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Research Article

Antibiotic Resistance Profiles and Biochemical Characterization of Bacteria Isolated from Gökçeada Salt Lake Lagoon (Çanakkale) Sediment Samples

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ABSTRACT

Gökçeada Salt Lake Lagoon in Çanakkale, Türkiye, is a hypersaline environment that supports halophilic bacterial communities. This study examined the antibiotic susceptibility of 60 bacterial isolates obtained from four seasonal sediment samples. Morphological and biochemical characterization of the isolates included Gram staining, indole production, nitrate formation tests, and elemental analysis using ICP-OES. Antibiotic resistance was assessed via the disk diffusion method using seven antibiotics: Novobiocin (5 µg), Erythromycin (15 µg), Streptomycin (10 µg), Bacitracin (10 µg), Penicillin G (10 µg), Ampicillin (10 µg), and Tetracycline (30 µg). ICP-OES results showed elevated S, Ca, Mg, Na, and Fe concentrations, particularly in April 2024. The Multiple Antibiotic Resistance (MAR) index exceeded 0.2 in all isolates, with the highest value (0.7142) also detected in April 2024. The Shapiro-Wilk test indicated non-normal distribution of MAR values; thus, the Kruskal-Wallis test was used for statistical analysis. Although no significant difference was found between sampling periods ($p > 0.05$), seasonal increases in resistance suggest gradual adaptation. The consistently high MAR indices point to ongoing anthropogenic pressure, likely due to tourism, agriculture, and livestock activities in the region. This persistent exposure may drive resistance development in microbial populations. The findings underscore the importance of monitoring antibiotic resistance in halophilic bacteria, as such resistance may pose public health risks through environmental pathways.

1. Introduction

Coastal lagoons are rich in biodiversity and represent environmentally sensitive ecosystems. These wetlands serve as transitional zones between freshwater and saltwater, creating unique hydrological conditions that support a diverse array of plants, animals, and microbial species [1]. The dynamic interplay between freshwater inflows and seawater intrusion results in fluctuating salinity levels, which shape the ecological structure of these environments and facilitate the adaptation of specialized organisms.

Gökçeada Salt Lake Lagoon (Çanakkale), located in western Türkiye, is one such unique ecosystem. It has a relatively shallow depth of approximately 0.8–1.2 meters and covers a surface area of 2 km². Due to its high salinity and distinctive environmental conditions, the lagoon provides an optimal habitat for extremophilic microorganisms, particularly halophiles [2, 3]. These microorganisms have evolved remarkable physiological and genetic adaptations that enable them to survive in hypersaline conditions, making them integral components of the lagoon's microbial community. The lagoon is located within the administrative boundaries of Eşelek village in Gökçeada district of Çanakkale

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province, with the village having a small population of approximately 170 people.

The lagoon is situated about 1 km from the village center and lies only 0.3 km from the main road, indicating relatively easy access. Its surroundings exhibit various anthropogenic influences: to the south and east, just 180 meters from the lagoon, there are livestock farming facilities, including a dairy farm and a goose breeding operation. Additionally, a beach used for tourism purposes is also located nearby, contributing to seasonal human activity in the area. Agricultural lands are present approximately 100 meters northeast of the lagoon, potentially impacting the ecosystem through runoff or nutrient input. Although there is no direct waste discharge into the lagoon at the sampling points, these localized human activities may influence its physicochemical and microbial characteristics, indicating a degree of anthropogenic pressure on this otherwise unique hypersaline environment.

Halophilic microorganisms play a crucial role in biogeochemical cycles, contributing to nutrient recycling, organic matter degradation, and overall ecosystem functioning in saline environments. Their unique adaptation mechanisms allow them to withstand extreme osmotic stress, which has also been linked to their ability to develop resistance to antibiotics [4]. The genetic plasticity of halophilic bacteria enables them to acquire and maintain antibiotic resistance genes, often through horizontal gene transfer, further enhancing their resilience to environmental stressors. Antibiotic resistance has emerged as a critical global health concern, with an increasing number of resistant bacterial strains being detected in natural ecosystems, particularly those subjected to anthropogenic pressures.

