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RESEARCH ARTICLE ARAŞTIRMA MAKALESİ

A critical transition zone for fan mussels (*Pinna nobilis*): The Dardanelles as a barrier against mass mortality

Pinalar (*Pinna nobilis*) için kritik bir geçiş bölgesi: Kitlesel ölümlere karşı bir bariyer olarak Çanakkale Boğazı

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Abstract: *Pinna nobilis* (fan mussel) is facing mass mortality event (MME) across the Mediterranean Sea due to a combination of several factors, including the pathogen *Haplosporidium pinnae* and other associated pathogens, as well as climate change, invasive species, habitat degradation, boat anchoring, exploitation, and disruptions in the food web. Despite a MME associated with mucilage event, the Sea of Marmara (SoM) still hosts high-density populations of fan mussels. Despite the severe impact across the Mediterranean, the persistence of populations in the SoM has raised questions about the factors contributing to their survival. This study investigates the role of salinity patterns in the survival of fan mussel populations in the Dardanelles, a critical transition zone between the Aegean Sea and the SoM. The objective is to determine whether the unique salinity patterns in the Dardanelles provide a protective effect against the MME. Underwater observations were conducted at 23 sites in the Dardanelles in August 2024, and salinity patterns were analysed. The results reveal a significant increase in mortality rates as salinity rises above 24.9 psu, with nearly 100% mortality observed at the higher salinity levels. These findings, synthesized with existing literature, suggest that the salinity patterns in the Dardanelles play a crucial role in the survival of fan mussel by either preventing the pathogen from entering the SoM or mitigating its lethal effects. The Dardanelles, which serves as a critical transition point by supporting the survival of fan mussel populations, should be the focus of additional scientific research.

Keywords: Critically endangered, mass mortality event, *Pinna nobilis*, salinity, Çanakkale Strait, Mediterranean Sea

Öz: *Pinna nobilis* (Pina), *Haplosporidium pinnae* patojeni ve diğer ilişkili patojenlerin etkisiyle kitlesel ölüm olayı (MME) ile karşı karşıyadır, bunun yanı sıra iklim değişikliği, istilacı türler, habitat bozulması, çapalama, aşırı avcılık ve besin ağındaki bozulmalar da dahil olmak üzere çeşitli faktörlerin birleşimi nedeniyle Akdeniz boyunca kritik düzeyde tehlike altındadır. Müsilaj olayıyla ilişkilendirilen bir MME'ye rağmen, Marmara Denizi (SoM) hala yüksek yoğunluklu pina popülasyonlarına ev sahipliği yapmaktadır. Akdeniz'deki şiddetli etkiye rağmen, SoM'deki popülasyonların devam etmesi, hayatta kalmalarına katkıda bulunan faktörler hakkında soruları gündeme getirmiştir. Bu çalışma, Ege Denizi ile SoM arasında kritik bir geçiş bölgesi olan Çanakkale Boğazı'ndaki pina popülasyonlarının hayatta kalmasında tuzluluğun rolünü araştırmaktadır. Bu çalışma, Çanakkale Boğazı'ndaki benzersiz tuzluluk değerlerinin MME'ye karşı koruyucu bir etki sağlayıp sağlamadığını belirlemeyi amaçlamaktadır. Ağustos 2024'te Çanakkale Boğazı'ndaki 23 noktada su altı gözlemleri yapılmış ve tuzluluk modelleri analiz edilmiştir. Sonuçlar, tuzluluk değerlerinin 24,9 psu'nun üzerine çıktığında pinaların ölüm oranlarında önemli bir artış olduğunu ve daha yüksek tuzluluk seviyelerinde neredeyse %100 ölüm oranının gözlemlendiğini ortaya koymaktadır. Mevcut literatürle sentezlenen bu bulgular, Çanakkale Boğazı'ndaki tuzluluk değerlerinin, patojenin SoM'ne girmesini önleyerek veya ölümcül etkilerini azaltarak yelpaze midyesinin hayatta kalmasında önemli bir rol oynadığını düşündürmektedir. Pina popülasyonlarının hayatta kalmasını destekleyerek kritik bir geçiş noktası görevi gören Çanakkale Boğazı, ek bilimsel araştırmaların odak noktası olmalıdır.

