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DETERMINATION OF THE BIOACTIVE COMPOSITION AND ANTIMICROBIAL ACTIVITY OF THE AQUEOUS EXTRACT OF WILD BLUEBERRIES COLLECTED FROM KURT DAĞI HIGHLANDS (TRABZON, TÜRKİYE)

KURT DAĞI YAYLASI'NDAN (TRABZON, TÜRKİYE) TOPLANAN YABAN MERSİNİ MEYVESİNİN SULU EKSTRAKTININ BİYOAKTİF İÇERİĞİNİN VE ANTİMİKROBİYAL AKTİVİTESİNİN BELİRLENMESİ

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Abstract

Blueberries *(Vaccinium arctostaphylos* L.), which grow naturally in the Black Sea region and are consumed by the local population for their health benefits, are known as a functional food characterized by small, dark purple-blue berries. Considering that the bioactive content and health effects of blueberries may vary depending on the environmental conditions in which they are grown, we aimed to measure the polyphenol and flavonoid contents of blueberries naturally grown on the Kurt Dağı plateau and to determine their antimicrobial activity. A single pooled aqueous extract derived from Vaccinium arctostaphylos fruits (n=1) was prepared: floral samples collected from the Kurt Dağı plateau in August 2024 were dried at 45°C for 24 hours; a 700 mg portion of this sample was dissolved in 25 mL of pure water, and all measurements were performed on the resulting solution. The extraction process and chemical measurements were repeated three times. The total polyphenol (21.041 ± 0.976 µg/g GAE) and flavonoid content (1.733 ± 0.294 µg/g QE) were quantified. Antimicrobial susceptibility testing against three standard reference strains revealed that the pooled extract exhibited moderate-weak inhibitory activity against *Staphylococcus aureus* ATCC 25923 and *Escherichia coli* ATCC 25922 (MIC: 6.5 mg/mL), whereas only weak inhibitory activity was observed against *Pseudomonas aeruginosa* ATCC 27853 (MIC: 25 mg/mL). These data indicate that the blueberry population in the region has a significant antimicrobial potential, consistent with its high phenolic content, and can be considered a natural inhibitor of pathogenic microorganisms.

Keywords: Antimicrobial, Blueberry, Flavonoids, Polyphenols

Öz

Karadeniz bölgesinde doğal olarak yetişen ve yerel halk tarafından sağlık açısından faydalı etkisi yüzünden tüketilen yaban mersini (*Vaccinium arctostaphylos* L.) küçük koyu mor/mavi renkli meyvelere sahip fonksiyonel bir gıda olarak bilinmektedir. Yaban mersininin yetiştiği çevre koşullarına göre, biyoaktif içeriği ve sağlık üzerine etkisinin farklılık gösterebileceğini göz önüne alarak; Kurt Dağı yaylasında doğal ortamda yetişen yaban mersininin polifenol ve flavonoid içeriğini ölçmek ve buna bağlı olarak antimikrobiyal aktivitesini belirlemeyi amaçladık. Kurt Dağı platosundan Ağustos 2024'te toplanan meyve örneklerinden (n=1) tek bir birleşik sulu ekstrakt hazırlanmıştır. Örnekler 45°C'de 24 saat boyunca kurutulmuş; bu örnekten 700 mg'lık bir kısım 25 mL saf su içinde çözülmüş ve tüm ölçümler elde edilen çözelti üzerinde gerçekleştirilmiştir. Ekstraksiyon işlemi ve kimyasal ölçümler üç kez tekrarlanmıştır. Toplam polifenol içeriği (21.041 ± 0.976 µg/g GAE) ve flavonoid içeriği (1.733 ± 0.294 µg/g QE) kantitatif olarak belirlenmiştir. Üç standart referans suşa karşı yapılan antimikrobiyal duyarlılık testleri, birleşik sulu ekstraktın *Staphylococcus aureus* ATCC 25923 ve *Escherichia coli* ATCC 25922'ye karşı orta-zayıf düzeyde inhibitör aktivite gösterdiğini (MİK: 6.5 mg/mL), buna karşın *Pseudomonas aeruginosa*

ATCC 27853'e karşı yalnızca zayıf inhibitör aktivite sergilediğini ortaya koymuştur (MİK: 25 mg/mL). Elde edilen bu veriler, bölgedeki yaban mersini popülasyonunun yüksek fenolik madde içeriğiyle paralel olarak kayda değer bir antimikrobiyal potansiyele sahip olduğunu ve patojen mikroorganizmalara karşı doğal bir inhibitör ajan olarak değerlendirilebileceğini göstermektedir.

