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To achieve open access to scholarly journal literature, we recommend two complementary strategies.

I. Self-Archiving: First, scholars need the tools and assistance to deposit their refereed journal articles in open electronic archives, a practice commonly called, self-archiving. When these archives conform to standards created by the Open Archives Initiative, then search engines and other tools can treat the separate archives as one. Users then need not know which archives exist or where they are located in order to find and make use of their contents.

II. Open-access Journals: Second, scholars need the means to launch a new generation of journals committed to open access, and to help existing journals that elect to make the transition to open access. Because journal articles should be disseminated as widely as possible, these new journals will no longer invoke copyright to restrict access to and use of the material they publish. Instead, they will use copyright and other tools to ensure permanent open access to all the articles they publish. Because price is a barrier to access, these new journals will not charge subscription or access fees, and will turn to other methods for covering their expenses. There are many alternative sources of funds for this purpose, including the foundations and governments that fund research, the universities and laboratories that employ researchers, endowments set up by discipline or institution, friends of the cause of open access, profits from the sale of add-ons to the basic texts, funds freed up by the demise or cancellation of journals charging traditional subscription or access fees, or even contributions from the researchers themselves. There is no need to favor one of these solutions over the others for all disciplines or nations, and no need to stop looking for other, creative alternatives.

Open access to peer-reviewed journal literature is the goal. Self-archiving (I.) and a new generation of open-access journals (II.) are the ways to attain this goal. They are not only direct and effective means to this end, they are within the reach of scholars themselves, immediately, and need not wait on changes brought about by markets or legislation. While we endorse the two strategies just outlined, we also encourage experimentation with further ways to make the transition from the present methods of dissemination to open access. Flexibility, experimentation, and adaptation to local circumstances are the best ways to assure that progress in diverse settings will be rapid, secure, and long-lived.

The Open Society Institute, the foundation network founded by philanthropist George Soros, is committed to providing initial help and funding to realize this goal. It will use its resources and influence to extend and promote institutional self-archiving, to launch new open-access journals, and to help an open-access journal system become economically self-sustaining. While the Open Society Institute's commitment and resources are substantial, this initiative is very much in need of other organizations to lend their effort and resources.

We invite governments, universities, libraries, journal editors, publishers, foundations, learned societies, professional associations, and individual scholars who share our vision to join us in the task of removing the barriers to open access and building a future in which research and education in every part of the world are that much more free to flourish.

For various reasons, this kind of free and unrestricted online availability, which we will call open access, has so far been limited to small portions of the journal literature. But even in these limited collections, many different initiatives have shown that open access is economically feasible, that it gives readers extraordinary power to find and make use of relevant literature, and that it gives authors and their works vast and measurable new visibility, readership, and impact. To secure these benefits for all, we call on all interested institutions and individuals to help open up access to the rest of this literature and remove the barriers, especially the price barriers, that stand in the way. The more who join the effort to advance this cause, the sooner we will all enjoy the benefits of open access.

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2. Pre-Evaluation Process

In the pre-evaluation process, the field editors examine the studies, introduction and literature, methods, findings, results, evaluation and discussion sections in detail in terms of journal publication policies, scope and authenticity of study. Study which is not suitable as a result of this examination is returned to the author with the field editor's evaluation report within four weeks at the latest. The studies which are suitable for the journal are passed to the referee process.

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TABLE OF CONTENTS

Mar. Sci. Tech. Bull. (2025) 14(2): 70-79
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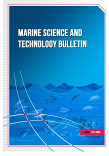

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RESEARCH ARTICLE

Use of freshness indicators containing red beetroot and red cabbage extracts in monitoring shrimp freshness

Fatma Öztürk[1] • Hatice Gündüz[1*]

[1] *Izmir Katip Celebi University, Faculty of Fisheries, Department of Fisheries and Fish Processing Technology, Izmir, Türkiye*