Anahtar kelimeler: Kritik düzeyde tehlike altında, toplu ölüm olayı, *Pinna nobilis*, tuzluluk, Çanakkale Boğazı, Akdeniz

INTRODUCTION

Pinna nobilis (Linnaeus, 1758), commonly known as the fan mussel or noble pen shell, is the largest bivalve native to the Mediterranean Sea. Since 2016, the species has been experiencing a devastating and geographically widespread mass mortality event (MME) throughout the Mediterranean basin (Vázquez-Luis et al., 2017; Katsanevakis et al., 2021; Labidi et al., 2023). This event represents one of the most severe and rapid population collapses of a marine species in the Mediterranean basin in recent years. The primary culprits behind this MME are believed to be *Haplosporidium pinnae*, a species-specific pathogenic protozoan of unknown origin (Catanese et al., 2018), and a poorly characterized *Mycobacterium* sp. (Carella et al., 2019). Although *H. pinnae* has long been recognized as the primary cause of MMEs (Grau et al., 2022; Donato et al., 2023; Foulquie et al., 2023), it often coexists with other pathogens, which together exacerbate mortality rates (Čižmek et al., 2020; García-March et al., 2020). Other pathogens, such as *Vibrio* sp. and *Perkinsus* sp., have occasionally been reported in affected populations (Carella et al., 2020; Künili et al., 2021; Carella et al., 2023). As a result, the population of the fan mussel across nearly the entire Mediterranean Sea has been severely impacted, leading the International Union for Conservation of Nature (IUCN) to classify this rare species as Critically Endangered. This classification reflects the combined effects of multiple threats, including climate change, invasive species, habitat loss, boat

anchoring, alterations in the food web, and exploitation (Kersting et al., 2019). Despite the rapid spread of the disease, some Mediterranean regions with unique water conditions, including coastal lagoons, which can exhibit very high or low salinity compared to the open sea, have managed to maintain surviving populations of fan mussel. These isolated areas are characterized by specialized temperature and salinity gradients that affect the prevalence or survival of the disease (Catanese et al., 2018; Cabanellas-Reboredo et al., 2019; Zotou et al., 2020; Giménez-Casalduero et al., 2020; Çınar et al., 2021a; Papadakis et al., 2023; Martínez-Martínez et al., 2024; Nebot-Colomer et al., 2024; Nikolaou et al., 2024).

Among the isolated areas where fan mussel has managed to persist despite widespread MME across the Mediterranean basin, the Sea of Marmara (SoM) stands out as a remarkable exception. Following an extreme MME in the SoM, potentially linked to an epidemic infection or a catastrophic mucilage event (Çınar et al., 2021a), populations of fan mussel continue to persist at relatively high densities (Öndes et al., 2020; Çınar et al., 2021b; Karadurmuş and Sarı, 2022; Acarlı et al., 2024; Karadurmuş et al., 2024), offering a rare opportunity to investigate factors contributing to their resilience. Recent studies have confirmed the presence of *Haplosporidium* and *Mycobacterium* species in fan mussel populations in the SoM (Karadurmuş et al., 2025), indicating that the parasite responsible for MMEs has indeed reached this region. Despite this, high-density populations of fan mussels continue to persist, suggesting that the unique environmental conditions of the SoM may mitigate or suppress the lethal effects of these pathogens. Alternatively, the fan mussel populations in this semi-enclosed basin may possess a distinct genetic structure that confers greater resistance to infection. These possibilities highlight the urgent need for comprehensive multidisciplinary research to understand the mechanisms underpinning population survival in this area.