Anahtar Kelimeler: Antimikrobiyal, Yaban mersini, Flavonoidler, Polifenoller

1. Introduction

Vaccinium arctostaphylos L. commonly known as bearberry, is a plant species belonging to the Ericaceae family. This species is a fruit called likapa (blueberry) by the local people, growing naturally in the northeastern Black Sea region and holding an important place in both traditional medicine and modern pharmaceutical applications (Bighamanganeh et al., 2025). Not only the fruit but also the leaves of the plant have a rich phytochemical content and have attracted the attention of scientific studies in recent years due to their biological activities (Shamilov et al., 2022). Furthermore, this fruit has been shown to be used in traditional medicine for many health problems such as skin diseases, liver diseases, hyperlipidemia, and gastrointestinal disorders (Bighamanganeh et al., 2025). In recent years, especially with the impact of the pandemic, interest in natural phytotherapy products has increased, and studies on the beneficial effects of *V. arctostaphylos* on health are on the rise (Bighamanganeh et al., 2025).

V. arctostaphylos has a very rich composition in terms of bioactive components. Its fruits contain the essential sugars fructose and glucose and are also rich in organic acids, especially citric acid (Ozgen et al., 2014). The fruit is also rich in protein, sugar, fat, and fiber, and is noteworthy for its mineral and vitamin content (Bighamanganeh et al., 2025). Both the fruits and the leaves of *V. arctostaphylos* contain abundant bioactive componds including chlorogenic acid, quercetin, kaempferol, myricetin, procyanidin, catechin, epicatechin, flavonoids, coumarins, tannins, anthocyanins, isoflavones, flavonols, lignins, and resveratrol, among other phenolic compounds. In particular, it has a very high total polyphenolic content and exhibits strong antioxidant activity (Ozgen et al., 2014; Ozkan et al., 2018). The fruits and leaves, which are also rich in volatile compounds, increase the plant's potential for use in the food industry and pharmaceutical field (Bighamanganeh et al., 2025).

The health effects of *V. arctostaphylos* are being extensively studied, and research reveals that it possesses antihypertensive, antidiabetic, anti-hyperlipidemia, anti-inflammatory, antioxidant, anticancer, and antimicrobial properties (Bighamanganeh et al., 2025). Antimicrobials remain essential tools in the treatment of infectious diseases; however, their inappropriate and excessive use has accelerated the emergence and spread of antimicrobial resistance (AMR), which the World Health Organization has identified as one of the leading global health threats, contributing to increased morbidity, mortality, and reduced treatment efficacy worldwide (WHO, 2026). This growing challenge has prompted the search for novel antimicrobial agents, particularly from natural sources. Plant-derived compounds, including phenolics and flavonoids, have attracted attention due to their diverse mechanisms of action, which may reduce the likelihood of resistance development compared with single-target synthetic agents (Vaou et al., 2021; Cos et al., 2006).

The chemical composition of *V. arctostaphylos* can vary significantly depending on its growing location. Significant differences have been found in morphological characteristics such as weight, shape, and color, as well as in macro and micronutrients, of fruits grown in different regions (Ozkan et al., 2018). These differences stem not only from genetically distinct plant species but also from the climate and soil characteristics of the growing environment (Åkerström et al., 2010).

The bioactive components in the fruit also change with processing. The extraction methods and solvents used alter the concentration, biological activity, and bioavailability of compounds such as polyphenols and flavonoids. Therefore, it is important to conduct studies on aqueous and solvent extracts and to prepare them in a form that can be used without harming human health.

In conclusion, the botanical characteristics, chemical composition, health effects, and extraction methods of *V. arctostaphylos* have been discussed in detail in national and international publications. Recent studies, in particular, show that this species can be a versatile resource in both traditional medicine and modern pharmaceutical applications. In our study, we aimed to determine the polyphenol and flavonoid contents and the antimicrobial activity of the aqueous extract of wild blueberries grown in their natural environment, untouched by any environmental pollution, and traditionally dried and consumed as tea by the local people.