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ABSTRACT

This study aimed to develop natural extract-based freshness indicators for real-time monitoring of shrimp spoilage during refrigerated storage (4°C) for up to nine days. The indicators were composed of 1% (w/v) red cabbage or red beetroot extract, 2% (w/v) sodium alginate, and 10% (v/v) glycerol, and were incorporated into packaging materials. To assess shrimp quality and spoilage, pH, total volatile basic nitrogen (TVB-N), total mesophilic aerobic bacteria (TMAB), and total psychrophilic aerobic bacteria (TPAB) counts were monitored. The results showed significant increases in pH (from 7.52 to 7.88), TVB-N (from 20.3 mg/100 g to 44.80 mg/100 g), TMAB (from 3.72 log CFU/g to 7.29 log CFU/g), and TPAB (from 6.30 log CFU/g to 8.21 log CFU/g) confirming microbial spoilage. The spoilage threshold for TVB-N (35 mg/100 g) was exceeded on the fifth day, indicating the end of shrimp shelf life. Accordingly, the color change (ΔE) values of the indicators changed markedly over time: the ΔE value increased from 0 to 11.34 for the red cabbage-based indicator, while it decreased from 8.53 to 3.51 for the red beetroot-based indicator. The red cabbage-based indicator exhibited strong and statistically significant correlations with pH ($r = 0.86$, $p = 0.029$) and TVB-N ($r = 0.83$, $p = 0.040$), indicating high potential for freshness detection. In contrast, the red beetroot-based indicator showed weaker and statistically insignificant correlations. These findings suggest that natural extract-based freshness indicators, particularly those containing red cabbage extract, offer a promising and non-invasive alternative to conventional methods for monitoring shrimp spoilage and enhancing food packaging systems.

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* Corresponding author
E-mail address: hatice.gunduz1@ikcu.edu.tr (H. Gündüz)

Introduction

In recent years, consumer interest in seafood has been steadily increasing due to its role as a primary source of long chain polyunsaturated fatty acids, essential vitamins, and minerals, all of which significantly contribute to human health (Mohammadalinejhad et al., 2020). Among seafood products, shrimp stands out as a valuable source of high-quality fatty acids and proteins, while containing minimal carbohydrates. Additionally, shrimp provides essential micronutrients such as vitamin B3, folate, calcium, magnesium, phosphorus, and potassium, making it an important component of a well-balanced diet. Due to its high protein content and low caloric value, shrimp is particularly recommended for individuals seeking a nutrient dense diet (Fan et al., 2022). However, despite its nutritional benefits, fresh shrimp has a limited shelf life (typically 4-6 days under refrigeration) and is highly susceptible to quality deterioration due to its elevated moisture content, free amino acids, and other soluble non nitrogenous compounds (Mohammadalinejhad et al., 2020). During storage, enzymatic reactions and microbial contamination accelerate the deterioration of seafood products, significantly affecting their quality and safety. Consequently, monitoring the freshness of seafood has become a critical concern for consumers, retailers, and the food industry (Wen et al., 2023; Kılınç et al., 2023; Ho et al., 2024). Traditional methods for evaluating the freshness of seafood typically rely on chemical, microbiological, or sensory analyses. While these methods provide reliable results, they often require extensive processing time, skilled personnel, and labor-intensive procedures, making them impractical for rapid assessments (Wu et al., 2019; Kuswandi et al., 2022). To overcome these limitations, various advanced techniques, including electrochemical sensors, Raman spectroscopy, electronic noses, electronic tongues, and hyperspectral imaging, have been developed for seafood freshness evaluation. While these approaches offer high sensitivity and ease of use, their widespread application remains limited due to the need for costly instrumentation and the lack of real time monitoring capabilities. Hence, there is an urgent need to develop cost effective, non-destructive, and real time assessment techniques for monitoring the freshness of seafood products within the industrial food chain (Wu et al., 2019; Wen et al., 2023). Conventional food packaging systems, on the other hand, do not provide real time information about the condition of the packaged food or the internal environment, making it difficult for consumers to assess product freshness accurately (Ho et al., 2024).