Although MMEs have been reported along the Mediterranean coast from Gibraltar to the Aegean Sea (Katsanevakis et al., 2021; Künili et al., 2021; Carella et al., 2023) and also Dardanelles (Acarlı et al., 2021; Aksu et al., 2021; Aksu et al., 2023), high-density populations of fan mussels still persist in the SoM (Çınar et al., 2021b; Karadurmuş and Sarı, 2022; Acarlı et al., 2024; Karadurmuş et al., 2024), just north of the Dardanelles. The Dardanelles, located between the Aegean Sea and the SoM, represents a critical transitional zone and may provide valuable insights into the factors influencing fan mussel survival. This striking contrast suggests the possibility that the factors causing MME on the southern side of Dardanelles do not affect the northern side. Acarlı et al. (2021) stated that the Dardanelles acts as a barrier to the survival of fan mussels, underscoring the need for further investigation into environmental drivers of MMEs in this region. Although the SoM has lower temperature and salinity than the Mediterranean, these conditions have been reported to be insufficient to inhibit *H. pinnae*, the pathogen responsible for mass mortality (Acarlı et al., 2023). This study aims to explore the relationship between salinity patterns and the survival of fan mussels in the Dardanelles. Through underwater observations and distribution mapping, we investigate whether the spatial occurrence of fan mussel populations corresponds with local salinity gradients.

MATERIALS AND METHODS

Study area

The Dardanelles, an essential component of the Turkish Straits System (TSS), serves as the primary focus of this study. TSS comprises the SoM, which connects to the Aegean Sea and the Black Sea through the Dardanelles and Bosphorus, respectively. Located in northwestern Türkiye, the Dardanelles is a narrow, natural strait of immense international significance, forming part of the continental boundary between Asia and Europe and separating Asian side from European side of Dardanelles. The Dardanelles is relatively narrow (1.2–7 km), long (61 km), and shallow (50–120 m) channel (Ünlülata et al., 1990). The strait is characterized by two sharp right-angle turns at the Nara Pass, where it also reaches its narrowest width. The average depth of the Dardanelles is approximately 55 meters, with a maximum depth of 103 meters at its narrowest point near Cape Nara. The topography of the Dardanelles is notably complex, with the strait featuring both shallow areas and a deep channel (Sannino et al., 2017). This deep channel, reaching depths of up to 75 meters, runs through the strait and then turns eastward in the southern part of the funnel-shaped area before merging with the western depression of the SoM. This intricate bathymetry creates unique environmental conditions that are hypothesized to influence the survival patterns of fan mussel within the region.

Site selection

The methodology involved a two-phase approach to underwater observations, with the aim of identifying the distribution patterns and mortalities of fan mussel within the Dardanelles. In the first phase, underwater observations were conducted along the 140 km coastline of the Dardanelles, covering both the Asian and European sides. Sites were systematically selected at 10 km intervals along the coast. These initial observations aimed to provide a broad overview of the fan mussel distribution and identify key transition zones where significant changes in mortalities were observed. First phase revealed a notable transition zone between Nara Burnu (40°11'43"N–26°25'41"E) and Dardanos (40°04'42"N–26°21'36"E) on the Asian side, and between Eceabat (40°11'27"N–26°21'31"E) and Kilitbahir (40°06'08"N–26°19'10"E) on the European side. These transition zones marked significant shifts in the survival of fan mussel populations, suggesting the need for more focused study. The study area was then narrowed down to the identified transition zones. In the second phase, micro-scale underwater observations were conducted at more closely spaced sites (set at 3 km intervals) between the transition zones. A total of 23 sites along the Dardanelles between August 8-18, 2024, were surveyed to analyze the distribution and survival patterns of fan

mussels in the Dardanelles investigated to provide a comprehensive data set.

Data collection and analysis

Underwater observations were conducted using SCUBA diving along strip transects at each selected site (Katsanevakis, 2007; Vafidis et al., 2014; Theodorou et al., 2017). A chain strip, segmented at 10-meter intervals, was deployed perpendicular to the shoreline (Hastie and Tibshirani, 1990). Two divers swam along the transect line, systematically counting all fan mussels, both alive and dead, encountered within a 2-meter-wide corridor on either side of the strip. The transect was limited to a depth of 20 meters, meaning the length of each transect varied depending on the topography of the sites. The total scanned area (m^2) for each transects was calculated by multiplying the length of the scanned transect and by the width of the strip corridor (4 meters). The vital status of each fan mussel within the transect boundaries was assessed easily *in situ* (Figure 1) and recorded on an underwater board. Alive fan mussels were easily identified by their characteristic behavior; they react to disturbances by rapidly closing their shells when touched or approached. In contrast, dead mussels were identified by their unresponsive shells, which were either permanently open or completely closed and contained no tissue. Broken or cracked shells were also classified as dead. The mean density of alive fan mussels was calculated by determining the number of individuals per hundred square meters (ind·100 m^{-2}). This metric was used to estimate the population density at each site along the transects.