2. Materials and Methods

These wild blueberries were harvested in August 2024 from the Kurt Dağı Plateau in the Solaklı Valley, Çaykara district Trabzon Province (at approximately 3000 meters altitude, 40°41'45.4"N, 40°17'17.9"E). These fruit parts were collected and combined to obtain a single representative composite sample (n = 1) for aqueous extraction. The harvested fruits were cleaned of branches and leaves, washed, and incubated at 45°C for 24 hours. The products were ground into powder in a mill, transferred to Falcon tubes, and stored in a deep freezer at -20°C until the experiments were conducted (Figure 1).

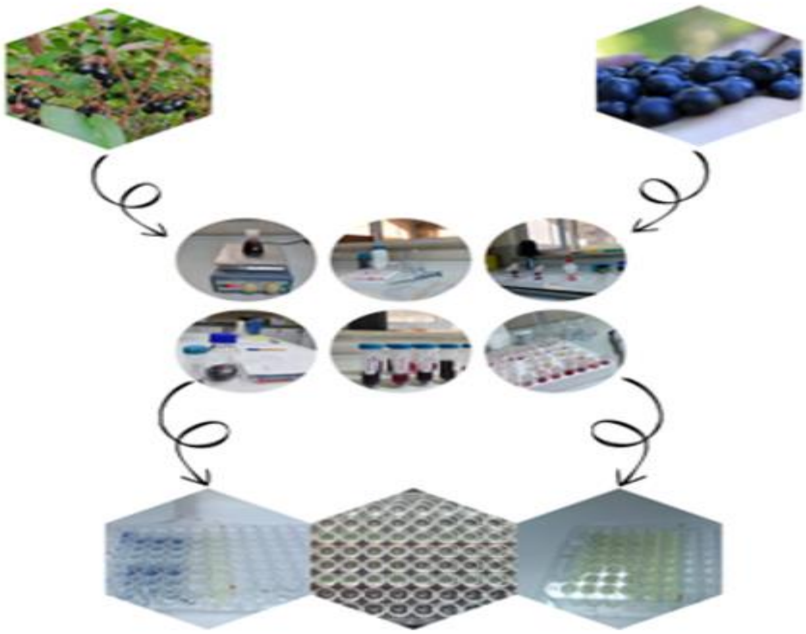


Figure 1. Schematic summary of the extraction processes and experimental procedure.

700 mg of blueberry samples were weighed and placed in 50 mL falcon tubes and their volume was adjusted to 25 mL with distilled water. The falcons were vortexed and then incubated in a shaker at 55°C for 20 minutes. After incubation, the samples taken from the device were centrifuged at 4000 rpm for 10 minutes and filtered through filter paper (No:1) (Drozdz et al., 2017). Analyses of total polyphenol and flavonoid compounds were performed on the filtrate.

Before determining polyphenol and flavonoid content in the samples, preliminary trials were conducted using fruits collected in 2023 from the same region and stored in a deep freezer at -20°C to achieve the standard concentration range. Total polyphenol determination was performed spectrophotometrically according to the modified Folin-Ciocalteu method. The method is based on the reducing power of phenolic compounds toward the Folin-Ciocalteu reagent in a basic environment. The Folin-Ciocalteu reagent is used as an oxidizing agent. The blue color of that developed in the sample after the reaction was measured spectrophotometrically to determine the total concentration of phenolic compounds. Gallic acid was used as a standard to determine the total polyphenol content (Horzic et al., 2007). Results are given as gallic acid equivalents in µg per gram dry weight of fruit.

The total flavonoid content in the samples was determined by the aluminum chloride colorimetric method. The principle of this method is based on the complex formation of $Al(NO_3)_3$ with the keto groups of flavones and flavonols in the sample in an acidic environment. Quercetin is used as a standard in this method (Lin & Tang, 2007). The results are given as quercetin equivalents in µg/. per gram dry weight of fruit.

