KSÜ Tarım ve Doğa Derg 28 (5), 1173-1185, 2025
KSU J. Agric Nat 28 (5), 1173-1185, 2025
https://doi.org/10.18016/ksutarimdoga.vi.1700158

Determination of Plant Growth Promotion and Antimicrobial Activity Potential of Identified *Actinobacteria* from Kula Geopark

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ABSTRACT

Actinobacteria, known as producers of bioactive compounds, also help enhance plant growth through nitrogen fixation, ammonia, siderophore, and indole-3-acetic acid (IAA) production, phosphate solubilization, and phytopathogen suppression. In this study, antimicrobial activity and the plant growth-promoting potentials of 34 *Actinobacteria* isolated from the Kula Geopark were investigated. Among these isolates, eight members of *Amycolatopsis* (KG3, KH8, KH9, KR1, KR2, KR3, KR6, KR12) performed ammonia production, nitrogen fixation, IAA production, phosphate solubilization, and siderophore production, while also exhibiting significant antimicrobial activity against eight different pathogens. Additionally, five isolates of the genus *Kribbella* (KS52, KS86, KS88, KS95, KS96) performed ammonia production, nitrogen fixation, IAA production, phosphate solubilization, and siderophore production. The *Actinomadura* sp. KS37 isolate, which was identified for its siderophore production, is also one of the two isolates that exhibit the broadest microbial activity spectrum, showing inhibition zones against nine pathogens. Another isolate with a broad spectrum, *Micromonospora* sp. KC97 demonstrated antimicrobial activity against nine pathogens. These findings indicate that the *Actinobacteria* from Kula Geopark have significant potential for promoting plant growth (PGP) and exhibiting antimicrobial activity.

Microbiology

Research Article

Article History
Received : 15.05.2025
Accepted : 17.06.2025

Keywords
Actinobacteria
Plant growth promote
Antimicrobial activity

Kula Jeoparkından Tanımlanan Aktinobakterilerin Bitki Büyümesini Teşvik Etme ve Antimikrobiyal Aktivite Potansiyelinin Belirlenmesi

ÖZET

Biyoaktif bileşiklerin üreticisi olarak bilinen aktinobakteriler ayrıca azot fiksasyonu, amonyak, siderofor ve indol-3-asetik asit (IAA) üretimi, fosfat çözünürleştirme ve fitopatojen baskılama yoluyla bitki büyümesini artırmaya yardımcı olmaktadır. Bu çalışmada, Kula Jeoparkı'ndan izole edilen 34 *Actinobacteria*'nın bitki büyümesini teşvik etme ve antimikrobiyal aktivite potansiyelleri araştırılmıştır. Bu izolatlar arasında sekiz *Amycolatopsis* üyesi (KG3, KH8, KH9, KR1, KR2, KR3, KR6, KR12) hem siderofor üretimi, azot fiksasyonu, fosfat çözünürleştirme ve amonyak üretimi gerçekleştirmekte, hem de sekiz farklı patojene karşı önemli antimikrobiyal aktivite sergilemektedir. Ayrıca, *Kribbella* cinsine ait beş izolat (KS52, KS86, KS88, KS95, KS96) siderofor üretimi, IAA üretimi, azot fiksasyonu, fosfat çözünürleştirme ve amonyak üretimi gerçekleştirmektedir. Siderofor üretimi yaptığı belirlenen *Actinomadura* sp. KS37 izolatı, dokuz patojene karşı inhibisyon zonları göstererek en geniş mikrobiyal aktivite spektrumunu sergileyen iki izolattan biri olmuştur. Geniş spektrumlu bir diğer izolat olan *Micromonospora* sp. KC97 ise dokuz patojene karşı antimikrobiyal aktivite göstermektedir. Bu bulgular, Kula Jeoparkı'ndan elde edilen aktinobakterilerin bitki gelişimini destekleme ve antimikrobiyal aktivite sergileme konusunda önemli bir potansiyele sahip olduğunu göstermektedir.

Mikrobiyoloji

Araştırma Makalesi

Makale Tarihçesi
Geliş Tarihi : 15.05.2025
Kabul Tarihi : 17.06.2025

Anahtar Kelimeler
Actinobacteria
Bitki gelişimini teşvik etme
Antimikrobiyal aktivite

Atıf Şekli: Bayraktar, B., Sarıcaoğlu, S., & Işık, K., (2025) Kula Jeoparkından Tanımlanan Aktinobakterilerin Bitki Büyümesini Teşvik Etme ve Antimikrobiyal Aktivite Potansiyelinin Belirlenmesi. *KSÜ Tarım ve Doğa Derg 28(5)*, 1173-1185. https://doi.org/10.18016/ksutarimdoga.vi.1700158

To Cite : Bayraktar, B., Saricaoglu, S., & Isik, K., (2025). Determination of Plant Growth Promotion and Antimicrobial Activity Potential of Identified *Actinobacteria* from Kula Geopark. *KSU J. Agric Nat 28(5)*, 1173-1185 https://doi.org/10.18016/ksutarimdoga.vi.1700158

INTRODUCTION

Antibiotic resistance and how to feed a growing world population are some of the major global challenges. Today, chemical fertilizers and pesticides are used extensively to increase plant growth and yields. However, health hazards arise from the introduction of these chemicals into the food chain. The use of microorganisms as biofertilizers as an alternative to chemical fertilizers and pesticides is currently an important research area in agriculture and microbiology (Krell & Matilla, 2022; He et al., 2024).

