase activity was determined by streaking the isolates onto starch-containing agar plates, followed by iodine staining and observation of clear hydrolysis zones around the colonies, indicating starch degradation (Singh et al., 2016). Carboxymethyl cellulase (CMCase), xylanase, and avicelase activities were evaluated on agar media supplemented with carboxymethyl cellulose (CMC), xylan, and avicel, respectively, under high-salt (10% NaCl) and alkaline (pH 10.0) conditions. After incubation, the plates were flooded with 0.1% Congo red solution and subsequently rinsed with 1 M NaCl. The formation of yellowish clearance zones around the colonies was considered indicative of positive enzymatic activity. Protease activity was assessed on casein-containing agar media, and the presence of clear zones surrounding the colonies was regarded as evidence of proteolytic activity (Gupta et al., 2017).

2.3. Determination of metal and salt tolerance

The tolerance of the bacterial isolate to heavy metals and salt stress was evaluated using agar-based assays. For heavy metal tolerance testing, Mueller–Hinton Agar (MHA) was supplemented with increasing concentrations (100, 200, 400, 800, and 1600 mg L⁻¹) of CoCl₂.2H₂O, NiCl₂.6H₂O, CuSO₄.5H₂O, FeSO₄.7H₂O, ZnCl₂, AgNO₃, and Pb(NO₃)₂. The agar plate method was employed, as it is a reliable and widely accepted approach for assessing microbial resistance to heavy metals. Following incubation, bacterial growth was monitored, and tolerance was determined based on the ability of the isolate to grow at increasing metal concentrations (Gupta and Diwan, 2017). Three replicate plates were prepared for each metal concentration, and bacterial cultures were streaked aseptically. Plates were incubated at 35 °C for 24–48 h. Following incubation, plates showing visible colony growth were recorded as “positive,” while the lowest metal concentration that completely inhibited bacterial growth was defined as the Minimum Inhibitory Concentration (MIC). Salt tolerance was determined on Nutrient Agar (NA) medium containing different NaCl concentrations (0.5%, 1%, 2%, 4%, 8%, 16%, 20%, and 25%). The concentrations were prepared by taking into account the inherent salt content of the NA medium. Plates were incubated at 35 ± 2 °C for 24 h, and bacterial growth was evaluated based on colony formation. The highest NaCl concentration at which visible growth occurred was considered the MIC value (Olur, 2021).

2.4. Assessment of antimicrobial resistance

Antimicrobial activity was evaluated using the agar diffusion method. From the standard inoculum solution of the bacterial strains, 0.1 mL was spread onto Mueller-Hinton agar plates. Antibiotic disks used included Ampicillin (AMC 30 µg), Linezolid (LNZ 30 µg), Cefoxitin (FOX 30 µg), Penicillin-G (P 10 µg), and Novobiocin (NV 30 µg). Following placement of the disks on the agar, the plates were incubated overnight at 35 ± 2 °C. After incubation, the diameters of the inhibition zones (mm) against the antibiotics were measured from the edge of the zone to the edge of the agar. Based on these measurements, the susceptibility or resistance of the bacterial strains to the respective antibiotics were determined. The interpretive criteria for susceptibility were established according to the Clinical and Laboratory Standards Institute guidelines (CLSI, 2023).

2.5. Preparation of bacterial inoculum

The bacterial strain obtained from stock cultures was inoculated into Nutrient Broth and incubated overnight at 35 ± 2 °C and 120 rpm using a New Brunswick Scientific shaker. Following incubation, the culture was centrifuged to pellet the cells, and the pellet was resuspended in distilled water and adjusted to a turbidity equivalent to 1.0 McFarland standard (3×10^8 CFU mL⁻¹). From this suspension, a 6 mL working sample was prepared.

2.6. Pot experiment design

Arugula seeds were sown in pots (25 × 22 cm) containing 2 kg of soil, with three replicates per treatment. Each pot was inoculated with 6 mL of bacterial suspension prepared to a turbidity of 1.0

McFarland (3×10^8 CFU mL⁻¹). The same procedures were applied to the control group. Soil samples were collected from control pots both before inoculation and after harvest. The experiment was conducted in the greenhouse of the Soil Science and Plant Nutrition Department at Kahramanmaraş Sutcu Imam University. For inoculation, the AOB29 culture stored at +4 °C was used; the inoculated soil was incubated overnight at 35 °C. All pots, including controls, were irrigated to maintain soil at field capacity throughout the experiment. Arugula plants were harvested after 10 weeks. Following harvest, roots were washed with distilled water, and parameters including fresh and dry weights of shoots, total plant height, root length, and fresh and dry weights of roots were measured. Samples were dried at 65°C for 48 hours until constant weight was reached, then ground and prepared for analysis.

2.7. Soil and plant analyzes

The soil used in this study was analyzed for pH and electrical conductivity using a pH meter with the saturated paste method (Black, 1965; Richard, 1954). Lime content was determined via a Scheibler calcimeter (Gülçur, 1974), while organic matter was quantified using the Walkley-Black method (Nelson and Sommers, 1996). Exchangeable cations were extracted with 1 N ammonium acetate (Helmke and Sparks, 1996), and available phosphorus was assessed according to the Olsen procedure (Kuo, 1996).