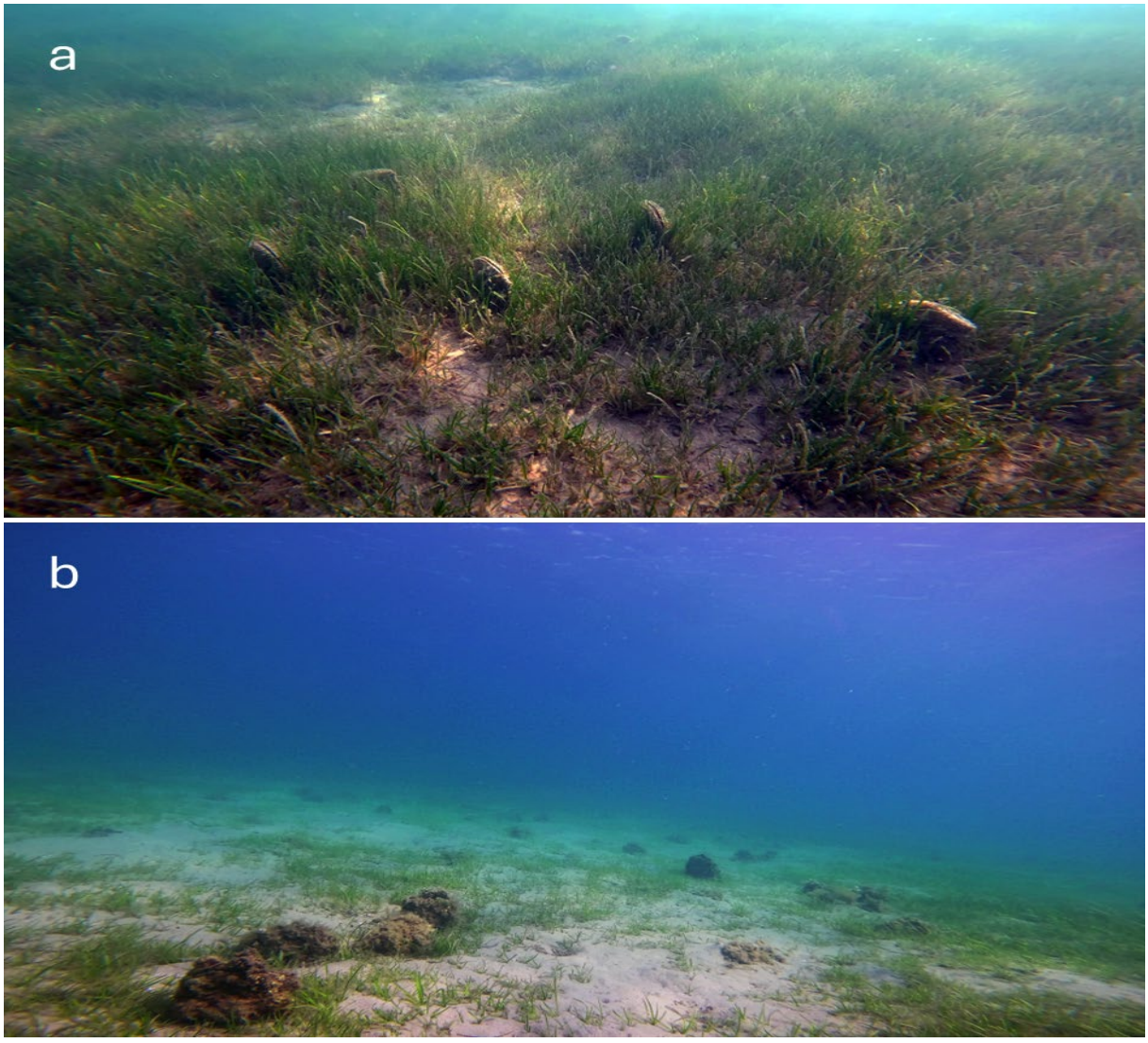

Figure 1. Juvenile and alive individuals observed at the Eceabat station (No: 19; 40°11'27"N–26°21'31"E) (a), individuals with broken and deformed shells, likely long dead, observed at the Kilitbahir station (No: 14; 40°06'08"N–26°19'10"E) (b)