Plant growth-promoting rhizobacteria (PGPR) are a group of bacteria that improve plant growth, increase crop and soil fertility, and reduce biotic or abiotic stresses through phytohormone production, solubilization of inorganic phosphate, nitrogen fixation, ammonia production, and siderophore production. PGPR also indirectly promotes plant growth by suppressing phytopathogens through the production of antimicrobial compounds, siderophores, and extracellular hydrolytic enzymes. Among these bacteria, *Actinobacteria* are recognized as an important source of natural compounds of biologically active importance. *Actinobacteria*, a Gram-positive phylum with high guanine and cytosine (G+C) content in their genomes, are widespread in various terrestrial and aquatic ecosystems, including extreme environments such as deserts, hot springs, salt lakes, caves, deep seas, and volcanic regions (Hui et al., 2021; Giacomelli Ribeiro & Teresinha Van Der Sand, 2024).

Antibiotics have saved innumerable lives since their discovery in the early 20th century, but resistance to antibiotics is another major challenge we face today. This global crisis is due to the misemployment and overuse of antibiotics, as well as the adaptability of microorganisms. Among these microorganisms, bacteria known as ESKAPE pathogens (*Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter* spp.) are of clinical importance. The development of new bioactive compounds effective against these pathogens takes a long time and requires high costs. *Actinobacteria*, which produce approximately two-thirds of all clinically used antibiotics, have significant potential in addressing this issue (Van Bergeijk et al., 2020; Muteeb et al., 2023; Miller & Arias, 2024).

Extreme and unique environments, such as the Kula Geopark, a volcanic region, are regarded as valuable sources of new *Actinobacteria* and, consequently, new bioactive compounds (Qin et al., 2019). Therefore, this study aims to explore the bioactive potential of identified *Actinobacteria* from Kula Geopark in terms of both suppressing sixteen different pathogens and promoting plant growth (IAA production, siderophore production, ammonia production, phosphate solubilization, and nitrogen fixation).

MATERIAL and METHOD

Cultivation of *Actinobacteria* from Kula Geopark

In a previous study, 34 isolates identified as *Actinobacteria* based on 16S rRNA gene region analysis were cultured on GYM agar to determine their antimicrobial potential and plant growth-promoting properties (Table 1-3; Bayraktar and Işık, 2024).

Investigation of plant growth-promoting capacities

Within the scope of investigating plant growth-promoting potentials, IAA production, siderophore production, ammonia production, phosphate solubilization, and nitrogen fixation tests were carried out. Positive results were recorded as good (+), moderate (++), very good (+++), and negative results were recorded as (-).

Indole-3-acetic acid (IAA) production of the isolates was determined according to the method described by Ali et al. (2009). Isolates were incubated in SMS medium (28 °C, 7 days) containing L-tryptophan (1mg/mL). Then, 2 mL of Salkowski reagent was added to the colonies and kept in the dark for 20 min. The resulting pink-red color indicates a positive test.

The siderophore production of the isolates was tested by the disk diffusion method using LB-CAS Agar as determined by Schwyn and Neilves (1987) and subsequently modified by Arora and Verma (2017). Isolates impregnated on disks placed in groups of seven on petri dishes containing LB-CAS Agar were incubated at 28 °C for 5 days. At the end of the incubation, orange zones formed around the disks indicated that the test was positive.

Ammonia production of the isolates was tested according to the method described by Cappuccino and Sherman (2002). Isolates grown on ISP-2 liquid medium (28 °C, 7 days) were transferred to peptone-water mixture (4%) and

incubated at 28 °C for 14 days. After incubation, 1 mL of the colonies was transferred to an Eppendorf tube and centrifuged at 10,000 rpm for 5 min. Finally, the supernatants were taken into a glass tube, and 0.5 mL of Nessler reagent was added. Isolates with yellow-brown coloration were recorded as positive for ammonia production.

After a 14-day incubation at 28 °C on Pikovskaya Agar to determine phosphate solubilization ability, the presence of a clear zone surrounding the isolates was considered a positive result. (Gaur et al., 1990). For screening of nitrogen fixation ability, the isolates were cultured on Ashby's Mannitol Agar and NFC Medium. After incubation at 28 °C for 14 days on agar plates, the isolates were considered positive for nitrogen fixation activity based on colony growth (Li et al., 2018).

Investigation of antimicrobial activity of the isolates

The antimicrobial activity of 34 isolates was evaluated against sixteen different pathogenic microorganisms using the overlay method. Eight of these pathogens — *Bacillus subtilis* ATCC 6633, *Staphylococcus aureus* ATCC 25923, *Klebsiella pneumoniae* ATCC 700603, *Escherichia coli* ATCC 25922, *Enterococcus faecalis* ATCC 29212, *Pseudomonas aeruginosa* ATCC 27853, *Aspergillus niger* ATCC 16404, and *Candida albicans* ATCC 1023 — were registered from the culture collection of our research laboratory. The remaining eight pathogens — *Bipolaris sorokiniana*, *Botrytis cinerea*, *Fusarium equiseti*, *Fusarium oxysporum*, *Rhizoctonia solani*, *Clavibacter michiganensis* subsp. *michiganensis*, *Pseudomonas syringae* pv. *phaseolicola*, and *Xanthomonas campestris* pv. *campestris* were obtained from the Faculty of Agriculture, Ondokuz Mayıs University (OMU). Colonies grown on modified Bennett Agar plates were exposed to 1.5 mL of chloroform (40 minutes) to kill the colonies. Afterward, the dead colonies were overlaid with 5-7 mL of sloppy nutrient broth containing the pathogens. The inhibition zones, observed after 24 hours of incubation at 37 °C for clinical pathogens and 72 hours of incubation at 25 °C for phytopathogens, were recorded (Williams et al., 1983; Veyisoglu & Tatar, 2021). Amphotericin B (5 mg/mL) was used as a positive control for fungal pathogens, while chloramphenicol (30 µg/mL) was employed as a positive control for other pathogens. Nutrient Agar was utilized as a negative control for all pathogens.