The widespread and often indiscriminate use of antibiotics in human medicine, agriculture, and aquaculture has contributed to the selection and proliferation of resistant bacterial populations [5]. Coastal ecosystems, including lagoons, are particularly vulnerable to the accumulation and dissemination of antibiotic-resistant bacteria due to their exposure to agricultural runoff, industrial discharge, and untreated or partially treated wastewater [6].

One of the key indicators used to assess antibiotic resistance in bacterial populations is the Multiple Antibiotic Resistance (MAR) index, which reflects the extent to which bacteria have developed resistance to multiple antibiotics. A high MAR index suggests significant selective pressure exerted by anthropogenic activities, leading to the persistence of resistant strains in the environment. In ecosystems influenced by human activity, such as coastal lagoons, the presence of MAR bacteria poses potential risks not only to microbial communities but also to public health, as resistant genes can be transferred to clinically relevant pathogens [7].

Given the ecological significance of Gökçeada Salt Lake Lagoon and the increasing concerns regarding antibiotic resistance in extreme environments, this study aims to characterize the biochemical properties and antibiotic resistance profiles of halophilic bacteria isolated from the lagoon. Specifically, the study focuses on evaluating the MAR index to assess the impact of environmental and anthropogenic factors, such as agriculture, animal husbandry, and tourism, on the prevalence of antibiotic-resistant bacteria in this hypersaline ecosystem. Understanding these resistance patterns is essential for developing strategies to mitigate the spread of antibiotic resistance and for preserving the ecological integrity of saline environments.

2. Materials and Methods

2.1. Field studies and halophile isolation

Sediment samples were taken from the lagoon at 20-25 cm depth in four different periods (September 2023, December 2023, April 2024, July 2024), brought to the laboratory under aseptic conditions, and stored at +4°C for isolation. In situ measurements of physicochemical parameters, including temperature, dissolved oxygen (DO), pH, and electrical conductivity (EC), were conducted using a Hach-Lange multiparameter probe (Model HQ40d18).

ICP-OES elemental analyses (sulfur (S), calcium (Ca), magnesium (Mg), sodium (Na), manganese (Mn), copper (Cu), iron (Fe), zinc (Zn), boron (B), selenium (Se)) of sediment samples collected from field studies were carried out as a service purchase.

SW-25 medium (NaCl; 202,5 g/L, $MgCl_2$; 17,5 g/L, $MgSO_4$; 24 g/L, $CaCl_2$; 0,9 g/L, KCl; 5 g/L, $NaHCO_3$; 0,15 g/L, NaBr; 0,065 g/L, Yeast extract; 5 g/L, Agar; 20 g/L) was determined to be suitable for halophilic bacteria by Bozkurt [8] and SW-25 medium was used in the studies. 10 g of sample was suspended in 0.9% physiological serum isotonic solution, and serial dilutions were made from this solution up to 10^{-5}. The spread plate method cultured 100 µL of each dilution on selective media for halophiles. After 7 days of incubation at 37-40°C, the purification process of bacterial isolates was carried out on SW-25 agar. All purified isolates were stored in a glycerol medium at –20°C [8].

2.2. Biochemical analysis

The cell morphology of pure cultures was examined by Gram staining. Gram (+) bacteria were observed in purple, and Gram (-) bacteria were observed in pink [8]. For the indole test, bacteria were incubated at 40°C for 7 days in a SW-25 medium containing 1% tryptone, and a red ring was considered a positive result [9]. The nitrite test was incubated in a SW-25 medium containing 1% KNO_3. Nitrite and nitrate presences were determined by color changes [10, 11].