Water salinity (SaL, psu) was measured at approximately 1 m depth at all sites using a YSI® ProDss multiparameter instrument. To gain a comprehensive understanding of salinity patterns in the Dardanelles, seawater temperature, salinity,

and depth profiles from the Black Sea, SoM, and Aegean Sea were examined, along with relevant studies that model high-resolution surface and bottom salinity vectors across different seasons in the Dardanelles (Türkoğlu et al., 2006; Sannino et al., 2017; Aydogdu et al., 2018; Ilicak et al., 2021; Brovchenko et al., 2022) were included in the literature. While instantaneous measurements provide valuable insights into marine conditions, they can vary due to a range of factors and seasonal changes. Therefore, parameters such as sea surface temperature, dissolved oxygen, pH, turbidity, total dissolved solids, and suspended solids—despite their potential influence on the distribution and survival of fan mussels—were excluded from this dataset to focus on salinity as the primary variable of interest. *In situ* salinity measurements included in the data set were used to confirm the relationship of survivals to salinity through statistical analysis. Underwater video footage of all scanned stations is available and stored for data transparency.

Statistical analyses

A Pearson correlation analysis was performed to evaluate the strength and direction of the relationship between salinity levels and mortality rates. The relationship was found to be non-linear, displaying a threshold-like pattern. Therefore, different regression models were tested, including linear, second-degree polynomial, and third-degree polynomial regression. This method was chosen because it allows for modelling and predicting the extent to which changes in salinity (independent variable) can explain variations in mortality rate (dependent variable). By estimating the slope and intercept of the regression line, the analysis helps identify potential trends and the magnitude of salinity's influence on mortality. To compare fan mussel densities between the Asian and European sides of the Dardanelles, a two-sample t-test was conducted. The Shapiro-Wilk test confirmed that the data were normally distributed, allowing for the use of a parametric test. A two-sample t-test (assuming unequal variances) was performed to test if there was a significant difference between the mean densities on both sides. The test was conducted at a 0.05 significance level. All statistical analyses were performed using SPSS v26.0.

RESULTS

The results revealed that there was a significant increase in mortality rates of fan mussels on both sides of the Dardanelles, extending from Çardak and Gelibolu in the north to Kumkale and Seddülbahir in the south (Figure 2a; Table 1). In the northernmost parts of the Asian side, mortality rates were initially moderate, ranging from 6.7% to 22.2% between Çardak (Site 1) and Cape Nara (Site 6), where salinity levels varied between 22.5 and 24.3 psu. However, as one moves southward towards Cape Kepez (Sites 7-9), mortality rates escalated sharply to between 63.6% and 90%, with salinity levels rising slightly to 24.5-24.9 psu. In the southernmost region from Cape Kepez to Kumkale (Sites 10-12), the mortality rates reached 100%, corresponding with higher salinity levels of 24.9-29.3 psu along this 25 km coast. Mortality rates were low (0-16.7%) from Gelibolu to Kilitbahir (Sites 17-23) in the northernmost parts of the European side, where salinity levels ranged from 23.1 to 24.2 psu. However, further south from Kilitbahir to Seddülbahir (Sites 18-22), mortality rates abruptly increased to 100%, coinciding with higher salinity levels of 27.4 to 29.5 psu (Figure 2b; Table 1). This stark contrast within a relatively short distance (approximately 20 km) suggests a critical threshold of salinity beyond which fan mussels are unable to survive. In conclusion, 100% mortality of fan mussel was observed when salinity levels reached approximately 29.3 psu on the Asian side and 27.5 psu or higher on the European side of the Dardanelles.