Statistical analysis

Statistical analyses were performed using IBM SPSS version 22.0. Due to the non-normal distribution of the data, the Kruskal-Wallis test was employed to evaluate the developmental differences among the groups. A p-value of less than 0.05 was considered statistically significant. Multiple comparisons were performed using Dunn's test. For the Kruskal-Wallis test, the effect size was calculated using eta squared (η^2), as recommended by Cohen (2008). Accepted and interpreted threshold values according to Cohen are 0.01= small effect; 0.06 = medium effect; 0.14 = large effect.

$$\eta^2=(H-k+1)/(n-k)=(80.79-6+1)/(448-6)=0.17$$

- H: Kruskal-Wallis H statistic=80.79
- k: Number of groups=6
- n: Total number of samples=448

RESULTS and DISCUSSION

Agriculture faces the challenge of providing safe and nutritious food to a growing world population. In this respect, microorganisms seem promising for application as biostimulants and biocontrol agents through nitrogen fixation, phosphorus solubilization, siderophore production, production of phytohormones, ammonia production, and production of substances with antagonistic effects against plant pathogens (Chandran et al., 2021).

Actinobacteria are among the largest bacterial phyla that can live in aquatic and terrestrial environments. These bacteria are well known as important producers of secondary metabolites with antiviral, antimicrobial, antioxidant, larvicidal, insecticidal, and anticancer properties. *Actinobacteria* are also thought to be unique among rhizosphere microbes in terms of promoting plant growth and managing diseases. The biodiversity and biotechnological applications of *Actinobacteria* in extreme environments such as acidic or alkaline pH, high or low temperatures, saturated salt concentrations, high radiation, and high pressures are of great interest. There is limited research on the plant growth-promoting abilities of *Actinobacteria* isolated from volcanic regions, which are among extreme environments (Kaari et al., 2023; Muñoz-Torres et al., 2023).

In this context, this study investigates whether *Actinobacteria* isolated from unique environments such as the Kula Geopark contribute to plant growth. The results indicate that members of the *Amycolatopsis*, *Kribbella*, and *Streptomyces* genera, in particular, have significant potential to enhance plant growth. For instance, siderophore production was observed in members of *Actinomadura* (KS37), *Amycolatopsis* (KG3, KH8, KH9, KR1, KR2, KR3, KR6, KR12), *Kribbella* (KS52, KS86, KS88, KS95, KS96), *Saccharothrix* (KH50) and *Streptomyces* (KC28, KC48, KS97). Indole acetic acid production was noted in *Kribbella* (KS52, KS86, KS88, KS95, KS96), *Pseudonocardia*

(KH104, KH114), and *Streptomyces* (KS12, KS15, KS97), while phosphate solubilization was found in *Amycolatopsis* (KG3, KH8, KH9, KR1, KR2, KR3, KR6, KR12), *Kribbella* (KS52, KS86, KS88, KS95, KS96), *Nocardia* (KH76), *Saccharothrix* (KH50), and *Streptomyces* (KC48, KC66, KS12, KS97) members. Additionally, ammonia production was recorded in members of *Actinomadura* (KS37), *Amycolatopsis* (KG3, KH8, KH9, KR1, KR2, KR3, KR6, KR12), *Kribbella* (KC83, KS52, KS86, KS88, KS96), *Nocardia* (KC93, KH76), *Saccharothrix* (KH50) and *Streptomyces* (KC28, KC48, KC66, KS12, KS15). All isolates except *Actinomadura* sp. KS37, *Kribbella* sp. KC83, and *Nonomuraea* sp. KS108 was observed to be able to grow on NFC and ASHBY medium (Table 1, Figure 1). Considering the plant growth promotion potential of the isolates, it is seen that they give positive results over 50% in terms of nitrogen fixation, ammonia production, phosphate solubilization, and siderophore production (Figure 2).