2.3. Characterization of antibiotic resistance profiles

To assess antibiotic resistance profiles, the resistance of isolated bacterial strains to various antibiotics was evaluated. Bacterial cultures were prepared and spread on SW-25 agar according to the 0.5 McFarland standard. Novobiocin (NV, 5 µg), Erythromycin (E, 15 µg), Streptomycin (S, 10 µg), Bacitracin (B, 10 µg), Penicillin G (P, 10 µg), Ampicillin (AM, 10 µg), and Tetracycline (TE, 30 µg) disks were placed on each bacterial strain using the disk diffusion method. Plates were incubated at 37°C for 24 hours. At the end of incubation, inhibition zone diameters formed around each antibiotic disk were measured, and resistance was classified as intermediate or susceptible according to CLSI (Clinical and Laboratory Standards Institute) standards. The selection of these antibiotics was made both to evaluate the resistance profile of environmentally derived bacteria and to determine their susceptibility levels to different antibiotic classes. In addition, the combined use of antibiotics from different groups allows the determination of broad-spectrum resistance profiles of halophilic bacteria.

The number of antibiotics to which each isolate showed resistance was recorded to determine the Multiple Antibiotic Resistance (MAR) index. The MAR index was calculated by dividing the number of antibiotics to which the isolate was resistant by the total number of antibiotics tested, and strains higher than 0.2 were considered high-risk groups [12].

2.4. Statistical analysis

In this study, a one-way ANOVA test was applied to evaluate whether the MAR index values obtained in different periods showed a statistically significant change. The Levene test was performed to evaluate whether the variances of the groups were homogeneous. Mean, standard deviation (SD), minimum (min), and maximum (max) values were calculated for each period. Shapiro-Wilk normality test and Kruskal-Wallis were applied to test the conformity of the data to a normal distribution [13].

PCA (Principal Component Analysis) was used to scale and visualize large data sets based on antibiotic resistance profiles of bacterial isolates. This analysis was applied to determine the variability in the dataset and to visually represent the similarities between isolates. The resistance and susceptibility profiles of each isolate against antibiotics (S: susceptible, R: resistant) were converted into numerical data and made suitable for PCA. The data were analyzed in a standardized manner, and the first two principal components obtained (PC1 and PC2) were selected to reflect the largest variation in the resistance profiles of bacterial isolates. PCA analysis was applied to visualize the representation of each isolate on a two-dimensional plane, and the grouping trends among the isolates were revealed [14]. NMDS (Non-metric Multidimensional Scaling) was used to visualize the multi-dimensional data of the resistance profiles of bacterial isolates against antibiotics.

This analysis provides a non-metric method to represent similarities between isolates and allows visualization of data in two or more dimensions without reducing the number of dimensions of the dataset, preserving the original structure. Each bacterial isolate was converted to numerical values according to its resistance to antibiotics, and a distance matrix was created. This distance matrix was used to determine similarities between isolates. Using this distance data, NMDS analysis located the isolates based on their antibiotic resistance profiles and color-coded them according to their resistance levels. This visualization was used to clearly distinguish isolates with high and low resistance levels [15].

3. Results

3.1. Isolation and biochemical characterization of halophilic bacteria

Seasonal variation in physicochemical parameters of the Gökçeada Salt Lake Lagoon was evident across the sampling periods. The highest water temperature was recorded in Sep 2023 (32.1 ± 0.31 °C) and Jul 2024 (30.6 ± 0.54 °C), while the lowest was observed in Dec 2023 (14.2 ± 1.47 °C). pH values ranged from slightly acidic to neutral, with the lowest in Sep 2023 (5.06 ± 0.16) and the highest in Dec 2023 (7.41 ± 0.29). Dissolved oxygen levels were markedly elevated in Dec 2023 (16.15 ± 3.37 mg/L), whereas lower concentrations were detected during the warmer months. Electrical conductivity showed a clear increase during the summer, reaching its peak in Jul 2024 (140.1 ± 2.74 mS/cm), and the lowest values occurred in Dec 2023 (52.07 ± 1.71 mS/cm).