Leaf samples were subjected to block digestion with a mixture of nitric acid (HNO₃) and perchloric acid (HClO₄), following the protocol described by Jones and Case (1990), and the resulting digestates were filtered for subsequent analyses. Phosphorus concentrations were measured using the vanadomolybdophosphoric acid method (Kuo, 1996) with a UV spectrophotometer. Macro- and micronutrient levels, including K, Ca, Mg, Mn, Cu, Zn, and Fe, were determined using atomic absorption spectrophotometry (Agilent 240 AA)

2.8. Statistical analyses

Graphical representations and statistical analyses were performed using GraphPad Prism 10.4.2 (GraphPad Software, San Diego, CA, USA). Differences between the control and bacterial treatments were evaluated using an unpaired t-test. Statistical significance was set at $p < 0.05$. Significant differences are indicated by asterisks (*), and non-significant comparisons are denoted as “ns”.

3. Results

3.1. Characteristics of the experimental soil

The pH of the soils from the pots and sampling area, as determined by analyzes at the Soil Science Laboratory of the Faculty of Agriculture, Kahramanmaraş Sutcu Imam University, was found to be in the slightly alkaline range. Additionally, the soils exhibited low salinity and high lime content (Akkaya et al., 2025). The phosphorus and potassium concentrations of the experimental soil were determined as 4.55 mg kg⁻¹ and 221 mg kg⁻¹, respectively (Table 1)

Table 1. Characteristics of the soil used in the study

	pH %	OM %	EC µS cm ⁻¹	Lime %	P mg kg ⁻¹	K
Isolation soil	7.45	2.48	655	27.35	-	-
Experimental Soil	7.86	0.86	350	16.55	4.50	227

¹OM: Organik matter, EC: Electrical Conductivity.

The *B. mojavensis* AOB29 isolate formed white, opaque colonies with smooth margins. The colonies exhibited a mucoid appearance, and endospore formation was observed. The cells were Gram-positive, and the colony diameter was approximately 3 mm (Table 2).

Table 2. Colony morphological characteristics of *B. mojavensis* AOB29 isolates

Strain	Colony Color	Endospore	Mucoid	Size (mm)	Optical Appearance	Margin	Cell Wall Type
<i>B.mojavensis</i> AOB29	White	+	+	3	Opaque	Straight	Gr(+)

B. mojavensis AOB29, as determined by Biolog GEN III MicroPlate Analysis, exhibited broad metabolic versatility, utilizing various sugars, sugar alcohols, amino acids, and organic acids, grew in 1–8% NaCl and Lithium Chloride at pH 6, displayed resistance to several antibiotics (Nalidixic Acid, Vancomycin, Aztreonam, Lincomycin, Fusidic acid), and showed positive reactions in miscellaneous tests. including Gelatin, Tetrazolium dyes, and Tween, while some substrates and were compounds not metabolized (Table 3).

Table 3. Biochemical Characteristics of the isolate based on Biolog GEN III MicroPlate analysis

	Positive Reactions	Negative Reactions
Carbohydrates	Dextrin, D-Maltose, D-Trehalose, D-Cellobiose, Gentioibiose, Sucrose, D-Turanose, Stachyose, D-Raffinose, α -D-Lactose, D-Malibiose, β -Methyl-D-Glucoside, D-Salicin, N-Acetyl-D-Glucosamine, N-Acetyl- β -D-Mannosamine, N-Acetyl-D-Galactosamine, N-Acetyl-D-Neuraminic acid, α -D-Glucose, D-Mannose, D-Fructose, D-Galactose, , D-Fucose, D-Glucose 6-PO ₄ , D-Fructose 6-PO ₄ , %1sodium Lactate	3-Methyl glucose, L-Fucose, L-Rhamnose, Inosine
Sugar Alcohols	D-Sorbitol, D-Mannitol, D-Arabitol, myo-Inositol, Glycerol	Glycyl-L-Proline, L-Histidine
Amino Acids and Peptides	L-Alanine, L-Arginine, L-Aspartic Acid, L-Glutamic Acid, L-Pyroglutamic Acid, L-Serine, D-Aspartic Acid, Gelatin	–
Polymers	Pectin	p-Hydroxy-Phenylacetic acid, D-Galacturonic Acid Lactone, Methyl Pyruvate, D-Lactic Acid Methyl Ester,
Organic Acids	D-Galacturonic Acid, D-Gluconic Acid, D-Glucuronic Acid, Glucuronamide, Mucic Acid, Quinic Acid, D-Saccharic Acid, D-Malic Acid, L-Lactic Acid, Citric Acid, α -Keto-Glutaric Acid, Bromo-Succinic Acid, Propionic Acid, Acetic Acid, Formic Acid	pH 5 (–)
Growth Conditions	1%, 4%, 8% NaCl, Lithium Chloride; pH 6 (+)	Troleandomycin, Rifamycin SV, Minocycline, Niaproof 4,
Antibiotic Resistance	Nalidixic Acid, Vancomycin, Aztreonam, Lincomycin, Fusidic acid	γ -Aminobutyric acid, α -Hydroxybutyric acid,
Miscellaneous	Gelatin, Guanidine HCl, Tetrazolium violet, Tetrazolium blue, Tween, β -Hydroxy-D,L-butyric acid, α -Ketobutyric acid, Acetoacetic acid, Sodium butyrate, Sodium bromate, Potasyum Telurite	–

Salt tolerance tests of the *B. mojavensis* AOB29 strain demonstrated that the strain was able to grow well at NaCl concentrations ranging from 0 to 16%. However, no growth was observed in media containing 20% NaCl, indicating that the strain has a limited adaptation capacity to extremely high salt concentrations (Table 4).