In this study, the strains *S. aureus* ATCC 25923, *E. coli* ATCC 25922, and *P. aeruginosa* ATCC 27853 were used. The minimum inhibitory concentrations (MICs) of the plant extract against these microorganisms were determined by the microdilution method. For this purpose, sterile U-bottom 96-well microtiter plates and cation-adjusted Mueller-Hinton broth (CAMHB) were employed. The bacterial isolates were cultured on cation-adjusted Mueller-Hinton agar (CAMHA). Four to five colonies from each isolate were selected, and suspensions were prepared at a turbidity equivalent to the McFarland 0.5 standard. Appropriate dilutions were made according to EUCAST (2024, version 3.0) procedures, and the final bacterial density was adjusted to 5 × 10^5 cfu/mL. Positive and negative controls were included in each plate to ensure validity of the assay. Each well of prepared microtiter plates was inoculated with microorganisms. In the eleventh well, 50 µL of the bacterial inoculum was added as the growth control, while the twelfth well was served as the sterility control. Plates were sealed and incubated at 37 °C for 18–24 hours. The MIC value was defined as the lowest concentration at which no visible bacterial growth was observed (Jafri et al., 2020).

The collected samples were extracted three times, and measured three times (n = 3). Data were expressed as mean and ± standard deviation (SD).

3. Results

This study utilized blueberries that were naturally grown at high altitude on the Kurt Dağı Plateau of the Solaklı Valley in Çaykara district of Trabzon, a region of international biodiversity importance in Türkiye, and had not been exposed to environmental pollution. The aim of our study was to determine the total polyphenol and flavonoid content of these fruits and to assess their antimicrobial activity against *S. aureus* ATCC 25923, *E. coli ATCC 25922* and *P. aeruginosa* ATCC 27853. The extraction process and chemical measurements were repeated three times.

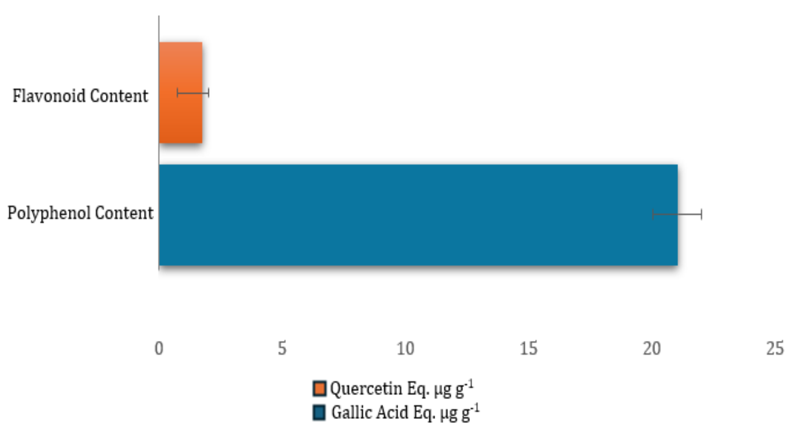
The analysis showed that samples collected from high-altitude, pollution-free environments possess considerable antioxidant capacity. The total polyphenol content was measured at 21.041 ± 0.976 µg/g gallic acid equivalent (GAE), while the total flavonoid content reached 1.733 ± 0.294 µg/g quercetin equivalent (QE) (Table 1; Figure 2). These results highlight the nutritional richness and bioactive potential of naturally occurring blueberries from this distinctive ecological region of Türkiye.

Table 1. Findings on the total polyphenol and flavonoid content of blueberries.

***V. arctostaphylos* L.**	**Mean**	**(SD)**	**n**
Total Polyphenol Content (µg/g GAE)	21.041	0.976	3
Flavonoid Content (µg QE/g)	1.733	0.294	3

*GAE; gallic acid equivalents in µg per gram dry weight of fruit.; *QE; quercetin equivalents in µg/. per gram dry weight of fruit.

In this study, an aqueous extract obtained from the ripe fruits of *Vaccinium arctostaphylos L*. (Caucasian blueberry), a species endemic to the Eastern Black Sea and Caucasus regions, was tested for antimicrobial activity against *S. aureus* ATCC 25923, *E. coli* ATCC 25922, and *P. aeruginosa* ATCC 27853 using the microdilution method. Antimicrobial activity was found to be 6.5 mg/mL for *S. aureus* ATCC 25923, 6.5 mg/mL for *E. coli* ATCC 25922, and 25 mg/mL for *P. aeruginosa* ATCC 27853. Each experiment was repeated three times, and the results were consistent across all replicates. The determined MIC values are presented in Table 2.