In this study, the concentrations of S, Ca, Mg, Na, Mn, Cu, Fe, Zn, B, and Se were evaluated across four sampling periods—Sep 2023, Dec 2023, Apr 2024, and Jul 2024 using ICP-OES analysis. The results revealed a notably high concentration of Ca (14,869.75 ppm), Mg (1,765.0 ppm), Na (571.25 ppm), and Fe (4,932.0 ppm) in Apr 2024. In the same period, Zn (66.585 ppm) and B (98.11 ppm) levels were also within a sufficient range. In Sep 2023, the highest concentrations were observed for S (8,718.5 ppm) and Na (73,609.25 ppm).

In contrast, elemental concentrations in Dec 2023 were generally low, with particularly minimal levels of S (21.068 ppm), Fe (<0.006 ppm), and Cu (<0.689 ppm). In Jul 2024, elevated levels of Mg (2,147.75 ppm) and Na (3,267.25 ppm) were detected, while B remained below the threshold (<13.232 ppm). The markedly elevated concentrations of Ca, Mg, Na, and Fe in Apr 2024 highlight this period as a peak phase for elemental accumulation.

A total of 60 halophilic bacteria were isolated within the scope of the study (Fig 1).

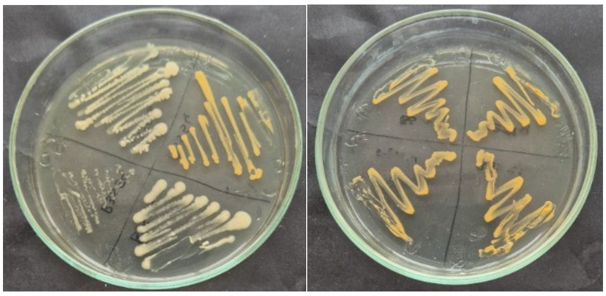

Figure 1. Halophilic bacteria isolated from sediment samples

When the Gram properties were evaluated, 33 of the isolates were determined as gram-positive bacilli, 15 as gram-positive cocci, 7 as gram-negative bacilli, 2 as gram-negative cocci, 2 as gram-negative cocci and 1 as gram-positive coccobacillus. In addition, when the biochemical test results of 60 isolates were examined, it was found that 37 isolates were indole negative (-), 23 isolates were indole positive (+), 32 were nitrite negative (-), and 28 were nitrite positive (+). The results related to nitrate show that 38 isolates were nitrate negative (-) and 22 were nitrate positive (+) (Fig. 2).

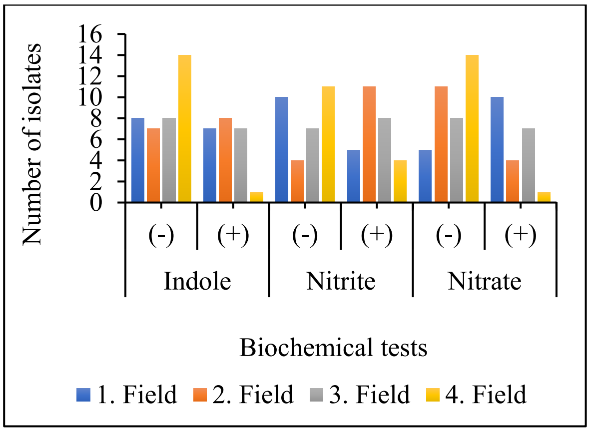

Figure 2. Biochemical analysis results of isolates

3.2. Antibiotic resistance profiles of isolates

The antibiotic susceptibility profiles of bacterial strains isolated from Gökçeada Salt Lake Lagoon were analyzed, revealing variations in resistance (R), intermediate resistance (I), and sensitivity (S) rates to different antibiotics (Table 1, Fig 3). The highest resistance rate was observed for the antibiotic E15, where 55.0% of the strains were found to be resistant. The intermediate resistance rate was the highest for the antibiotic TE30, which was determined as 16.7%. The highest sensitivity rates were determined as 45.0% for S10 and AM10 antibiotics.