Intelligent packaging films represent an advanced packaging technology designed to monitor the condition of food products during storage and transportation, thereby enhancing food safety and quality. These systems often incorporate colorimetric indicator films, which respond to environmental changes such as variations in pH. When the pH level of the packaged food fluctuates, the colorimetric indicator undergoes a visible color change, allowing consumers to assess food freshness without opening the package. This approach has the potential to enhance food quality while simultaneously reducing food waste (Ho et al., 2024). Given their efficiency, cost effectiveness, and ease of application, colorimetric pH sensitive indicator tags could serve as real time freshness monitoring tools for food products (Yan et al., 2021). A typical visual pH indicator consists of two fundamental components: a pH responsive dye and a solid support matrix that immobilizes the dye. Natural dyes are generally preferred over synthetic alternatives due to their lower toxicity, environmental compatibility, renewability, and non-polluting nature (Mohammadalinejhad et al., 2020). These natural pH indicators can be derived from various plant-based sources, including flowers, fruits, vegetables, and food industry by products. Several groups of natural pigments, such as anthocyanins, betalains, curcumin, chlorophyll, and shikonin, exhibit pH responsive behavior and possess additional functional properties such as antimicrobial and antioxidant activities, making them highly suitable for intelligent food packaging applications (Abedi-Firoozjah et al., 2022; Zheng et al., 2022; Chaari et al., 2024; Kaewprachu et al., 2024; Tavana et al., 2024).

Red cabbage (*Brassica oleracea* L.) is recognized as a rich source of natural anthocyanins, which are valued for their nutritional benefits and bioactive properties. This vegetable contains high levels of micronutrients, oligosaccharides, minerals, vitamins, and bioactive compounds such as flavanols and glucosinolates, which contribute to human health. Due to its low cost, widespread availability, and strong halochromic properties, red cabbage anthocyanins have garnered significant attention for use in pH responsive indicator films compared to anthocyanins from other natural sources (Abedi-Firoozjah et al., 2022; Cheng et al., 2022).

Similarly, red beetroot (*Beta vulgaris* L.), a biennial herbaceous plant belonging to the Amaranthaceae family, serves as an abundant source of betalains and phenolic compounds, making it a potent antioxidant (Aykın-Dinçer et al., 2021). Red beetroot contains two primary pigment groups: red betacyanins and yellow betaxanthins, collectively referred to as betalains (Eshaghi et al., 2020). In addition to their strong biological and antioxidant properties, betacyanins exhibit notable pH sensitivity, particularly under alkaline conditions, making them promising candidates for freshness monitoring in protein rich food products such as meat, fish, pork, and poultry (Chaari et al., 2024).

This study aims to develop a cost effective, eco-friendly, and pH sensitive freshness indicator by incorporating red beetroot and red cabbage extracts, with the goal of enabling real-time and non-destructive monitoring of shrimp freshness and spoilage. By doing so, it seeks to advance the development of intelligent food packaging systems that enhance consumer safety and contribute to the reduction of food waste.

Material and Methods

Materials

For the purposes of this study, 1 kg of fresh red beetroot (*Beta vulgaris* L.) and red cabbage (*Brassica oleracea*), along with 2 kg of fresh shrimp (*Parapenaeus longirostris*), were sourced from local markets in Izmir.

Methods

Preparation of Extracts from Red Beetroot and Red Cabbage

Fresh red cabbage and red beetroot were washed with tap water to remove dust and other impurities. They were then dried in a drying oven at 50°C and ground into powder. A total of 100 g of each dried plant material was used for extraction. Specifically, 20 g of dried red beetroot and 20 g of red cabbage powder were extracted using 400 mL of ethanol (80% v/v). The solvent was removed using a rotary evaporator, and the extracts were lyophilized in a freeze dryer. The resulting extracts were stored at +4°C in a refrigerator until further use (Alizadeh-Sani et al., 2021).

Preparation of Freshness Indicators

A 2% (w/v) sodium alginate solution was prepared by dissolving 2 g of sodium alginate in 100 mL of distilled water, followed by stirring and maintaining the mixture in a shaking water bath at 60°C for 40 min to ensure complete dissolution. Then, 10% (v/v) glycerol was added as a plasticizer and homogenized using a magnetic stirrer for 30 min. Subsequently, 1% (w/v) red cabbage and red beetroot extracts were incorporated into the mixture, followed by continuous stirring for an additional 30 min.

The final mixture was cast into 20 cm diameter metal trays and dried in an incubator at 30°C for 48 hours under controlled conditions. The dried films were then cut into approximately 3 × 3 cm^2 squares and stored in a desiccator until use. As a result, two distinct types of freshness indicator films (red cabbage based and red beetroot based) were obtained (Chen et al., 2023; Ranjbar et al., 2023; Wu et al., 2024).