*GAE; gallic acid equivalents in µg per gram dry weight of fruit.; *QE; quercetin equivalents in µg/. per gram dry weight of fruit.

Figure 2. Total polyphenol and flavonoid content of blueberries.

Table 2. MIC values of blueberries fruit extract and gentamicin against ATCC strains

Strain	Extract (mg/mL)	Gentamicin (µg/mL)
***S. aureus* ATCC 25923**	6.5	1
***E. coli* ATCC 25922**	6.5	2
***P. aeruginosa* ATCC 27853**	25	2

ATCC: American Type Culture Collection, mg/mL: milligrams/milliliter, µg/mL: micrograms/milliliter

4. Discussion

The antioxidant capacity of blueberry cultivars is closely linked to both the quantity and diversity of their phenolic constituents. Phenolic compounds, which are secondary metabolites widely distributed in plants, play a crucial role in protecting against environmental stressors (Nurzyńska Wierdak, 2023). Within this group, polyphenols and flavonoids are particularly significant due to their strong antioxidant properties. Polyphenols act by neutralizing free radicals, thereby reducing oxidative stress and contributing to protective effects on human health (Rahman et al., 2021). Flavonoids, meanwhile, are notable not only for their antioxidant activity but also for their anti-inflammatory potential, offering possible benefits in the prevention and management of chronic diseases (Rahman et al., 2021).

Studies examining the phenolic composition of wild blueberries grown in high-altitude natural habitats have shown that these species possess greater antioxidant capacity than cultivated varieties. For example, research conducted in the Artvin region reported that naturally occurring *V. arctostaphylos L.* and *V. myrtillus* L. contained higher levels of total polyphenols (11.539–20.742 mg GAE/g), flavonoids (1.182–2.676 mg QE/g), and anthocyanins (3.305–11.473 mg Cyn/g) compared with cultivated *Vaccinium corymbosum* L. (Saral et al., 2015). These findings suggest that blueberries that grown in their native environments are biologically richer.

Similarly, research conducted in different regions of Türkiye shows that blueberries are rich in phenolic compounds. In the studies by Okan et al., it was reported that the total phenolic content of blueberry fruits produced in Türkiye ranged from 77.26 – 215.12 mg GAE/100 g; and the total flavonoid content ranged from 30.44 – 91.69 mg QE/100 g (Okan et al., 2018). In the same study, it was emphasized that naturally grown blueberries have more phenolic compounds and higher antioxidant activity compared to cultivated varieties (Okan et al., 2018).

Recent studies have shown that blueberry leaves are as rich in phenolics and flavonoids content as fruit. Another study reported that the total phenolic content of blueberry leaves grown in the Black Sea Region ranged from 8.36 to 121.61 mg GAE/g, and the total flavonoid content ranged from 0.91 to 3.07 mg QE/g (Okan et al., 2024). This study also indicated that chlorogenic acid was the dominant compound in all leaf samples and emphasized that blueberry leaves can be used as an antioxidant source in the food and cosmetic industries (Okan et al., 2024). Compared to previous studies, our findings were of lower value, which may be primarily due to the extraction method used. While other studies prepared extracts using organic solvents, we used aqueous extracts. The main reason we use the liquid extract is that local people consume this fruit traditional forms (dried fruits, tea, compote, etc.). From a nutritional standpoint, we chose the aqueous extract because dissolving the products in an organic solvent would be unsuitable for human health.

The amount and composition of phenolic compounds in plants are affected by many factors, including genetic structure, growing environment, climatic conditions, and harvest time (Nurzyńska wierdak, 2023). The concentrations of these compounds may be higher, especially in plants growing in natural areas unaffected by environmental pollution. For example, analyses of organically grown blueberries in the Trabzon region reported chlorogenic acid levels of 644.25 mg/kg and also high levels of important flavonoids such as myricetin (Karaağaç & Uçurum, 2019). The same study emphasized that blueberries are rich in phenolic acids and offer significant health benefits (Karaağaç & Uçurum, 2019). Because the area where the blueberry samples were collected is an ecological conservation area and is free of vehicle traffic, the fruit can be grown entirely organically. In addition, challenging climatic conditions positively affect the quality of polyphenols and flavonoids, which are secondary metabolites of plants. In this case, we expected higher levels of polyphenols and flavonoids in our study. However, polyphenols and flavonoids are more likely to be extracted in organic solvents.