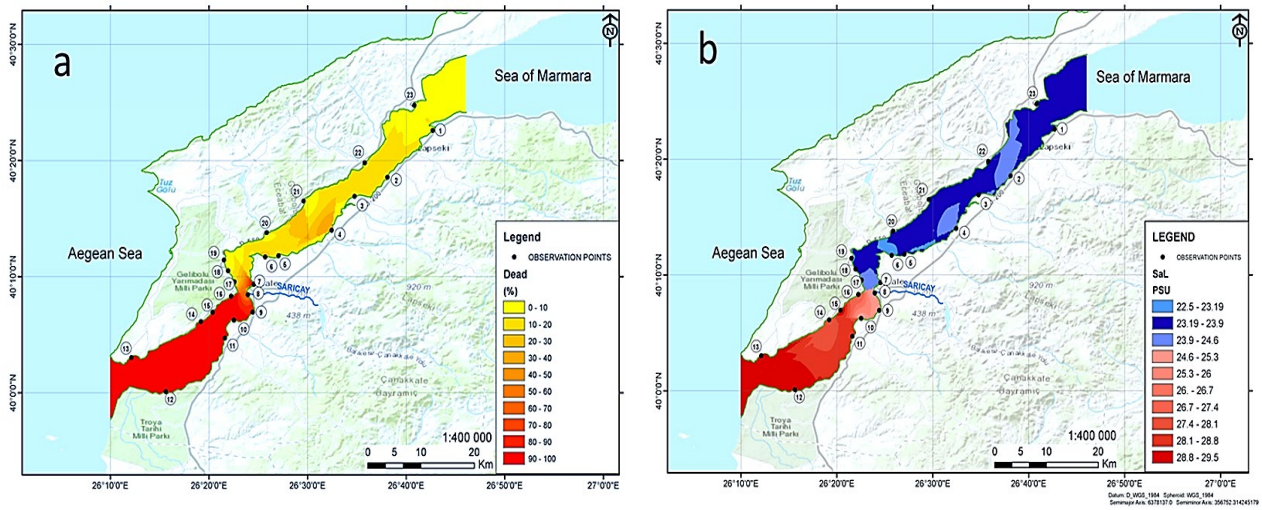

Figure 2. Spatial distribution of mortality rates (a) and salinity (b) of *Pinna nobilis* across sampling sites in the study area (Dardanelles, August 2024)

Table 1. Summary on the geographic information of surveyed sites and the status of fan mussel populations in the Dardanelles

Geographic Information				Population Structure			
Site no	Side & direction	Coordinate (Latitude, Longitude)	SaL (psu)	Alive	Dead	Mortality rate (%)	Density (alive)
1	Asian, North	40°22'36"N–26°42'39"E	23.7	14	1	6.7	5.0
2		40°18'33"N–26°38'05"E	24.3	8	1	11.1	2.3
3		40°16'55"N–26°34'45"E	23.5	21	5	19.2	4.5
4		40°14'01"N–26°32'25"E	24.3	17	11	39.3	4.7
5		40°11'48"N–26°27'02"E	23.9	32	6	15.8	11.4
6		40°11'43"N–26°25'41"E	22.5	7	2	22.2	2.1
7		40°09'21"N–26°24'32"E	24.5	5	40	88.9	1.1
8		40°08'27"N–26°23'56"E	24.5	4	7	63.6	1.1
9		40°06'57"N–26°24'24"E	24.9	2	18	90.0	0.6
10		40°06'16"N–26°22'31"E	24.9	0	17	100.0	–
11	South	40°04'42"N–26°21'36"E	28.5	0	11	100.0	–
12		40°00'06"N–26°15'37"E	29.3	0	2	100.0	–
13	European, South	40°03'02"N–26°12'07"E	29.5	0	8	100.0	–
14		40°06'08"N–26°19'10"E	27.4	0	26	100.0	–
15		40°06'57"N–26°20'22"E	29.3	0	21	100.0	–
16		40°08'19"N–26°22'14"E	27.5	0	16	100.0	–
17		40°09'34"N–26°22'34"E	24.2	5	1	16.7	1.9
18		40°10'31"N–26°21'55"E	23.4	36	1	2.7	15.0
19		40°11'27"N–26°21'31"E	23.1	42	0	0.0	19.1
20		40°13'48"N–26°25'50"E	23.6	20	1	4.8	7.4
21		40°16'30"N–26°29'34"E	23.6	8	0	0.0	2.6
22	North	40°19'47"N–26°35'47"E	23.8	22	3	12.0	9.2
23		40°24'46"N–26°40'48"E	23.4	13	1	7.1	6.2