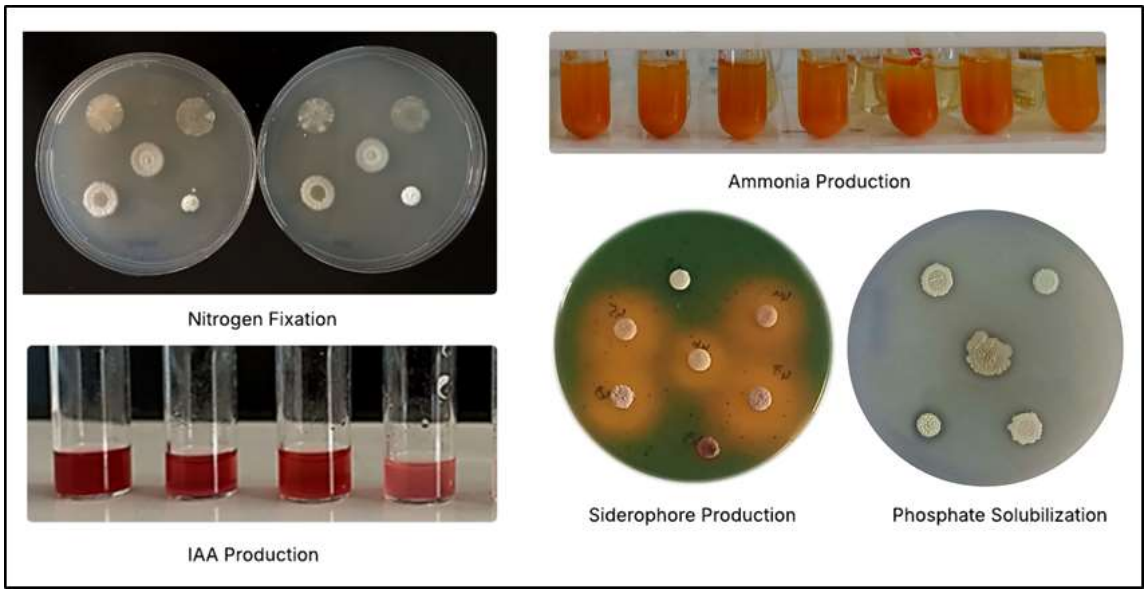

Figure 1. Plant growth-promoting abilities of *Actinobacteria* isolated from Kula Geopark
Şekil 1. Kula Jeoparkı'ndan izole edilen aktinobakterilerin bitki gelişimini teşvik etme yetenekleri

Nitrogen deficiency, a critical element for plant nutrition, is a major factor contributing to the decline in agricultural productivity worldwide. Atmospheric molecular nitrogen can be transformed into a plant-useable form by microorganisms. In addition to the well-known *Frankia*, nitrogen-fixing *Actinobacteria* also include members of the genus *Actinomadura*, *Kribbella*, *Micromonospora*, *Nocardia*, and *Streptomyces*. In addition, ammonia production is carried out by *Actinobacteria* belonging to the genus *Amycolatopsis*, *Actinomadura*, *Kribbella*, *Nocardia*, *Pseudonocardia*, *Streptomyces* (Swarnalakshmi et al., 2016; Borah et al., 2020; Chaiya et al., 2021).

Microorganisms produce Fe+3-chelating molecules called siderophores for the uptake of iron (Fe), an essential element for the growth and development of living organisms. By producing siderophores, bacteria enhance iron absorption and suppress phytopathogens. *Actinomadura*, *Amycolatopsis*, *Kribbella*, *Nocardia*, *Nonomuraea*, *Pseudonocardia*, *Saccharothrix*, and *Streptomyces* are among the *Actinobacteria* genus known for producing siderophores (Acquah et al., 2020; Ay, 2020; Borah et al., 2020; Shen et al., 2021).

Phosphorus (P), one of the main nutrients for plants, requires an eco-friendly supply for agriculture because of the scarcity of degradable natural resources. Microorganisms are effective in dissolving and mineralizing inorganic and organic phosphate by taking part in the transformation processes of phosphate. *Actinomadura*, *Kribbella*, *Micromonospora*, *Nocardia*, and *Streptomyces* are some phosphate-solubilizing *Actinobacteria* genera (Borah et al., 2020; Aliyat et al., 2024).

Indole-3-acetic acid (IAA), an important plant hormone belonging to the auxin family, is a natural plant hormone that plays a role in plant growth and development, such as cell division, fruit development, elongation, and senescence. IAA is synthesized not only in plants but also by many microorganisms, including bacteria and fungi. Actinobacteria that produce indole acetic acid include members of the genus *Actinomadura*, *Kribbella*, *Micromonospora*, *Nocardia*, *Pseudonocardia*, *Saccharothrix*, and *Streptomyces* (Ghodhbane-Gtari et al., 2019; Borah et al., 2020; Benadjila et al., 2022; Tang et al., 2023).

Table 1. Plant growth promotion results of *Actinobacteria* from Kula Geopark
Çizelge 1. Kula Jeoparkı aktinobakterilerinin bitki büyümesini teşvik etme sonuçları

Isolate	Siderophore Production	IAA Production	Nitrogen Fixation	Phosphate Solubilization	Ammonia Production
Actinomadura sp. KS37	++	-	-	-	++
Amycolatopsis sp. KG3	++	-	+++	++	+++
Amycolatopsis sp. KH8	+++	-	+++	++	+++
Amycolatopsis sp. KH9	++	-	+++	++	+++
Amycolatopsis sp. KR1	+++	-	+++	++	+++
Amycolatopsis sp. KR2	+++	-	+++	++	+++
Amycolatopsis sp. KR3	++	-	+++	++	+++
Amycolatopsis sp. KR6	+++	-	+++	++	+++
Amycolatopsis sp. KR12	+++	-	+++	++	+++
Kribbella sp. KC37	-	-	+	-	-
Kribbella sp. KC83	-	-	-	-	++
Kribbella sp. KS52	++	+	++	++	++
Kribbella sp. KS86	+	+	++	+++	+++
Kribbella sp. KS88	++	+++	++	++	++
Kribbella sp. KS95	++	+++	++	+	-
Kribbella sp. KS96	++	+++	++	++	++
Micromonospora sp. KC40	-	-	+	-	-
Micromonospora sp. KC97	-	-	+	-	-
Nocardia sp. KC93	-	-	+	-	+
Nocardia sp. KH76	-	-	++	+	++
Nonomuraea sp. KH2	-	-	++	-	+
Nonomuraea sp. KH16	-	-	++	-	-
Nonomuraea sp. KH19	-	-	+	-	-
Nonomuraea sp. KS108	-	-	-	-	-
Pseudonocardia sp. KH104	-	+	++	-	-
Pseudonocardia sp. KH114	-	+	++	-	-
Saccharothrix sp. KH50	+	-	+++	+	+++
Streptomyces sp. KC28	++	-	+	-	+++
Streptomyces sp. KC48	++	-	+	+	+++
Streptomyces sp. KC66	-	-	+	++	++
Streptomyces sp. KS12	-	++	+++	+++	+++
Streptomyces sp. KS15	-	++	+++	-	+
Streptomyces sp. KS97	+	+	++	+++	-
Streptomyces sp. KS109	-	-	+++	-	+