Table 4. Colony growth of selected isolates at different NaCl concentrations

Strain	Salt tolerance %						
	0.5	1	2	4	8	16	20
<i>B.mojavensis</i> AOB29	+	+	+	+	+	+	–

To evaluate the heavy metal tolerance of the *B. mojavensis* AOB29 isolate, growth assays were performed at increasing concentrations of Co, Fe, Ni, and Pb, and positive growth was observed across all tested concentration ranges. Notably, the *B. mojavensis* AOB29 strain sustained growth at 400 ppm

Zn²⁺, 800 ppm Cu²⁺ and Ag⁺, and at the highest tested concentration of Co²⁺, Pb²⁺, Fe³⁺, and Ni (Table 5).

Table 5. Growth of the *B. mojavenensis* AOB29 strain at different concentrations of selected heavy metals

Metal Conc. (mg L ⁻¹)	CoCl ₂ ·6H ₂ O	FeSO ₄ ·7H ₂ O	CuSO ₄ ·5H ₂ O	AgNO ₃	ZnCl ₂	NiCl ₂ ·6H ₂ O	Pb(NO ₃) ₂
100	+	+	+	+	+	+	+
200	+	+	+	+	+	+	+
400	+	+	+	+	+	+	+
800	+	+	-	+	-	+	+
1600	+	+	-	+	-	+	+

Among the antibiotics tested, the bacterial strain *B. mojavenensis* AOB29 exhibited the narrowest inhibition zone against AMC30, with a diameter of 13.7 mm. The strain was found to be sensitive to FOX30, NV30, and P10, showing inhibition zone diameters of 32.5 mm, 29.0 mm, and 36.3 mm, respectively (Table 6, Figure 1). Based on the CLSI 2023 guidelines, the inhibition zone diameter observed for AMC30 was classified as intermediate (I). Since no inhibition zone diameter could be measured for LN30, it was excluded from further analysis.



Figure 1. Antibiotic inhibition zone.

Table 6. Antibiotic inhibition zones of *B. mojavenensis* AOB29

Strain	AMC30(mm)	NV30(mm)	FOX30(mm)	P10(mm)
<i>B. mojavenensis</i> AOB29	13,7	29	32,5	36,3

Susceptibility breakpoints were interpreted according to the CLSI (Clinical and Laboratory Standards Institute) 2023 guidelines: ampicillin (AMC30), no susceptibility criteria available; novobiocin (NV30), susceptible (S) ≥ 16 mm, intermediate (I) 13–15 mm, resistant (R) ≤ 12 mm; cefoxitin (FOX30), susceptible (S) ≥ 22 mm, intermediate (I) = 22 mm, resistant (R) ≤ 21 mm; and penicillin G (P10), susceptible (S) ≥ 30 mm, intermediate (I) = 29 mm, resistant (R) < 29 mm.

Enzymatic characterization of *B. mojavenensis* AOB29 revealed limited cellulolytic activity for CMCase (Kr: 7 mm, Zr: 25 mm), whereas Avicelase and Xylanase activities were not detected. Amylase activity was observed at moderate levels (Kr: 5 mm, Zr: 15 mm), while protease activity was markedly high (Kr: 15 mm, Zr: 22 mm) (Table 7).

Table 7. Selected enzymatic properties of the *B. mojavenensis* AOB29 strain

Strain	CMCase (Cd/Zd, mm)	Avicelase (Cd/Zd, mm)	Xylanase (Cd/Zd, mm)	Amylase (Cd/Zd, mm)	Protease (Cd/Zd, mm)
<i>B. mojavenensis</i> AOB29	7/25	0/0	0/0	5/15	15/22

Cd, colony diameter; Zd, zone diameter.

Application of *B. mojavenensis* AOB29 slightly increased root length compared with the control (9.3 cm vs. 8.0 cm), although the difference was not statistically significant ($p > 0.05$). In the control

group, mean total plant length was 18.0 cm. In contrast, plants treated with *B. mojavensis* AOB29 showed a significant increase in total plant length, reaching 20.7 cm, which corresponds to an approximately 15% increase relative to the control ($p < 0.05$) (Figure 2).