The analysis of data set revealed a significant correlation between increasing salinity and higher mortality rates of fan mussels (Figure 3). The second-degree polynomial regression model provided the best fit to the data ($R^2 = 0.77$). This model revealed that mortality rates increase sharply beyond a certain salinity threshold. Specifically, a salinity value around 24.9 psu emerged as a critical tipping point. Below this value, mortality rates were relatively low and variable, whereas above it, mortality rates rapidly approached 100%.

The mean density of surviving fan mussels on the Asian side was 3.4 ind·100 m^{-2} (ranged from 0.6 to 11.4 ind·100 m^{-2}), while on the European side, it was 8.3 ind·100 m^{-2} (ranged from 1.9 to 19.1 ind·100 m^{-2}). While the European side showed a higher mean density, the difference between the two sides was not statistically significant at the 0.05 level (t-test, t= -1.944, p = 0.085).

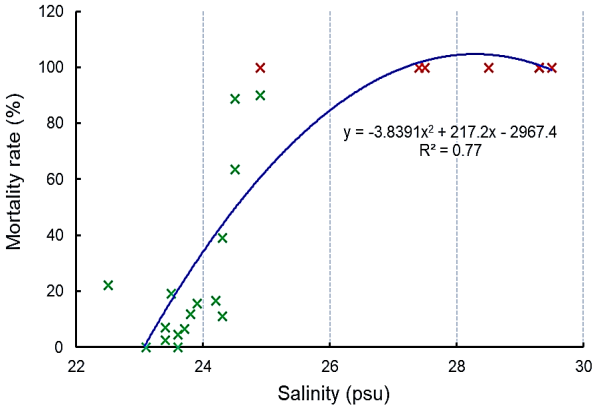

Figure 3. Scatter plot of salinity (psu) vs. fan mussel mortality (%) in the Dardanelles. The solid blue line represents the regression line for sites with surviving individuals (green icon) and sites with completely dead individuals (red icon), respectively.

DISCUSSION

This study highlighted that there was a significant increase in fan mussel mortality rates from north to south on both sides of the Dardanelles (gradual on the European side and abrupt on the Asian side). This pattern suggests that environmental conditions, possibly influenced by Mediterranean waters, become increasingly unfavourable for fan mussel survival as one moves southward. The secret behind the survival of fan mussels may be closely linked to the salinity patterns of the Dardanelles, which appear to play a critical role in mitigating the effects of MME, as suggested by Acarlı et al. (2024).

The Dardanelles narrows significantly between Kilitbahir and Çanakkale, leading to distinct temperature and salinity differences between the northeastern and southwestern parts of the strait. Near Cape Nara, salinity dramatically increases to around 27 psu. These changes exhibit a synchronous oscillatory pattern from Cape Nara to the Aegean exit, and, together with the narrow constriction of the strait, contribute to the formation of Kelvin-Helmholtz instabilities—a physical phenomenon that occurs when two fluid layers with different densities and velocities slide past one another, creating turbulence at their interface (Stashchuk and Hutter, 2001). Such mixing processes may influence the vertical and horizontal distribution of salinity in the water column. The rise in mortality rates observed south of Kilitbahir and Cape Nara underscores this critical salinity threshold beyond which the survival of fan mussels is severely compromised. In this study, mortality rates near or at 100% were consistently recorded in stations with salinity levels of 24.9 psu and above (Table 1). Notably, Acarlı et al. (2024) reported 100% mortality around the Dardanos region in the southern Dardanelles, where salinity was measured at 24.6 psu. Moreover, the polynomial regression model (Figure 3) suggest that high salinity conditions might correspond with an increased likelihood of mass mortality events in fan mussel populations.