When comparing the information from the literature with the results obtained in this study, it is observed that they are found to be consistent, except for the phosphate solubilizing capability of *Saccharothrix* sp. KH50 and ammonia production ability of *Pseudonocardia* sp. KH104 and *Pseudonocardia* sp. KH114. Research on the plant growth potential of *Actinobacteria* found in volcanic landscapes is very limited. The study by Yun et al. (2017), which has a common genus with this study, can be given as an example. Yun et al. revealed that some isolates belonging to the genus *Streptomyces* are capable of phosphate solubilization, siderophore production, and IAA production (Yun et al., 2017).

Actinobacteria also promote plant growth by suppressing phytopathogens. *Bipolaris sorokiniana*, *Botrytis cinerea*, *Clavibacter michiganensis* subsp. *michiganensis*, *Fusarium equiseti*, *Fusarium oxysporum*, *Pseudomonas syringae* pv. *phaseolicola*, *Rhizoctonia solani,* and *Xanthomonas campestris* pv. *campestris* are some of the important plant pathogens (Table 2). To give a few examples, *Clavibacter michiganensis* subsp. *michiganensis* causes canker in tomatoes, of which Türkiye ranks third in production according to FAO statistics, while *Pseudomonas syringae* pv. *phaseolicola* causes halo blight in beans, and *Xanthomonas campestris* pv. *campestris* causes black rot in cabbage (Arnold et al., 2011; Bekircan Eski & Darcan, 2023; Hong et al., 2024; FAO, 2025).

Although there is information on the antimicrobial activity of *Actinobacteria* against various clinical pathogens, including ESKAPE, there is limited information on their antimicrobial activity against plant pathogens (Table 2). For instance, the Da2B antibiotic from *Actinomadura roseola* Ao108 exhibited inhibitory activity against *Rhizoctonia solani*. Similarly, *Actinomadura* sp. COL08 demonstrated antifungal activity against *Fusarium*

oxysporum f. sp. *albedinis*, while *Streptomyces* sp. ActiF450 displayed broad-spectrum antifungal activity against *Fusarium oxysporum* (Kim et al., 2000; Benhadj et al., 2020; Meliani et al., 2022).