Table 1. Antibiotic susceptibility percentages of isolates

Antibiotics	S (%)	I (%)	R (%)
NV5	43.3	13.3	43.3
E15	31.7	13.3	55.0
S10	45.0	8.3	46.7
B10	36.7	11.7	51.7
P10	33.3	13.3	53.3
AM10	45.0	13.3	41.7
TE30	36.7	16.7	46.7

NV: Novobiocin, E: Erythromycin, S: Streptomycin, B: Bacitracin, P: Penicillin G, AM: Ampicillin, T: Tetracycline, S: Susceptible, I: Intermediate, R: Resistant

MAR index data show (Fig 4) the antibiotic resistance profiles of bacterial isolates obtained in different periods. MAR indexes of isolates isolated in Sep 2023 ranged between 0.285 and 0.571, which reveals that some isolates (1T9 and 1T6) had high resistance values (0.571) in Sep 2023.

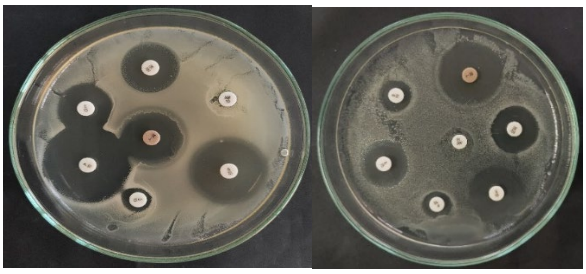

Figure 3. Antibiotic susceptibility test images of sediment isolates

In Dec 2023, MAR indexes were again observed to be between 0.285 and 0.571, with isolates such as 2T10 and 2T4 showing high resistance. There was an increase in the Apr 2024 period. Isolates coded 3T2 and 3T9 reached the highest resistance level with 0.714. Data from the Jul 2024 period show that resistance levels generally decreased slightly compared to Apr 2024, but isolates coded 4T2 and 4T5 still exhibited high values.

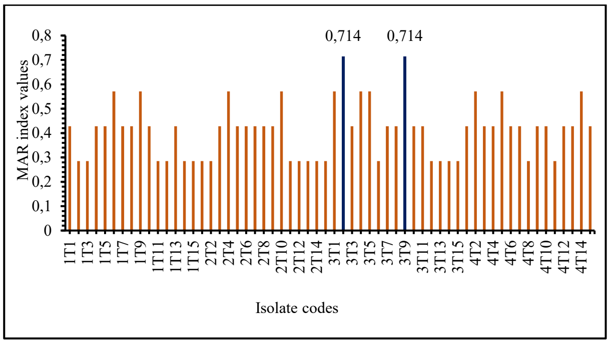

Figure 4. MAR index values of isolates (1T1: 1st sample of 1st fieldwork)

3.3. Statistical analysis

Descriptive statistics for MAR index values obtained in different periods are presented (Table 2) and Shapiro-Wilk analysis results are presented (Table 3).

Table 2. Statistical data on MAR index values

Period	Mean values	Standard deviation (SD)	Min.	Max.	Sample number (n)
Sep 2023	0.3899	0.1006	0.285	0.571	15
Dec2023	0.3803	0.1035	0.285	0.571	15
Apr 2024	0.4471	0.1516	0.285	0.714	15
Jul 2024	0.4375	0.0849	0.285	0.571	15
Control Strain (*Halomonas elongata* ATCC 33173)	0.3125	0.0678	0.250	0.400	5

Table 3. Shapiro-Wilk analysis results

Period	Shapiro-Wilk Test (p)
Sep 2023	0.003
Dec 2023	0.002
Apr 2024	0.026
Jul 2024	0.001

As a result of the Shapiro-Wilk Test (p), it was determined that the MAR index data did not conform to the normal distribution since $p < 0.05$ in all periods. These p-values indicate that the null hypothesis of the test (H_0: Data are normally distributed) was rejected for each period. In other words, MAR index values do not exhibit normal distribution. This is a common situation in data obtained from natural microbial communities. Resistance profiles of environmental microorganisms are generally affected by many factors, including antibiotic exposure, seasonal changes, environmental stresses, and microbial competition.