Salinity seems to significantly inhibit the spread of *H. pinnae*, as noted by several studies (Cabanellas-Reboredo et al., 2019; Catanese et al., 2018; Katsanevakis et al., 2021; Prado et al., 2022). The optimal salinity range for *H. pinnae* is reported to be between 36.5 and 39 psu, according to Prado et al. (2022), or 36.7 and 39.5 psu, as indicated by Cabanellas-Reboredo et al. (2019). Salinity appears to significantly inhibit the lethal effect of *H. pinnae* and can suffer from increased mortality when salinity levels deviate significantly from the optimum range (Cabanellas-Reboredo et al., 2019; García-March et al., 2020). Cabanellas-Reboredo et al. (2019) strongly suggest that disease expression appears to be closely associated with the salinity range of 36.5–39.7 psu. Similarly, in the Mar Menor, high salinity is implicated in preventing the spread of pathogens and influencing mussel survival (Prado et al., 2022). Because the channels act as entry points for protozoans, individuals in the Mar Menor, which are nearer to the zones connecting to the Mediterranean Sea, are more vulnerable to salinity fluctuations and face a higher risk of infection (Martínez-Martínez et al., 2024). This study suggests that salinity plays a crucial role in the survival of fan mussels. Findings align with the broader understanding that extreme salinity levels, whether high or low, can be detrimental, and in this case, it seems salinity is the more critical factor (Nebot-Colomer et al., 2022).

The gradual increase in mortality observed on the European side contrasts with the more abrupt transition on the Asian side. The sharp divergence in mortality rates between the European and Asian sides, particularly near critical points like Kepez Burnu and Kilitbahir, underscores the influence of localized conditions on the health of fan mussel populations in this region. The discrepancy in salinity and mortality rates between Cape Nara and Cape Kepez may be due to the freshwater input via the Sarıçay Stream. As shown in Figure 2, the discharge area of Sarıçay Stream coincides with a zone where salinity drops to critical levels. This observation is consistent with findings from Alfacs Bay and other areas influenced by significant freshwater input, where lower salinity has been associated with reduced mortality (De Wit, 2011; Prado et al., 2021). The lower density of fan mussel on the Asian side aligns with the hypothesis that high-salinity Mediterranean waters can reach longer distances in this side and even affect the northern coasts of the SoM. High-resolution salinity models in the literature (Türkoğlu et al., 2006; Sannino et al., 2017; Ilicak et al., 2021) confirm that these high-salinity waters follow the Asian coast of the Dardanelles and penetrate to the entrance of the southern parts of the SoM.

CONCLUSION

This study provides significant insights into the survival mechanisms of fan mussel populations in the Dardanelles, a unique ecological transition zone between the Mediterranean Sea and the SoM. Our findings reveal the critical role that salinity plays in the survival of fan mussel populations. The distinct hydrodynamic conditions in the Dardanelles create sharp salinity gradients that act as a natural barrier, influencing the distribution and survival of fan mussels. Future research should aim to further elucidate the environmental and biological stress factors that contribute to the survival of fan mussel in the Dardanelles and investigate how these factors influence pathogen dynamics. Such studies will provide a deeper understanding of the mechanisms supporting fan mussel resilience and inform conservation strategies. Areas where surviving fan mussel persists are particularly important, not only as reservoirs for the species but also as potential sources of larvae that will aid the recovery of other populations. So, the findings emphasize the importance of monitoring the unique ecological conditions in the Dardanelles and SoM, which may be crucial for the long-term survival of this critically endangered species.

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AUTHOR CONTRIBUTIONS

Fieldwork was conducted by Uğur Karadurmuş and Mustafa Sarı. Mustafa Akkuş took part in mapping and data visualization. All authors reviewed the final version of the manuscript.

ETHICAL APPROVAL

No fan mussel was landed during the study. Underwater clinical examinations were performed using non-destructive methods. Therefore, formal approval is not required for this study.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DECLARATION OF AI USE

Generative artificial intelligence tools were not utilized in the preparation of this study. All text, analysis, and content were produced exclusively by the authors through human input.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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