Packaging and Storage of Shrimp Samples

Shrimp samples (100 g per container) were placed into lidded plastic containers. The developed freshness indicators were affixed to the inner upper surface of the containers to prevent direct contact with the shrimp. The packaged shrimp samples were stored at +4°C for nine days, and chemical, microbiological, and color analyses were performed at regular intervals.

Chemical Analyses

To assess the chemical changes during storage, pH and Total Volatile Basic Nitrogen (TVB-N) levels were analyzed. For pH measurement, a 10 g shrimp sample was homogenized in 100 mL of distilled water, and the mixture was filtered. The pH was then determined using a digital pH meter (Hanna, HI11312, UK) (Guran et al., 2015). TVB-N analysis were performed as described by (Goulas & Kontominas, 2005), and results were expressed in mg/100 g of shrimp sample.

Microbiological Analyses

Microbiological analyses were conducted to determine the total mesophilic aerobic bacteria (TMAB) and total psychrophilic aerobic bacteria (TPAB). For this purpose, 10 g of shrimp sample was transferred into 90 mL of sterilized Maximum Recovery Diluent solution under aseptic conditions, followed by homogenization. Serial dilutions were prepared up to a 10^6 dilution level using a 1:10 dilution ratio. From the appropriate dilutions, 0.1 mL aliquots were plated on Petri dishes containing Plate Count Agar (PCA, Merck). The inoculated plates for TMAB enumeration were incubated at 30°C for 24 to 48 hours, while the plates for TPAB were incubated at 6.5°C for 10 days. Following incubation, colony counts were performed to determine the bacterial load (Halkman, 2005).

Color Analysis of Freshness Indicators

The color properties of the freshness indicators were evaluated using a portable colorimeter (Color Muse, Variable Inc., Tennessee, USA). The *L* (lightness), *a* (redness), and *b* (yellowness) values were recorded for each indicator type. To assess the overall color variation during storage, the total color difference (ΔE) was calculated using the following formula (1) (Chen et al., 2023):

$$\Delta E = \sqrt{[(L_1 - L_0)^2 + (a_1 - a_0)^2 + (b_1 - b_0)^2]} \quad (1)$$

where L_0, a_0, and b_0 represent the initial color values measured on Day 0, and L_1, a_1, and b_1 correspond to the values obtained on subsequent storage days. In the results table, "Day 0" values are explicitly designated as the reference (initial) values used in ΔE calculations.

Statistical Analysis

The data obtained were analyzed using one-way ANOVA (analysis of variance), and group differences were evaluated using Duncan's Multiple Comparison Test. Prior to ANOVA, the underlying assumptions of normal distribution and homogeneity of variances were verified and found to be satisfied. Additionally, Pearson correlation analysis was performed to assess the relationships between ΔE values and pH, TVB-N, TMAB, and TPAB counts. The strength and direction of these associations were determined by calculating correlation coefficients (r), with statistical significance set at $p < 0.05$. All statistical analyses were conducted using IBM SPSS Statistics 2012.

Results and Discussion

Changes in the pH and TVB-N Values of Shrimp

Table 1 presents the pH values of packaged shrimp over a nine-day storage period. Due to microbial growth and the decomposition of protein substances in shrimp, pH levels increased significantly ($p < 0.05$), rising from 7.52 on day 0 to 7.82 on day 9. Oner et al. (2018) reported that the pH value of shrimp varied between 6.81 and 8.67 during storage. Similarly, Uçak (2019) observed that the initial pH values of 7.26 and 7.13 in shrimp increased to 7.82-8.30 at the end of eight days of storage at 4°C. Additionally, Bilgin et al. (2006) reported that pH values of brown shrimps stored under refrigerator conditions (4°C) increased from 6.83 at the beginning to 7.95 by day 5. Çolakoğlu et al. (2006) found that the pH value rose from 7.01 to 7.91 after six days of storage at 7°C. The increase in pH is primarily attributed to microbial metabolic activities, notably the deamination and decarboxylation of amino acids, which result in the accumulation of basic compounds such as ammonia, trimethylamine, and dimethylamine (Balamatsia et al., 2007; Kim et al., 2022).