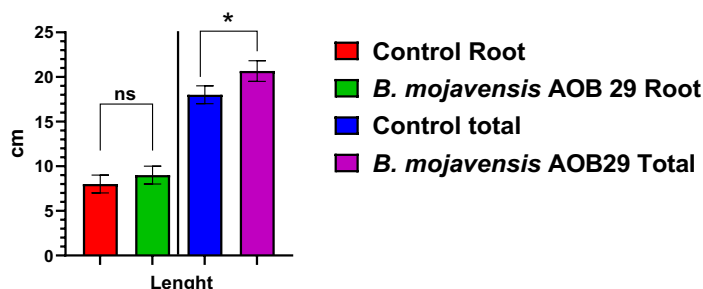


Figure 2. Growth parameters measured in arugula (*E. vesicaria*): root length and total plant length.

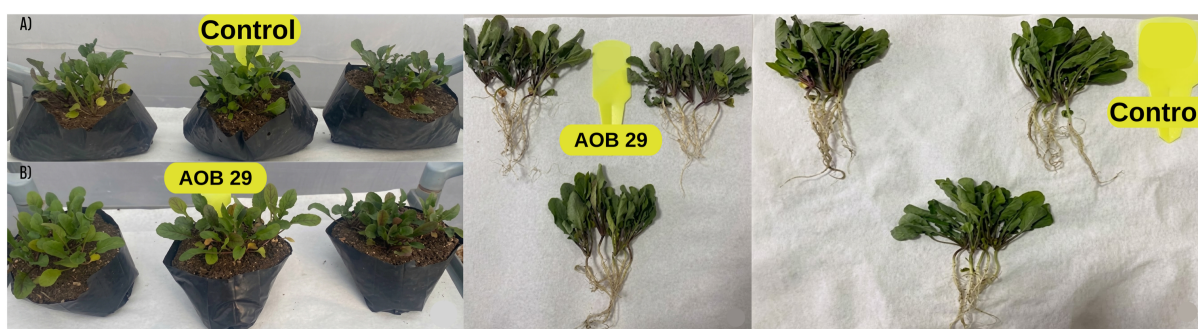


Figure 3. Growth of arugula (*E. vesicaria*).

The *B. mojavensis* AOB29 strain had a significant effect on biomass production of arugula plants ($p < 0.05$). Dry and fresh biomass were significantly higher in treated plants than in the control, with values of 2.21 and 1.40 g pot⁻¹ for dry biomass and 9.67 and 6.86 g pot⁻¹ for fresh biomass, respectively. Root, stem, and leaf biomass were also significantly higher in treated plants, reaching 0.73, 0.73, and 8.50 g pot⁻¹, compared with 0.51, 0.28, and 6.06 g pot⁻¹ in the control, respectively (Figure 3).

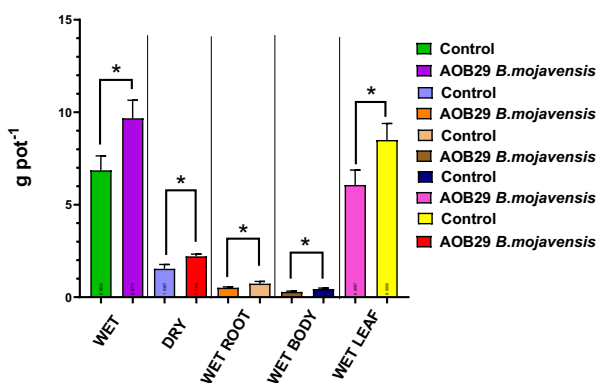


Figure 4. Biomass production of the arugula (*E. vesicaria*).

Evaluation of nutrient uptake revealed that plants treated with the *B. mojavensis* AOB29 strain showed a significant increase in potassium uptake compared with the control, with mean values of 60.03 and 37.8 mg pot⁻¹, respectively ($p < 0.05$). In contrast, calcium uptake was significantly lower in treated plants (18.0 mg pot⁻¹) than in the control (31.85 mg pot⁻¹). Changes in magnesium and phosphorus uptake were not statistically significant between treatments (Figure 4).

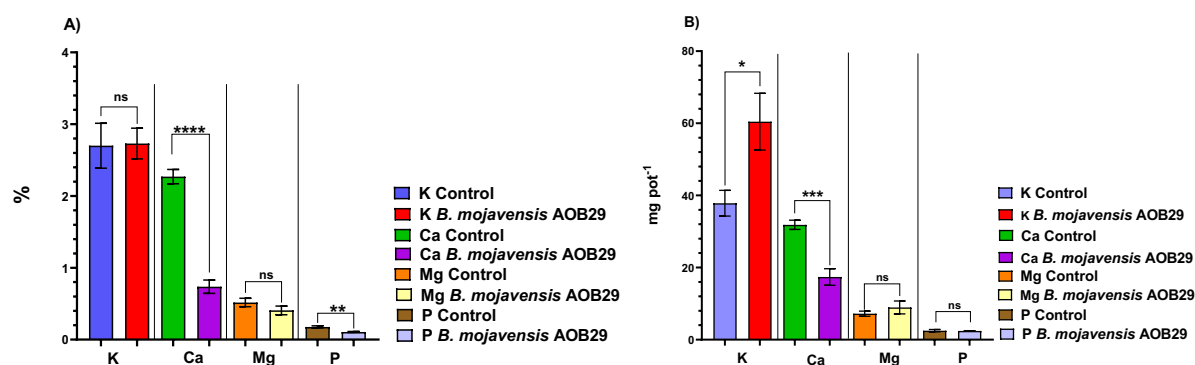


Figure 5. (A) Tissue macro-nutrient concentrations and (B) total macro-nutrient uptake in arugula (*E. vesicaria*).