The total polyphenol (21.041 ± 0.976 µg/g GAE) and flavonoid (1.733 ± 0.294 µg/g QE) values measured in the blueberry sample used in this study are generally consistent with those reported for other naturally occurring blueberry populations in the literature. Although our current findings show limited differences when compared with other studies in literature, these differences are thought to be attributable to the extraction method. Indeed, while aqueous extracts are known to contain fewer bioactive substances (anthocyanins, phenolics) than organic solvent extracts, they were preferred in this study because of their direct suitability for human use.

The rapid global spread of antibiotic resistance severely restricts current treatment protocols and has been recognized by the World Health Organization as one of the greatest threats to public health. This impasse has prompted the scientific community to intensify efforts in isolating new bioactive compounds from medicinal plants and to deepen research in this field (Vaou et al., 2021).

In the literature, it is generally accepted that plant extracts with MIC values ranging from 100 to 1000 µg/mL are considered potent, while values above 1 mg/mL indicate weaker antimicrobial activity (Ríos & Recio, 2005). In our study, the aqueous fruit extract of *V. arctostaphylos* exhibited weak-to-moderate inhibitory activity against *S. aureus* ATCC 25923 and *E. coli* ATCC 25922. Although these values are consistent with crude plant extracts, they are considerably higher than those of purified antibiotics. Similar findings have been reported in other publications. In a study using methanolic extracts of *V. arctostaphylos*, MIC values of 6.25 mg/mL for leaves and 3.125 mg/mL for fruits were reported against Acinetobacter baumannii (Kardil et al., 2024). In contrast, a study using *V. arctostaphylos* oil identified MIC values of 0.34 mg/mL for E. coli, 24 mg/mL for S. aureus, and 0.37 mg/mL for *P. aeruginosa* (Teimouri, 2015). The main difference between our study and previous studies lies in the extraction approach: while most reports used organic solvents such as methanol or ethanol, our study employed aqueous extraction. The polarity of water likely limited the solubility of certain bioactive compounds, leading to higher MIC values. This result is expected because synthetic antibiotics are purified compounds optimized for maximum specificity and efficacy; gentamicin consistently showed much lower MIC values (1–2 µg/mL) across all strains.

A key observation in our study is that the same MIC values were obtained for *E. coli* (Gram-negative) and *S. aureus* (Gram-positive). Gram-negative bacteria are generally more resistant to plant-derived extracts due to the complexity of their outer membrane structures (Burt, 2004). The comparable susceptibility of Gram-positive *S. aureus* and Gram-negative *E. coli* is noteworthy. While possible mechanisms such as changes in membrane permeability, protein denaturation, or interference with shared metabolic pathways could be considered, these explanations remain hypothetical in the context of our study. They are presented here as potential directions for future mechanistic investigations rather than definitive conclusions.

The MIC value of 25 mg/mL determined for Pseudomonas aeruginosa is consistent with the pathogen's well-known intrinsic resistance mechanisms. This bacterium possesses limited external membrane permeability, highly efficient efflux pump systems, and various enzymatic defense mechanisms. All of these mechanisms contribute to tolerance to natural products (Pang et al., 2019). Therefore, the observed high MIC value should be interpreted not as a lack of efficacy of the extract, but as evidence of the organism's capacity to withstand antimicrobial challenges.

The antimicrobial assays were conducted using internationally recognized ATCC reference strains (*S. aureus* ATCC 25923, *E. coli* ATCC 25922, and *P. aeruginosa* ATCC 27853) rather than clinical isolates. Therefore, the study was designed to provide standardized and reproducible preliminary data rather than to establish clinical efficacy. Future studies incorporating larger sample sizes and clinical isolates are warranted to validate these preliminary observations.