Table 1. The changes in pH and TVB-N values of the shrimps

Day	pH	TVBN (mg/100 g)
0	7.52±0.07^{b}	20.30±0.70^{c}
1	7.84±0.06^{a}	21.35±0.35^{c}
3	7.76±0.03^{a}	22.05±1.75^{c}
5	7.85±0.07^{a}	33.60±5.60^{b}
7	7.88±0.01^{a}	42.00±1.40^{ab}
9	7.82±0.06^{a}	44.80±2.80^{a}

Note: Mean(n=2) ± standard error a, b, c (↓); There is a statistically significant difference between days with different letters in the same column (p> 0.05)

TVB-N, a widely accepted freshness index, quantifies the sum of these volatile nitrogenous compounds (Balamatsia et al., 2007; Kim et al., 2022). In our study, a statistically significant increase in TVB-N levels was observed throughout the storage period ($p < 0.05$). As refrigeration time increased, microbial and enzymatic activity led to protein decomposition, resulting in the formation of amines. These amines reacted with organic acids formed by protein degradation, causing the TVB-N content to rise to 44.80 mg/100 g by day 9. Bilgin et al. (2006) reported a similar trend, with TVB-N levels reaching 42.53 mg/100 g in shrimp stored at 4°C by day 5. A TVB-N concentration exceeding 35 mg/100 g is considered unacceptable for fish and shrimp (Varlık et al., 2000). In the present study, the TVB-N value surpassed this threshold on day 7 of refrigeration at 4°C (Table 1), indicating the end of the shrimp's shelf life.

Microbial Quality Assessment of Shrimp

The microbial quality of the shrimp was evaluated based on total mesophilic aerobic bacteria (TMAB) counts and total psychrophilic aerobic bacteria (TPAB) counts, as presented in Table 2. The initial TMAB count was 3.72 log CFU/g on day 0 and remained relatively stable until day 3. However, a statistically significant increase ($p<0.05$) was observed after day 5, reaching 4.90 log CFU/g. By day 7, TMAB levels had increased to 7.19 log CFU/g, and by day 9, the bacterial count had further increased to 7.29 log CFU/g ($p<0.05$).

The rapid microbial growth during the later storage days is likely due to favorable conditions for bacterial proliferation, including nutrient availability and enzymatic activity. Similar trends have been reported in previous studies. For instance, Bilgin et al. (2006) found that TMAB levels in refrigerated shrimp exceeded 5 log CFU/g after five days of storage, indicating the end of shelf life. According to international seafood safety standards, a microbial load above 7 log CFU/g is considered unacceptable for human consumption (ICMSF, 1986). In the present study, the TMAB count surpassed this threshold on day 7, suggesting that the shrimp were no longer suitable for consumption beyond this point.

Table 2. Total mesophilic aerobic bacteria (TMAB) and total psychrophilic aerobic bacteria (TPAB) counts of the shrimps (log CFU/g)

Day	TMAB (log CFU/g)	TPAB (log CFU/g)
0	3.72±0.27^{c}	6.30±0,13^{c}
1	3.54±0.11^{c}	6.15±0.03^{cd}
3	4.12±0.08^{c}	5.96±0.01^{d}
5	4.90±0.28^{b}	7.39±0.03^{b}
7	7.19±0.01^{a}	8.29±0.06^{a}
9	7.29±0.12^{a}	8.21±0.07^{a}

Note: Mean(n=2) ± standard error a, b, c (↓); There is a statistically significant difference between days with different letters in the same column (p> 0.05)