Assessment of micronutrient concentrations in arugula plants indicated that application of *B. mojavensis* AOB29 was associated with a marked reduction in iron concentration, with mean values of 75.16 mg kg⁻¹ in treated plants compared with 194.8 mg kg⁻¹ in the control. Likewise, zinc, copper, and manganese concentrations were significantly lower in treated plants, with values of 35.7, 4.0, and 32.7 mg kg⁻¹, respectively, compared with 45.83, 8.1, and 36.3 mg kg⁻¹ in the control (Figure 5).

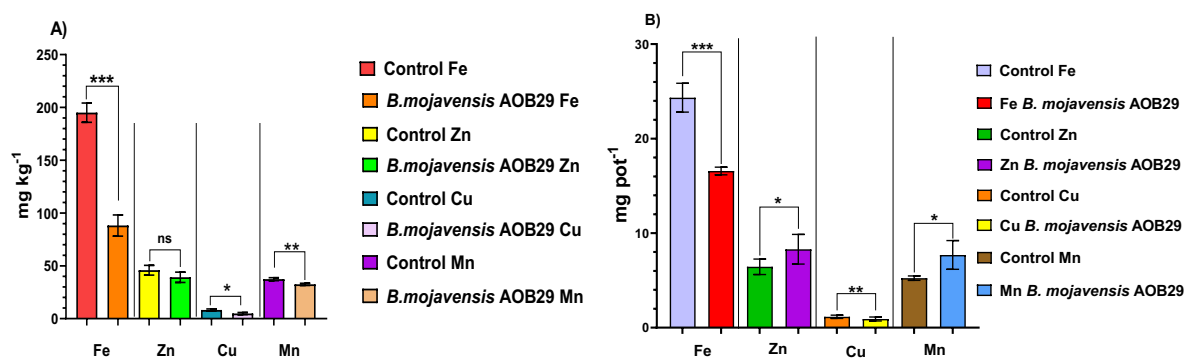


Figure 6. (A) Tissue micronutrient concentrations and (B) total micronutrient uptake in arugula (*E. vesicaria*).

Evaluation of micronutrient amounts removed by arugula plant biomass showed that application of *B. mojavensis* AOB29 was associated with a significant decrease in iron content, with values of 16.57 mg pot⁻¹ in treated plants compared with 24.33 mg pot⁻¹ in the control. In contrast, zinc and manganese contents were significantly higher in treated plants, reaching 8.31 and 7.69 mg pot⁻¹, respectively, compared with 6.44 and 5.24 mg pot⁻¹ in the control. No significant difference was observed in copper content between treatments.

4. Discussion

The *B. mojavensis* AOB29 isolate formed white, opaque colonies with smooth margins. The mucoid colony morphology, endospore formation, and Gram-positive cell structure observed are consistent with the morphological characteristics of *Bacillus* species reported by Logan and De Vos (2009), indicating tolerance to environmental stress conditions. Analysis of enzymatic activities showed substantial production of CMCase, amylase, and protease, whereas no avicelase or xylanase activity was detected. Previous studies by Gupta et al. (2017) and Demircioğlu and Ağca (2022) have reported that such enzymatic properties may contribute to the biological degradation of cellulose-containing wastes in soil.

The biochemical test results of the *B. mojavensis* AOB29 isolate indicate that the strain is capable of exhibiting resistance to high concentrations of heavy metal ions and possesses a tolerance to metal-induced stress. Notably, the ability of AOB29 to sustain growth even at elevated concentrations

of typically toxic metals such as silver (Ag), lead (Pb), and nickel (Ni) suggests that this strain is well adapted to environments subjected to heavy metal contamination.

The Biolog GEN III analysis of the *B. mojavensis* AOB29 strain revealed that this bacterium is capable of utilizing a wide range of carbon sources and exhibits a high level of adaptability to environmental conditions. The strain's ability to metabolize various sugars, amino acids, and organic acids demonstrates its capacity to survive in nutritionally variable environments (Priest, 2014; Logan and Vos, 2015). Moreover, its ability to grow in media containing 1–8% NaCl and lithium chloride suggests a halotolerant nature and resistance to osmotic stress conditions (Ait Bessai et al., 2023). Resistance to antibiotics such as nalidixic acid, vancomycin, aztreonam, lincomycin, and fusidic acid indicates the presence of intrinsic resistance traits, which may be associated with mechanisms such as cell wall structure (Blair et al., 2015). Positive reactions to gelatin, tetrazolium dyes, and Tween compounds further suggest that the strain possesses proteolytic and lipolytic activities, indicating a potential role in organic matter turnover (Gupta et al., 2017). Overall, these findings demonstrate that *B. mojavensis* AOB29 is a metabolically versatile, halotolerant microorganism with potential for application in industrial processes.