Failure to provide normal distribution restricted the use of parametric tests and required the use of nonparametric methods for statistical analysis. Therefore, the nonparametric Kruskal-Wallis test was applied to evaluate the difference between periods. The Shapiro-Wilk test results show that MAR index values show high variation and do not exhibit clearly normal distribution in different periods. According to the Kruskal-Wallis test results, the test statistics were calculated as H=3.57 and the p-value as p=0.312. Since this p-value is greater than the generally accepted significance level of α=0.05, it was concluded that the MAR index values did not show a statistically significant difference between the four different periods. The distribution of MAR index values of bacteria isolated in four different periods is shown (Fig. 5).

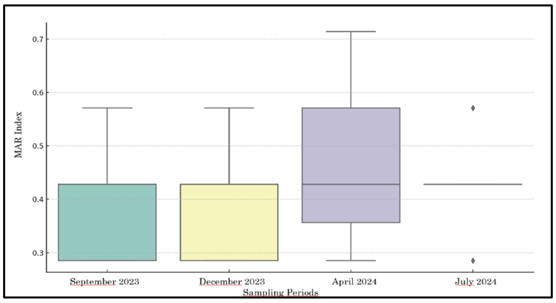

Figure 5. MAR index distribution by periods

The resulting PCA plot (Fig. 6) illustrates the spatial separation of isolates along the first two principal components (PC1 and PC2), which together account for the majority of the variance in the dataset. A gradient in MAR index values is evident, with isolates exhibiting higher resistance levels (MAR index > 0.57) clustering in specific regions of the plot, while those with lower resistance (MAR index < 0.43) are distributed more broadly. This suggests that bacterial isolates with higher antibiotic resistance share common resistance profiles, potentially influenced by selective pressures in the environment. Additionally, the dispersion of isolates indicates variability in resistance mechanisms among the bacterial population.

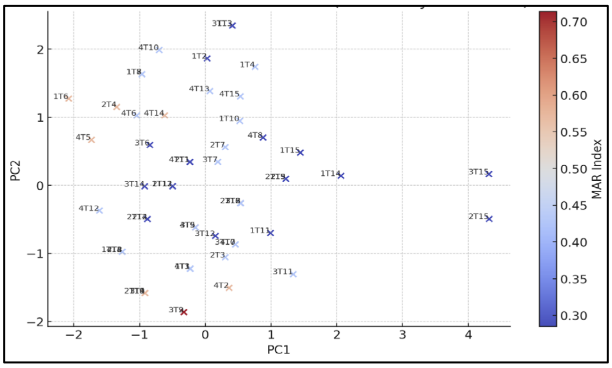

Figure 6. PCA analysis of antibiotic resistance profiles

The NMDS analysis graph (Fig. 7) shows that the points representing each bacterial isolate are positioned in a two-dimensional space according to their resistance patterns to antibiotics. The similarities and differences between the isolates are shaped according to their susceptibility to the antibiotics used in the analysis, and if the isolates are located close to each other, they have similar resistance profiles, while those that are far away indicate that they have different resistance patterns. The colored scale is visualized based on the MAR index of each isolate. Red tones indicate isolates with a high MAR index, and blue tones indicate isolates with a low MAR index.

This visualization allows visual discrimination of resistance levels between isolates. In particular, it was observed that isolates with a high MAR index are generally located in red tones, and isolates with a low MAR index are concentrated in blue tones. The resulting NMDS graph reveals that the resistance profiles of bacterial isolates to antibiotics are distributed in a multivariate structure and that different isolate groups cluster by exhibiting similar resistance patterns.