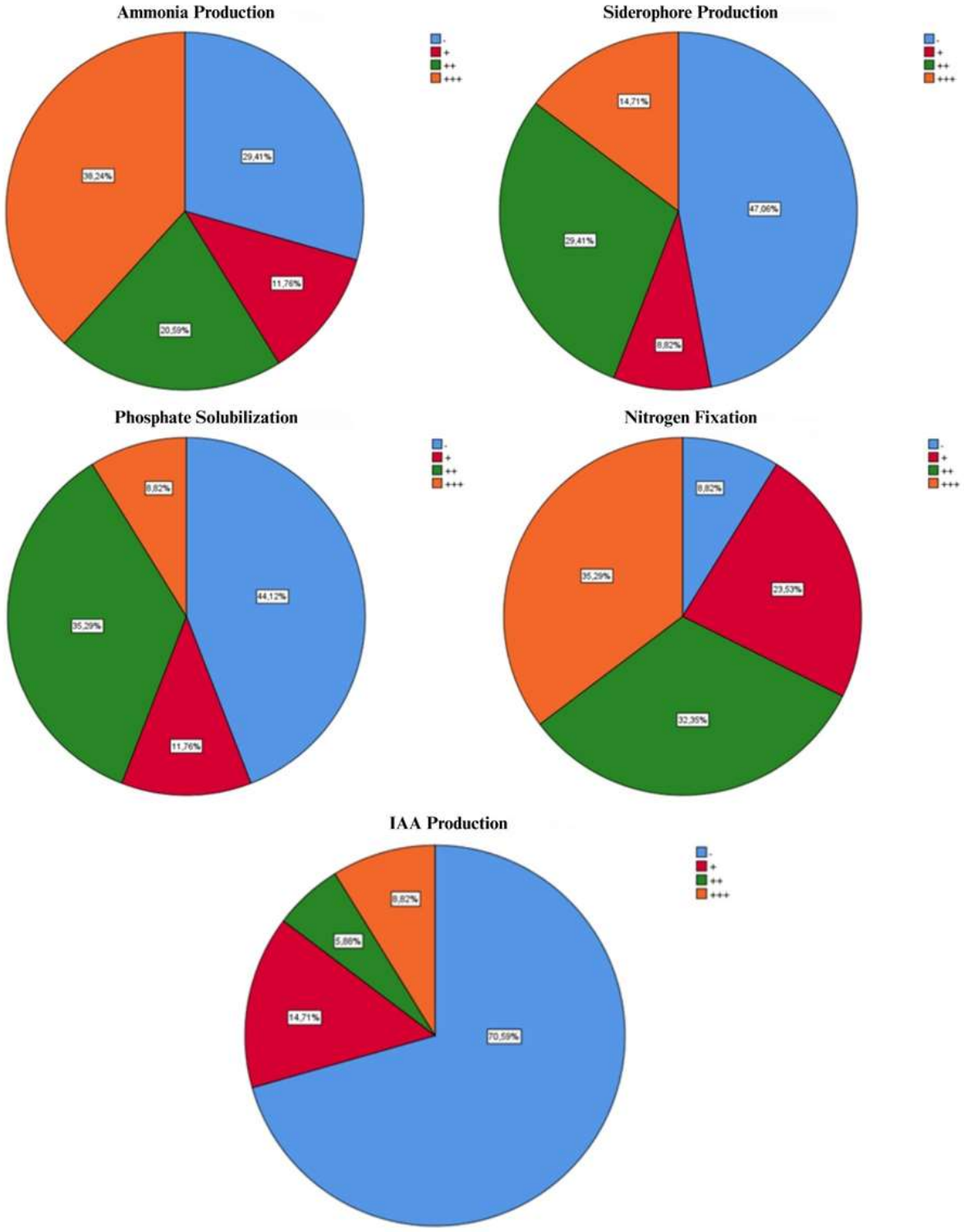

Figure 2. Distribution of plant growth promotion potential of isolates according to the results in Table 1.
Şekil 2. İzolatların bitki büyümesini teşvik etme potansiyellerinin Tablo 1'deki sonuçlara göre dağılımı

Table 2. Plant and human diseases caused by pathogens are tested for antimicrobial activity
Çizelge 2. Antimikrobiyal aktivite için test edilen patojenlerin neden olduğu bitki ve insan hastalıkları

Pathogen	Disease	References
Bacillus subtilis	Central nervous system infection	Tsonis et al., 2018
Staphylococcus aureus	Skin infections, pneumonia, and endocarditis	Tong et al., 2015
Klebsiella pneumoniae	Pneumonia and urinary tract infection	Chang et al., 2021
Escherichia coli	Gastrointestinal infections and urinary tract infections	Ismael et al., 2024; Bottignole et al., 2025
Enterococcus faecalis	Urinary tract infection and endocarditis	Neeva et al., 2024; Giuliano et al., 2025
Pseudomonas aeruginosa	Urinary tract infections, skin, and soft tissue infections	Shaaban et al., 2024; Ramesh et al., 2025
Aspergillus niger	Otomycosis, crown rot, and root rot (peanut)	Dai et al., 2024; Peng et al., 2024
Candida albicans	Oral candidiasis and vaginal infection	Ye et al., 2024; Faustino et al., 2025
C. michiganensis subsp. *michiganensis*	Wilt and canker in tomato	Bekircan Eski and Darcan, 2023
P. syringae pv. *phaseolicola*	Halo blight in beans	Arnold et al., 2011
X. campestris pv. *campestris*	Black rot in cabbage	Hong et al., 2024
Bipolaris sorokiniana	Root rot, spot blotch, and black point in wheat	Al-Sadi, 2021
Botrytis cinerea	Gray mold in strawberries	Petrasch et al., 2019
F. equiseti and *F.oxysporum*	Chili and Potato wilt	Hami et al., 2021; Bibi et al., 2024
Rhizoctonia solani	Potato black scurf	Yang et al., 2024

The antimicrobial activity results of *Actinobacteria* from Kula Geopark revealed that the widest inhibition zones were observed in isolates belonging to *Amycolatopsis*. Additionally, *Micromonospora* sp. KC97 exhibited the broadest spectrum of microbial activity, showing inhibition against *B. subtilis* ATCC 6633 (10 mm), *S. aureus* ATCC 25923 (40 mm), *K. pneumoniae* ATCC 700603 (30 mm), *E. coli* ATCC 25922 (30 mm), *E. faecalis* ATCC 29212 (20 mm), *P. aeruginosa* ATCC 27853 (5 mm), *A. niger* ATCC 16404 (30 mm), *Clavibacter michiganensis* subsp. *michiganensis* (40 mm), and *Pseudomonas syringae* pv. *phaseolicola* (10 mm). Moreover, *Actinomadura* sp. KS37 isolate exhibited inhibition zones against K. pneumoniae ATCC 700603 (10 mm), A. niger ATCC 16404 (10 mm), *C. albicans* ATCC 1023 (10 mm), *Clavibacter michiganensis* subsp. *michiganensis* (4 mm), *Pseudomonas syringae* pv. *phaseolicola* (30 mm), *Botrytis cinerea* (10 mm), *Fusarium equiseti* (10 mm), *Fusarium oxysporum* (1 mm), *Rhizoctonia solani* (30 mm), demonstrating the broadest microbial activity spectrum. *Nonomuraea*, *Pseudonocardia,* and *Kribbella* sp. KC83 isolates did not show antimicrobial activity in the tests performed (Table 3).

Statistically significant differences ($p< 0.05$) were observed between *Kribbella* and *Actinomadura* and *Amycolatopsis*; between *Nocardia* and *Amycolatopsis* and *Actinomadura*; and between *Saccharothrix* and *Amycolatopsis* ($p<0,001$). The lowest values were recorded in *Kribbella*, *Nocardia*, and *Saccharothrix*, respectively, while the highest values were observed in *Amycolatopsis*, *Micromonospora*, and *Actinomadura*. The effect size for the Kruskal-Wallis test was 0.17, and a large effect value was reached. $p<0.05$ was considered statistically significant (Figure 3 and Table 4).