The TPAB counts of shrimp samples significantly increased (p<0.05) during storage, with the initial value of 6.30 log CFU/g reaching 8.21 log CFU/g on the ninth day. The rapid increase in TPAB observed, especially after the fifth day, indicates the onset of microbial spoilage. This increase highlights the tendency of psychrophilic bacteria to proliferate under cold storage conditions and their significance as a microbial indicator of product spoilage. Similarly, in a study by Yang et al. (2017), it was reported that in shrimp stored at 4°C, psychrophilic bacteria count exceeded those of mesophilic bacteria by the sixth day, indicating the beginning of spoilage. This suggests that psychrophilic bacteria become dominant during cold storage, limiting the shelf life of the product. Furthermore, in a study by Canizales-Rodríguez et al. (2015), it was reported that in blue shrimp stored on ice, the initial psychrophilic bacteria count of 2.61 log CFU/g increased to 7.14 log CFU/g after 18 days, and this increase led to significant quality losses. These findings support the idea that psychrophilic bacteria are a reliable indicator of spoilage in shrimp and other seafood, and that TPAB counts are an important parameter for monitoring product freshness. The microbial spoilage correlated with pH and TVB-N increases, indicating a close relationship between microbial activity and the biochemical degradation of shrimp proteins.

Color Change of Freshness Indicators

The colors of freshness indicators during the storage period are given in Tables 3 and 4. The present study demonstrated a continuous increase in the ΔE value of freshness indicators containing red cabbage and red beetroot extracts during storage. Specifically, the ΔE value increased from 0 to 11.34 in the freshness indicator containing red cabbage extract, whereas it decreased from 8.53 to 3.51 in the freshness indicator containing red beetroot extract.

The visual progression of color changes in freshness indicators over the storage period is presented in Figure 1. As illustrated, the indicator containing red cabbage extract exhibited a noticeable color shift, whereas the indicator containing red beetroot extract showed a gradual darkening. These visual observations correspond well with the numerical ΔE values reported in Tables 3 and 4, thereby reinforcing the reliability of the colorimetric response to pH changes induced by spoilage.

The accumulation of volatile basic amines, resulting from microbial activity in packaged shrimp within the food package cavity, led to an increase in pH and a shift in the color of the freshness indicator (Kim et al., 2017). These changes align with the chemical and microbiological spoilage parameters discussed previously.

Table 3. The colors of freshness indicators containing red cabbage extract during the storage period

Day	L	a	b	ΔE
0	73.11±1.44^{a}	4.77±1.01^{a}	14.03±0.31^{a}	0.00±0.00^{c}
1	70.94±1.94^{ab}	2.47±1.34^{b}	10.63±0.72^{b}	5.21±0.57^{b}
3	67.33±2.12^{bc}	2.27±0.39^{b}	10.01±0.20^{b}	7.58±0.24^{b}
5	65.72±3.81^{cd}	1.93±0.62^{b}	14.43±2.54^{a}	10.56±2.25^{a}
7	62.53±1.46^{d}	1.30±1.31^{b}	14.61±1.47^{a}	11.25±1.99^{a}
9	62.86±0.21^{d}	1.46±0.52^{b}	15.80±2.3^{a}	11.34±0.06^{a}

Note: Mean(n=2) ± standard error a, b, c (↓); There is a statistically significant difference between days with different letters in the same column (p> 0.05). In the ΔE calculation, Day 0 (L_0, a_0, b_0) used as the initial values.

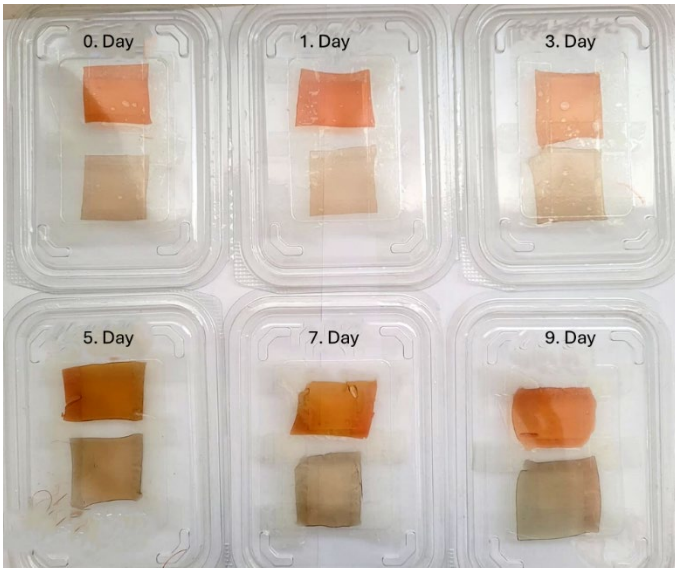

Figure 1. Color evolution of freshness indicators containing red cabbage and red beetroot extracts during the storage period. The top labeled samples correspond to red beetroot extract-based indicators, while the bottom labeled samples correspond to red cabbage extract-based indicators