Pot experiments demonstrated that inoculation with the *B. mojavensis* AOB29 strain led to significant improvements in the growth of arugula (*E. vesicaria*), as evidenced by increases of 57.8% in dry biomass and 40.9% in fresh biomass relative to the control, particularly in leaf, root, and stem tissues. These findings suggest that the bacterial strain supports plant growth through mechanisms such as the production of IAA, which promotes root development in the rhizosphere, the secretion of organic acids that enhance nutrient solubility, and physiological processes that facilitate mineral transport. Sattar et al. (2019) reported significant increases in biomass and nutrient uptake in wheat following inoculation with potassium-solubilizing *Bacillus* strains. Etesami et al. (2017) also reported that potassium-solubilizing *Bacillus* strains mobilize insoluble K pools through the coordinated secretion of low-molecular-weight organic acids and proton extrusion, thereby significantly enhancing K bioavailability in the rhizosphere. In addition, the multifunctional nature of *Bacillus* spp., including their capacity for phytohormone production and facilitation of mineral transport, enables the synergistic promotion of plant growth, particularly under nutrient-deficient or stress-prone conditions. Therefore, the pronounced growth responses observed in the present study strongly support the central role of potassium-solubilizing *Bacillus* strains in enhancing plant productivity and sustaining agricultural ecosystem performance.

Application of *B. mojavensis* AOB29 led to marked changes in mineral nutrient uptake by arugula plant, suggesting a broad influence of the strain on rhizosphere nutrient dynamics. In particular, the substantial increase in potassium (K) uptake (58.8%) strongly suggests an active potassium-solubilizing capacity, consistent with recent reports highlighting the pivotal role of *Bacillus* spp. in mobilizing insoluble K pools and enhancing plant K nutrition (Parmar and Sindhu, 2013; Etesami et al., 2017; Sattar et al., 2019; Widiatningrum et al., 2026; Yıldız and Dizikisa, 2026). Enhanced potassium availability is known to stimulate root development, improve nutrient acquisition efficiency, and support biomass accumulation. In parallel, the observed increases in magnesium (26.9%) and phosphorus (9.6%) uptake may reflect improved solubilization and mobilization of these nutrients in the rhizosphere, potentially mediated by the secretion of organic acids and proton extrusion by plant growth-promoting bacteria. Recent studies have demonstrated that *Bacillus* spp. can simultaneously enhance the availability of multiple macroelements, including P and Mg, thereby contributing to improved ionic balance and overall nutrient use efficiency in plants (Backer et al., 2018; Kumar et al., 2020). Conversely, the reduction in calcium content in present study (21.3%) may be attributable to nutrient antagonism between calcium and K, a phenomenon frequently observed under conditions of elevated K uptake and redistribution within plant tissues. Such antagonistic interactions among cations are increasingly recognized as an important factor shaping plant nutrient profiles in PGPR-inoculated systems (Fageria, 2001). Regarding micronutrients, the increased uptake of Zn (28.9%) and Mg (46.7%) suggests enhanced bioavailability in the rhizosphere, potentially driven by siderophore production and the release of low-molecular-weight organic compounds that facilitate micronutrient solubilization and transport. Recent evidence indicates that PGPR-mediated siderophore activity can substantially improve the uptake of micronutrients such as Zn and Mn, thereby supporting plant metabolic functions and stress resilience (Backer et al., 2018). In contrast, the observed reductions in iron (31.9%) and copper (20.0%) uptake may be associated with microbial siderophore-mediated chelation processes that preferentially

sequester Fe and, to a lesser extent, Cu in the rhizosphere, thereby modulating their bioavailability to plants. Such selective regulation of micronutrient availability by PGPR has been proposed as a mechanism for maintaining ionic homeostasis and preventing metal-induced oxidative stress in plants (Ahemad and Kibret, 2014; Ahmed and Holmström, 2014). Taken together, these findings demonstrate that *B. mojavensis* AOB29 influences plant nutrition not only through its potassium-solubilizing capacity but also via complex regulatory mechanisms governing nutrient interactions, ionic balance, and element transport in the rhizosphere. Given the increasing emphasis on soil health, ecosystem sustainability, and reduced chemical inputs in modern agriculture, microbial-based strategies that enhance nutrient availability through natural biological processes represent a promising approach for sustainable crop production systems (Rouphael and Colla, 2020; Yakupoğlu et al., 2022).

Conclusion

The results obtained as a result of the study should be stated in clear, understandable, and plain expressions. In addition, the contribution of the results of the study to the literature, the limitations of the study, and suggestions can be given.

Inoculation with *B. mojavensis* AOB29 led to a significant increase in the dry biomass of arugula plant. This response suggests that the strain promotes plant growth through mechanisms including IAA production, organic acid secretion, and potassium solubilization. With respect to nutrient uptake, increases in potassium, magnesium, phosphorus, zinc, and manganese indicate that the bacterium enhances the solubility and availability of these elements within the rhizosphere. In contrast, the reductions in calcium, iron, and copper contents may be explained by ion antagonism associated with increased potassium availability and the effects of siderophore production. Overall, these findings demonstrate that AOB29 influences plant nutrition not only through its potassium-solubilizing capacity but also via complex mechanisms involved in regulating ionic balance in the rhizosphere. Future field-based studies involving different crop species are required to further elucidate the potential of this strain as a biofertilizer and its effectiveness in reducing chemical fertilizer inputs under sustainable agricultural practices.