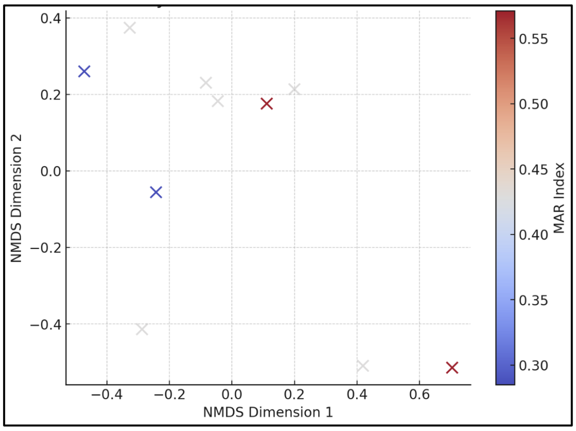

Figure 7. NMDS analysis of antibiotic resistance profiles

4. Discussion

Investigating bacterial diversity and antibiotic resistance profiles in lagoon ecosystems is of great importance for understanding the ecology of these dynamic environments and assessing potential sources of pollution. Compared to terrestrial systems, more variable environmental conditions in lagoons exert continuous selective pressure on microbial communities, promoting the development of diverse resistance mechanisms. The presence of bacterial isolates resistant to various contaminants reflects the ecosystem's exposure to such compounds [16, 17].

Antibiotic resistance is one of the most critical global health concerns of our time. The tendency of bacteria to adhere to surfaces such as sediments makes coastal and benthic zones particularly active areas for the persistence and spread of resistance traits against antibiotics and heavy metals [18-20].

This study investigated the antibiotic resistance profiles of culturable halophilic bacterial communities isolated from the Gökçeada Salt Lake Lagoon during different seasons. The marked differences in Gram staining and various biochemical reaction profiles of the isolates indicate that they belong to taxonomically diverse groups. This suggests that the observed antibiotic resistance patterns should not be attributed to resistance adaptation of a single bacterial lineage over time. Rather, they reflect the dynamic responses of distinct microbial groups or resistant fractions within the culturable community shaped by the lagoon's seasonal environmental conditions.

Highly dynamic habitats such as lagoons can alter the composition of microbial populations and the prevalence of resistance genes or genetic elements through seasonal environmental pressures. Therefore, the variations in resistance profiles observed across sampling periods are likely associated with shifts in community structure or seasonal fluctuations in selective pressures. This approach provides a valuable perspective for understanding environmental reservoirs of resistance.

The findings demonstrate that culturable bacterial isolates from the Gökçeada Salt Lake Lagoon exhibited resistance to a wide range of antibiotics. Notably, high resistance rates were observed against antibiotics such as E10, B10, and P10. Similar studies conducted in other marine and coastal environments of Türkiye have also reported a high prevalence of antibiotic resistance among sediment-derived bacteria.

Comparable results were found in isolates from the Red Sea, Gölbaşı Lake, Tuzla Lagoon, and Shatkhira, where high resistance rates were reported against antibiotics including AM10, TE30, P10, Cephalothin, and Oxacillin [21-26]. The overall high resistance levels detected in this study support the hypothesis that the culturable bacterial community in Gökçeada Lagoon has been exposed to antibiotics and harbors multiple resistance traits, aligning with general knowledge about resistance prevalence in hypersaline environments. However, direct quantitative comparisons remain limited due to differences in antibiotic panels and taxonomic compositions among studies.