In summary, the data obtained indicate significant biological activity. Rather than indicatin limited efficacy, the results suggest that the crude extract may not exhibit a strong effect at low concentrations but may function as a phytocomplex with broad potential for biological interactions. Previous studies have consistently reported that crude extracts exhibit activity on the mg/mL scale; however, subsequent fractionation and purification often yield compounds with substantially greater activity. In this context, our findings provide valuable preliminary evidence to support future bio-directed isolation studies aimed at identifying active components with higher potency at lower concentrations (Cos et al., 2006).). The preliminary results of this study highlight a promising connection between high polyphenol content and antimicrobial activity. As a pilot investigation, this work lays the groundwork for future studies employing compound-specific identification and correlation approaches to build upon these initial findings.

These results demonstrate that wild blueberries grown at high altitudes in unpolluted environments are a valuable resource for both human health and ecosystem services, thanks to their rich biochemical composition.

5. Conclusion

In conclusion, wild blueberries collected from the Kurt Dağı highlands exhibit a remarkable bioactive profile, characterized by elevated levels of total polyphenols (21.041 ± 0.976 µg/g GAE) and flavonoids (1.733 ± 0.294 µg/g QE). Antimicrobial testing using the microdilution method consistently demonstrated inhibitory effects, with the strongest activity observed against *S. aureus* ATCC 25923 and *E. coli* ATCC 25922 (MIC: 6.5 mg/mL). Notably, significant inhibition was also maintained against the more resistant *P. aeruginosa* ATCC 27853 (MIC: 25 mg/mL). These findings indicate that the region-specific phenolic richness could contribute to the observed antimicrobial activity. Although the extract demonstrated inhibitory activity against reference strains, the relatively high MIC values suggest that its aqueous extract has limited potency. Thus, while the results underline the phenolic richness and biological potential of the Kurt Dağı blueberry population, they should be interpreted cautiously and considered preliminary. Future studies aimed at achieving higher antimicrobial activity should focus on alcoholic extraction methods and evaluation against clinical isolates. Moreover, subsequent research should include larger sample sizes to improve statistical power, as well as seasonal and geographical comparisons to capture environmental variability. In addition, the identification of individual bioactive compounds and evaluation of antimicrobial activity using purified fractions are necessary to further support the proposed applications. Such approaches will provide more definitive insights into the therapeutic potential of *V. arctostaphylos* populations from the Kurt Dağı plateau. The present findings demonstrate that crude aqueous extracts of the Kurt Dağı blueberry population have measurable in vitro antimicrobial activity. While these results highlight the phenolic richness and biological potential of the fruit, conclusions regarding therapeutic applicability should be interpreted with caution because the study is limited to in vitro MIC determinations. Further investigations, including in vivo efficacy, bioavailability, pharmacokinetics, toxicity, and safety assessments, will be valuable to confirm whether the observed antimicrobial effects can be translated into physiological conditions. In this context, our study provides preliminary but encouraging evidence that warrants future research with purified fractions and clinical models.

Limitations

This study has several limitations that should be acknowledged. First, aqueous extraction was chosen to ensure direct suitability for human application; however, this approach may have limited the extraction of certain bioactive compounds compared with organic solvent extraction. Second, no phytochemical characterization of individual compounds was performed, preventing definitive conclusions regarding the specific molecules responsible for the observed activity. Third, given the exploratory nature of this pilot study, antimicrobial testing was conducted against only three reference bacterial strains and did not include clinical isolates. Fourth, no formal power analysis was performed prior to the study, which we acknowledge as a methodological limitation. Taken together, these constraints underscore the preliminary nature of the present work, which should be regarded as a pilot study providing initial evidence of the phenolic richness and antimicrobial potential of *V. arctostaphylos* fruits from this unique ecological region. Larger-scale investigations incorporating expanded sample sizes, diverse extraction methods, compound-level characterization, clinical isolates, and prospective power calculations are warranted to validate and extend these findings.

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Author Contributions

H.K: Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. S.Ö.: Formal analysis, Investigation, Supervision, Writing - original draft, Writing - review & editing. M.Ö.: Investigation, Data curation, Writing - original draft, Writing - review & editing.

Conflicts of interest

The author(s) has(have) no conflicts of interest to disclose.

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