Although this study demonstrates that *Actinobacteria* from the Kula Geopark exhibit significant PGP activity, their commercialization as biofertilizers faces several challenges, including shelf life, cost, formulation, soil type, environmental conditions, and local microbial diversity (Sarker et al., 2021). Furthermore, a number of actinobacterial isolates were found to exhibit strong antimicrobial activity in this investigation; however, identifying, characterizing, and optimizing the natural products responsible for this activity is still a significant challenge (Atanasov et al., 2021).

Table 3. Antimicrobial activity (millimeter-mm) results of *Actinobacteria* from Kula Geopark
Çizelge 3. Kula Jeoparkı aktinobakterilerinin antimikrobiyal aktivite (millimetre-mm) sonuçları

Isolate	*1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Actinomadura sp. KS37	-	-	10	-	-	-	10	10	4	30	-	-	10	10	1	30
Amycolatopsis sp. KG3	45	45	65	8	40	-	-	-	50	30	30	-	-	-	-	-
Amycolatopsis sp. KH8	40	40	60	9	40	-	-	-	50	30	30	-	-	-	-	-
Amycolatopsis sp. KH9	60	30	70	10	50	-	-	-	60	30	40	-	-	-	-	-
Amycolatopsis sp. KR1	50	50	70	8	40	-	-	-	50	20	20	-	-	-	-	-
Amycolatopsis sp. KR12	60	50	70	40	50	-	-	-	50	40	30	-	-	-	-	-
Amycolatopsis sp. KR2	70	60	70	50	70	-	-	-	50	30	30	-	-	-	-	-
Amycolatopsis sp. KR3	50	30	70	40	50	-	-	-	60	40	40	-	-	-	-	-
Amycolatopsis sp. KR6	60	50	70	40	50	-	-	-	60	40	40	-	-	-	-	-
Kribbella sp. KC37	-	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-
Kribbella sp. KS52	10	-	30	-	-	-	-	-	-	4	-	-	-	-	-	-
Kribbella sp. KS86	-	-	-	-	-	-	-	-	10	-	-	-	-	-	-	-
Kribbella sp. KS88	-	-	20	-	-	-	-	-	20	-	-	-	-	-	-	-
Kribbella sp. KS95	-	-	10	-	-	-	-	-	30	-	-	-	-	-	-	-
Kribbella sp. KS96	-	-	10	-	-	-	-	-	20	-	-	-	-	-	-	-
Micromonospora sp. KC40	30	-	20	-	-	-	-	-	4	-	-	-	-	-	-	-
Micromonospora sp. KC97	10	40	30	30	20	5	30	-	40	10	-	-	-	-	-	-
Nocardia sp. KC93	-	6	-	-	10	-	-	-	-	-	-	-	-	-	-	-
Nocardia sp. KH76	-	20	10	-	-	-	-	-	-	20	-	-	-	-	-	-
Saccharothrix sp. KH50	-	20	-	-	-	-	-	-	10	10	-	-	-	-	-	-
Streptomyces sp. KC28	-	-	40	-	-	-	-	-	40	-	-	-	-	-	-	-
Streptomyces sp. KC48	-	-	10	-	-	-	-	-	40	20	-	-	-	-	-	-
Streptomyces sp. KC66	30	-	20	-	-	-	-	-	10	-	-	-	-	-	-	-
Streptomyces sp. KS109	-	40	20	-	-	-	-	20	40	20	10	20	-	-	-	-
Streptomyces sp. KS12	-	-	-	-	-	-	-	-	-	-	20	-	-	-	-	-
Streptomyces sp. KS15	-	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Streptomyces sp. KS97	-	30	40	-	-	-	-	-	20	-	-	-	-	-	-	-
Positive control	15	15	20	10	10	-	15	5	10	10	4	-	-	4	-	-
Negative control	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

*1. *B. subtilis* ATCC 6633, 2. *S. aureus* ATCC 25923, 3. *K. pneumoniae* ATCC 700603, 4. *E. coli* ATCC 25922, 5. *E. faecalis* ATCC 29212, 6. *P. aeruginosa* ATCC 27853, 7. *A. niger* ATCC 16404, 8. *C. albicans* ATCC 1023, 9. *Clavibacter michiganensis* subsp. *michiganensis*, 10. *Pseudomonas syringae* pv. *phaseolicola*, 11. *Xanthomonas campestris* pv. *campestris*, 12. *Bipolaris sorokiniana*, 13. *Botrytis cinerea*, 14. *Fusarium equiseti*, 15. *Fusarium oxysporum*, 16. *Rhizoctonia solani*

Table 4. Distribution of the comparison of variations belonging to the *Actinobacteria* genera between groups
Çizelge 4. Actinobacteria cinslerine ait varyasyonların gruplar arasında karşılaştırılmasına ait dağılım

	Min	Max	Median	Mean	Standard Deviation	Test Statistics	*p*
Actinomadura	0	30	2,5	7,19	9,97[b]	80,79	0,000*
Amycolatopsis	0	70	4	22,42	25,26[c]		
Kribbella	0	30	0	1,51	5,36[a]		
Micromonospora	0	40	0	8,41	13,42[abc]		
Nocardia	0	20	0	2,06	5,39[a]		
Saccharothrix	0	40	0	4,3	10,32[ab]		