An examination of the relationship between total color change values (ΔE) and the results of chemical and microbiological analyses revealed a strong correlation between increasing ΔE values and rising TVB-N, pH, TMAB, and TPAB counts. Both freshness indicators exhibited significant color shifts over time ($p<0.001$), demonstrating their potential effectiveness in indicating shrimp spoilage. However, statistical analysis (independent samples t-test, $p=0.471$) showed no significant difference between the color changes in red cabbage and red beetroot-based indicators, suggesting that both films performed similarly in detecting spoilage.

A strong positive correlation was observed between ΔE values of the red cabbage indicator both pH ($r=0.86$, $p=0.029$) and TVB-N ($r=0.83$, $p=0.040$) as shown in Table 5. In contrast, the correlation between pH and TVB-N values and the red beetroot-based freshness indicator was lower and statistically insignificant ($r=0.69$, $p=0.129$ and $r=0.43$, $p=0.398$, respectively). The total mesophilic aerobic bacteria count showed a moderate positive correlation with ΔE red cabbage ($r=0.75$, $p=0.087$), whereas its correlation with ΔE red beetroot was weaker ($r=0.55$, $p=0.243$). Similarly, the total psychrophilic aerobic bacteria count exhibited a moderate correlation with ΔE red cabbage ($r=0.78$, $p=0.068$) but was lower for ΔE Red beetroot ($r=0.49$, $p=0.312$). These findings suggest that the red cabbage extract-based indicator is more sensitive to changes in shrimp spoilage parameters compared to the red beetroot-based indicator.

The observed color changes in freshness indicators are mechanistically linked to biochemical spoilage processes in shrimp. As microbial activity progresses, proteins undergo enzymatic degradation, leading to the accumulation of volatile basic compounds such as ammonia, trimethylamine, and dimethylamine. These compounds elevate the pH of the packaging environment, altering the chemical structure of pH-sensitive pigments in the indicators. Specifically, increased alkalinity promotes structural transitions in anthocyanins, thereby inducing visible color changes that correlate with the degree of spoilage. Thus, the real-time colorimetric response of the indicators is not merely a statistical observation but reflects underlying biochemical transformations in the shrimp matrix (Balamatsia et al., 2007; Kim et al., 2022; Hu et al., 2024).

Table 5. Pearson correlation coefficients between shrimp quality parameters and freshness indicators containing red cabbage and red beetroot extracts

Parameters	ΔE Red Cabbage (r; p)	ΔE Red Beetroot (r; p)
pH	0.86; 0.029	0.69; 0.129
TVB-N	0.83; 0.040	0.43; 0.398
TMAB	0.75; 0.087	0.55; 0.243
TPAB	0.78; 0.068	0.49; 0.312

Note: Bold values indicate statistically significant correlations at $p<0.05$

These findings indicate that pH and TVB-N levels are strongly correlated with the red cabbage extract-based freshness indicator, reinforcing its potential as an effective tool for real time freshness assessment in seafood products. The weaker and statistically insignificant correlations observed for the red beetroot-based indicator suggest that this extract might be less responsive to pH and TVB-N fluctuations during storage, potentially limiting its reliability in seafood freshness monitoring. Similarly, the moderate correlation between TMAB and TPAB counts and ΔE red cabbage suggests that color changes may indirectly reflect microbial activity. However, the lack of statistical significance in these correlations highlights the need for further investigation.

In a study conducted by Fang et al. (2024), colorimetric labels incorporating red cabbage anthocyanins were utilized to monitor the freshness of shrimp, and the results demonstrated a strong positive correlation between TVB-N values and ΔE values. Similarly, in another study where blueberry anthocyanins were employed as a freshness indicator, a comparable correlation between TVB-N and ΔE values was observed, indicating that ΔE values are closely associated with the degree of spoilage (Hu et al., 2024). A similar correlation was also identified in a study conducted by Chen et al. (2025) using purple sweet potato anthocyanins. In a similar study conducted by Ezati et al. (2019) it was reported that indicators containing Alizarin, used for detecting fish freshness, exhibited a positive correlation between changes in color values and TVB-N levels.