Ethical Statement

Ethical approval was not required for this study as there was no specific type of research involving humans or animals.

Conflict of Interest

No potential conflict of interest was reported by the authors.

Artificial Intelligence Declaration

The authors declare that no generative artificial intelligence (AI) tools were used for data analysis, interpretation of results, scientific decision-making, or the generation of scientific content, figures, tables, or conclusions during the preparation of this manuscript. OpenAI GPT-5.5 was used solely for language editing and improvement of the manuscript text. The authors take full responsibility for the accuracy, integrity, and scientific validity of the article.

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Author Contributions

The idea of conducting this study belongs to Nazan Çömlekçioğlu. Bacterial isolations from soil samples were carried out Ashabil Aygan, Osman Bedrettin Akkaya and İbrahim Seyfettin Çelik. K concentrations of supernatants were measured by Ömer Faruk Demir, Dilek Özkılıç, Melisa Güler and

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References

- Ahemad, M., & Kibret, M. (2014). Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. *Journal of King Saud University - Science*, 26(1), 1–20. <https://doi.org/10.1016/j.jksus.2013.05.001>
- Ahmed, E., & Holmström, S. (2014). Siderophores in environmental research: Roles and applications. *Microbial Biotechnology*, 7(3), 196–208. <https://doi.org/10.1111/1751-7915.12117>
- Ait Bessaï, S., Cruz, J., Carril, P., Melo, J., Santana, M. M., Mouazen, A. M., Cruz, C., Yadav, A. N., Dias, T., & Nabti, E. H. (2023). The plant growth-promoting potential of halotolerant bacteria is not phylogenetically determined: Evidence from two *Bacillus megaterium* strains isolated from saline soils used to grow wheat. *Microorganisms*, 11(7), 1687. <https://doi.org/10.3390/microorganisms11071687>
- Akkaya, O. B., Demir, Ö. F., Çelik, İ. S., Aygan, A., & Çömlekçioğlu, N. (2025). Isolation, molecular characterization and optimization of potassium solubilizing bacteria (KSBs) from the Kahramanmaraş region. *Geomicrobiology Journal*, 42(2), 105–112. <https://doi.org/10.1080/01490451.2024.2437455>
- Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., ... Smith, D. L. (2018). Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science*, 9, 1473. <https://doi.org/10.3389/fpls.2018.01473>
- Black, C. A., Evans, D. D., Esingoger, L. E., White, J. L., & Clark, F. E. (1965). Physical properties. Methods of soil analysis, part I and II. American Society of Agronomy.
- Blair, J. M. A., Webber, M. A., Baylay, A. J., Ogbolu, D. O., & Piddock, L. J. V. (2015). Molecular mechanisms of antibiotic resistance. *Nature Reviews Microbiology*, 13(1), 42–51.
- Clinical and Laboratory Standards Institute. (2023). Performance standards for antimicrobial susceptibility testing (33rd ed., M100). Clinical and Laboratory Standards Institute.
- Demircioğlu, M., & Ağca, N. (2022). Determination of spatial distribution of basic properties of the Arsuz plain soils with geostatistical methods. *Osmaniye Korkut Ata University Journal of Natural and Applied Sciences*, 5(3), 1419–1437. <https://doi.org/10.47495/okufbed.1085309>
- Etesami, H., Emami, S., & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB): Mechanisms, promotion of plant growth, and future prospects: A review. *Journal of Soil Science and Plant Nutrition*, 17(4), 897–911.
- Fageria, V. D. (2001). Nutrient interactions in crop plants. *Journal of Plant Nutrition*, 24(8), 1269–1290. <https://doi.org/10.1081/PLN-100106981>
- Fira, D., Dimkić, I., Berić, T., Lozo, J., & Stanković, S. (2018). Biological control of plant pathogens by *Bacillus* species. *Journal of Biotechnology*, 285, 44–55. <https://doi.org/10.1016/j.jbiotec.2018.07.044>
- Gupta, P., & Diwan, B. (2017). Bacterial exopolysaccharide mediated heavy metal removal: A review on biosynthesis, mechanism and remediation strategies. *Biotechnology Reports*, 13, 58–71.
- Gupta, R., Beg, Q. K., & Lorenz, P. (2017). Bacterial alkaline proteases: Molecular approaches and industrial applications. *Applied Microbiology and Biotechnology*, 101(4), 1259–1275. <https://doi.org/10.1007/s00253-016-8030-0>
- Gülçur, F. (1974). Bitki numunelerinin toplanması ve analize hazırlanması esasları. *Journal of the Faculty of Forestry Istanbul University*, 5–29.
- Helmke, P. A., & Sparks, D. L. (1996). Lithium, sodium, potassium, rubidium, and cesium. *Methods of Soil Analysis: Part 3 Chemical Methods*, 5, 551–574. <https://doi.org/10.2136/sssabookser5.3.c19>