*p<0,001

CONCLUSION

With this study, it has been revealed that *Actinobacteria* obtained from the Kula Geopark possess various plant growth promotion properties, such as nitrogen fixation, ammonia, siderophore, and indole-3-acetic acid (IAA) production, as well as phosphate solubilization. Additionally, these *Actinobacteria* exhibit antimicrobial activity against both plant and clinical pathogens. As a result, it has been found that *Actinobacteria* from the Kula Geopark have enormous potential in agricultural and biotechnological applications. However, further research and development efforts are needed to enhance the real-life applicability of this potential. Bioformulation studies should be carried out to make these *Actinobacteria* with identified PGP potential into effective biofertilizers. And

the effects of these *Actinobacteria* on plant growth under different soil types and environmental conditions should be comprehensively studied through long-term field experiments. In addition, the chemical structures of bioactive compounds of isolates showing antimicrobial activity should be identified and characterized.

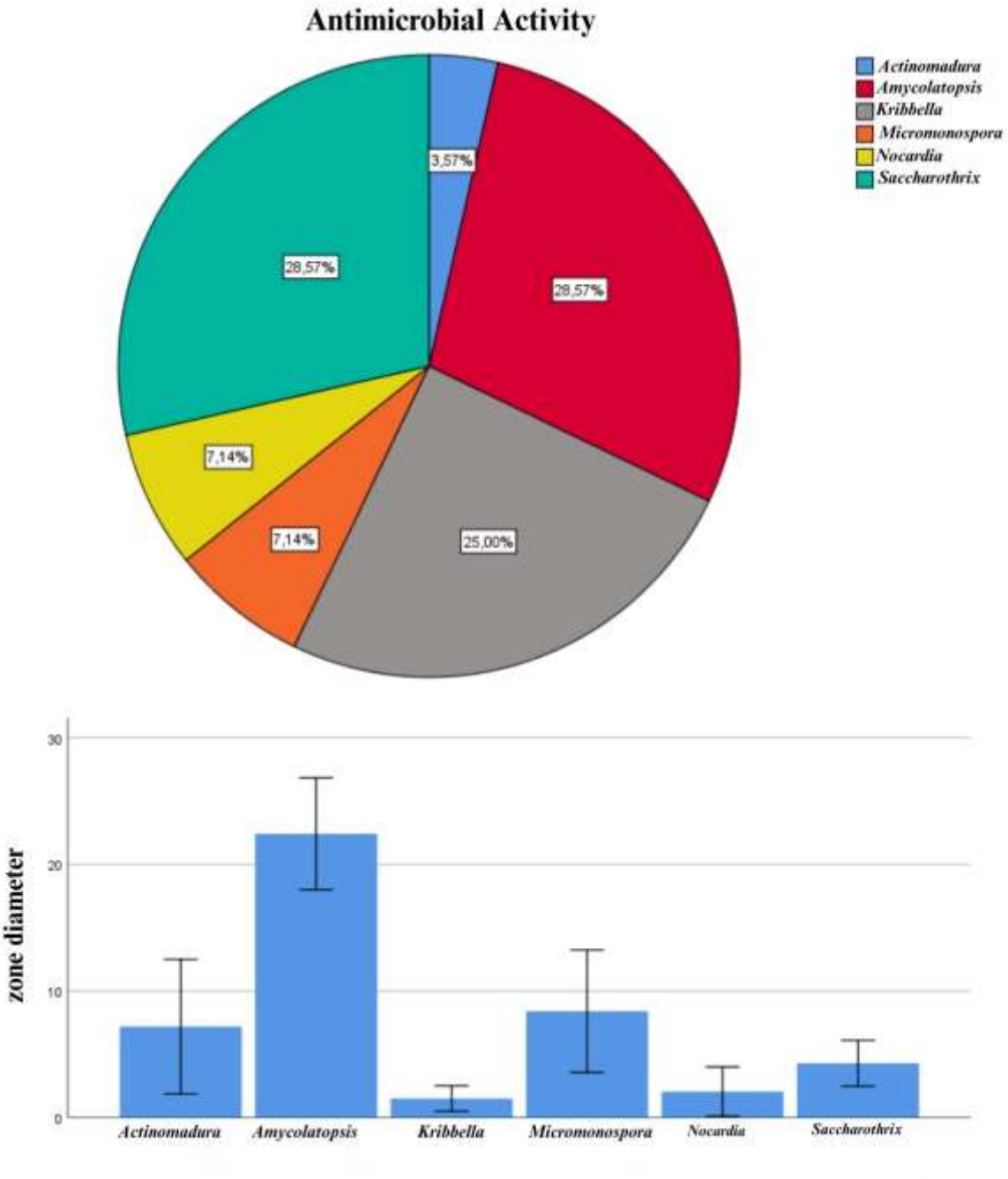

Figure 3. Percentage distribution of *Actinobacteria* genera according to their antimicrobial activities
Şekil 3. Actinobacteria cinslerinin antimikrobiyal aktivitelerine göre yüzdesel dağılımı

ACKNOWLEDGMENTS

This study was supported by Ondokuz Mayıs University Scientific Research Projects Coordination Unit (BAPKOB) under the project number PYO.FEN.1904.23.008.

Contribution of the Authors as a Summary

The authors declare that their contributions of the authors is equal.

Conflict of Interest

The authors declare they have no conflict of interest.

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