Seasonal variations in environmental element concentrations and physicochemical parameters are believed to influence the microbial community structure in the lagoon, thereby affecting resistance profiles. The study identified significant seasonal fluctuations in water temperature, salinity, dissolved oxygen, and pH. Sediment elemental analyses also revealed notable differences in element concentrations across sampling periods. Particularly in Apr 2024, elevated levels of Ca, Mg, Na, and Fe were detected. Previous studies in the Gökçeada region have reported the presence and, in some cases, high concentrations of heavy metals in various environmental matrices [26]. Heavy metals, commonly found in marine environments due to both natural processes and anthropogenic activities, tend to accumulate in sediments. These metals can exert co-selective pressure on antibiotic resistance through metal resistance genes that are often co-located with antibiotic resistance genes on mobile genetic elements [27].

The MAR index is a key indicator for assessing the risk of antibiotic pollution in the environment, with values above 0.2 generally considered indicative of high-risk contamination. In the current study, a substantial proportion of the culturable bacterial isolates (95.5%) exhibited MAR index values exceeding this threshold, suggesting a significant potential risk of antibiotic resistance in the sediments of the Gökçeada Salt Lake Lagoon.

Although no statistically significant differences were found between sampling periods in terms of MAR index values, descriptive statistics and isolate-specific data revealed a trend toward higher average MAR values in isolates obtained in Apr 2024. This period also included isolates with the highest individual MAR values. This trend suggests that environmental conditions specific to Apr 2024 may have selected for or enriched bacterial populations with higher resistance levels. Increased water temperature and biological activity during this period could promote bacterial growth [28].

More importantly, the high concentrations of certain elements detected in Apr 2024 may reflect elevated environmental loading. The intensification of agricultural and livestock activities during spring in the region could lead to the runoff of fertilizers and animal waste into the lagoon, thereby increasing both elemental concentrations and the potential introduction of antibiotic residues or resistance determinants. This co-selective pressure driven by increased elemental load may be a critical factor contributing to the observed rise in resistance during Apr 2024.

The increase in MAR index during Apr 2024, compared to the tourism-heavy month of Jul 2024, suggests that environmental resistance is shaped not only by direct human density but also by complex seasonal environmental pressures. PCA and NMDS analyses showed that isolates clustered based on their resistance profiles, with high MAR isolates sharing similar patterns. These analyses highlight the presence of distinct resistance groups within the culturable community and the concentration of multidrug resistance in specific subpopulations. This supports the idea that the resistance profile of the lagoon's culturable bacterial community is not homogeneous and varies according to environmental factors.

The location of the Gökçeada Salt Lake Lagoon along major migratory bird routes raises concerns about the potential dissemination of environmental antibiotic resistance via wildlife to other ecosystems or human and animal populations [29]. Resistant bacteria and resistance genes in environmental settings may be transmitted through the food chain or direct contact, posing significant public health risks. Therefore, monitoring and understanding antibiotic resistance in ecologically dynamic and wildlife-interactive systems such as this lagoon are crucial not only for ecological health but also for human and animal health.

5. Conclusion

In conclusion, this study revealed that the antibiotic resistance profiles of culturable halophilic bacterial communities in the Gökçeada Salt Lake Lagoon vary seasonally and are shaped by the lagoon's physicochemical dynamics, elemental composition, and potential anthropogenic inputs. The increased resistance observed in Apr 2024, along with elevated elemental concentrations and MAR indices, suggests that specific environmental pressures during this period may favor the enrichment of resistant phenotypes. Focusing on the culturable community level, this study provides important baseline data on the functional status of environmental resistance reservoirs. It also establishes a solid foundation for future molecular investigations into the mechanisms underlying these complex interactions and resistance dynamics. A deeper understanding of environmental resistance in vulnerable ecosystems, such as the Gökçeada Salt Lake Lagoon is essential for managing potential public health risks.

Article Information Form

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Authors' Contribution

İK: Conducted the field studies, performed the halophile isolation and biochemical analyses, characterized antibiotic resistance profiles, and drafted the initial manuscript. NHD: Served as the supervisor for the research, contributed to the study's conception and design, assisted with data interpretation, and critically reviewed and revised the manuscript.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by authors.

Artificial Intelligence Statement

No artificial intelligence tools were used while writing this article.

Copyright Statement

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