- Hemdan, B. A., El-Liethy, M. A., El Mahdy, M. E. I., & El-Taweel, G. E. (2019). Metagenomics analysis of bacterial structure communities within natural biofilm. *Heliyon*, 5(8). <https://doi.org/10.1016/j.heliyon.2019.e02271>
- Jones, J. B., Jr., & Case, V. W. (1990). Sampling, handling, and analyzing plant tissue samples. *Soil Testing and Plant Analysis*, 3, 389–427.
- Kumar, A., Singh, S., Gaurav, A. K., Srivastava, S., & Verma, J. P. (2020). Plant growth-promoting bacteria: Biological tools for the mitigation of salinity stress in plants. *Frontiers in Microbiology*, 11, 1216. <https://doi.org/10.3389/fmicb.2020.01216>
- Kuo, S., & Sparks, D. L. (1996). Methods of soil analysis. Part 3: Chemical methods (pp. 894–895). Soil Science Society of America.
- Logan, N. A., & Vos, P. (2015). *Bacillus*. In Bergey's manual of systematics of archaea and bacteria. John Wiley & Sons. <https://doi.org/10.1002/9781118960608.gbm00530>
- Logan, N. A., Berge, O., Bishop, A. H., Busse, H. J., De Vos, P., Fritze, D., Heyndrickx, M., Kampfer, P., Rabinovitch, L., Salkinoja-Salonen, M. S., & Seldin, L. (2009). Proposed minimal standards for describing new taxa of aerobic, endospore-forming bacteria. *International Journal of Systematic and Evolutionary Microbiology*, 59(8), 2114–2121. <https://doi.org/10.1099/ijss.0.013649-0>
- Luo, L., Zhao, Z., Huang, X., Du, X., Wang, C. A., Li, J., Wang, L., & Xu, Q. (2016). Isolation, identification, and optimization of culture conditions of a bioflocculant-producing bacterium *Bacillus megaterium* sp1 and its application in aquaculture wastewater treatment. *BioMed Research International*, 2016(1), 1–9. <https://doi.org/10.1155/2016/2758168>
- Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. *Methods of Soil Analysis: Part 3 Chemical Methods*, 5, 961–1010. <https://doi.org/10.2136/sssabookser5.3.c34>
- Olur, Ü., & Uçar, C. P. (2021). Determination of some plant growth promoting mechanisms of endophytic bacteria isolated from plants grown under salt stress and their effects on cucumber seedling growth. *Mustafa Kemal University Journal of Agricultural Sciences*, 26(3), 635–648. <https://doi.org/10.37908/mkutbd.954216>
- Parmar, P., & Sindhu, S. S. (2013). Potassium solubilization by rhizosphere bacteria: Influence of nutritional and environmental conditions. *Journal of Microbiology Research*, 3(1), 25–31. <https://doi.org/10.5923/j.microbiology.20130301.04>
- Priest, F. G. (2014). Systematics and ecology of *Bacillus*. In *Bacillus subtilis and other gram-positive bacteria: Biochemistry, physiology, and molecular genetics*. ASM Press. <https://doi.org/10.1128/9781555818388.ch1>
- Richard, J. P. (1954). Stendhal et Flaubert. Éditions du Seuil.
- Rouphael, Y., & Colla, G. (2020). Biostimulants in agriculture. *Frontiers in Plant Science*, 11, 40. <https://doi.org/10.3389/fpls.2020.00040>
- Sattar, A., Naveed, M., Ali, M., Zahir, Z. A., Nadeem, S. M., Yaseen, M., ... Meena, H. N. (2019). Perspectives of potassium solubilizing microbes in sustainable food production system: A review. *Applied Soil Ecology*, 133, 146–159. <https://doi.org/10.1016/j.apsoil.2018.09.012>
- Singh, R., Kumar, M., Mittal, A., & Mehta, P. K. (2016). Microbial enzymes: Industrial progress in 21st century. *3 Biotech*, 6(2), 174. <https://doi.org/10.1007/s13205-016-0485-8>
- Widiatningrum, T., Herlina, L., Aprilia, K. R., Nurhidayah, F., Hartanti, F. F., & Fatma, S. D. U. (2026). Characterization of plant growth promoting rhizobacteria from dominant weeds inhabited in Kaligarang River Delta, Indonesia. *Yuzuncu Yil University Journal of Agricultural Sciences*, (1), 1379858. <https://doi.org/10.29133/yyutbd.1379858>
- Yakupoglu, G., Saltali, K., Rodrigo-Comino, J., Yakupoğlu, T., & Cerda, A. (2022). Manure effect on soil–plant interactions in capia pepper crops under semiarid climate conditions. *Sustainability*, 14(20), 13695. <https://doi.org/10.3390/su142013695>
- Yıldız, N., & Dizikısa, T. (2025). Effects of organomineral fertilizer treatments on morphological parameters and leaf macronutrient contents of maize plant. *Yuzuncu Yil University Journal of Agricultural Sciences*, (1), 1772892. <https://doi.org/10.29133/yyutbd.1772892>