The stronger correlation between the red cabbage extract-based indicator (ΔE red cabbage) and shrimp spoilage parameters compared to the red beetroot-based indicator (ΔE Red beetroot) can be attributed to differences in anthocyanin composition, stability, and pH sensitivity (Chigurupati et al., 2002; Khoo et al., 2017). In contrast, red beetroot pigments mainly consist of betalains, including betacyanins and betaxanthins, which, while also pH responsive, are generally more stable in mildly acidic to neutral conditions and exhibit a narrower color transition range (Giuliani et al., 2016).

Additionally, anthocyanins from red cabbage undergo significant structural modifications in response to pH, transitioning from red (acidic) to purple (neutral) and eventually green/yellow (alkaline) due to changes in their molecular charge distribution (Khoo et al., 2017; Chen et al., 2025). This results in a more pronounced ΔE value that accurately reflects spoilage related pH changes. In contrast, betalains degrade more gradually and are less sensitive to small pH variations, potentially explaining the weaker correlation with TVB-N and microbial spoilage indicators.

Another factor influencing the performance of the freshness indicators is their oxidative stability. Betalains are known to be more susceptible to oxidation and thermal degradation than anthocyanins, which may have contributed to inconsistencies in the colorimetric response of the red beetroot-based indicator (Yang et al., 2021).

These findings suggest that the red cabbage extract-based freshness indicator provides a more reliable and sensitive real time assessment of shrimp spoilage due to its superior pH responsiveness, oxidative stability, and ability to interact with spoilage related volatile compounds. Future studies should further investigate the structural stability of different natural pigments in smart packaging applications to optimize their performance.

Conclusion

The results demonstrated a strong correlation between the ΔE values of the red cabbage extract-based indicator and key spoilage parameters, including pH and TVB-N, reinforcing its reliability as a freshness marker. Although TMAB and TPAB counts also showed moderate correlations with ΔE red cabbage, these were not statistically significant. In contrast, the red beetroot-based indicator exhibited weaker and statistically insignificant correlations with all tested parameters, limiting its potential for effective freshness monitoring.

Based on the chemical and microbiological quality criteria, the shrimp meat exhibited clear signs of deterioration by the fifth day, which aligns with the observed changes in ΔE values. Therefore, these findings suggest that freshness indicators containing red cabbage and red beetroot extracts can serve as reliable, visual tools for monitoring shrimp freshness without requiring complex laboratory analyses.

These natural, biodegradable, and visually detectable indicators provide a practical, cost effective, and consumer friendly solution for monitoring seafood freshness. Their integration into food packaging could enhance food safety, extend shelf life, and reduce food waste, making them a promising tool for the food industry. Further studies should focus on testing these freshness indicators with other protein-rich and highly perishable foods, such as poultry and fish. Additionally, efforts should be made to optimize the formulation for enhanced sensitivity and to evaluate their performance under real-life supply chain conditions through pilot-scale packaging applications.

Compliance With Ethical Standards

Authors' Contributions

FÖ: Investigation, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing
HG: Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing,
All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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All data generated or analyzed during this study are included in this published article.

AI Disclosure

The authors confirm that no generative AI was used in writing this manuscript or creating images, tables, or graphics.

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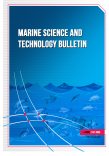

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RESEARCH ARTICLE

Thresholds and trends in wave steepness: A data-driven study of coastal wave breaking risk

Ahmet Durap[1*]

[1] *İstanbul Medipol University, School of Natural Science and Engineering, Civil Engineering, 34469, İstanbul, Türkiye*

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ABSTRACT

Wave steepness plays a crucial role in coastal engineering, sediment transport, and maritime safety, as steeper waves exert stronger forces on coastal structures, enhance sediment mobilization, and increase risks for vessels and swimmers. Despite its importance, previous studies have often treated wave steepness in generalized contexts, lacking region-specific evaluations or failing to account for temporal variability and localized wave dynamics. Moreover, many analyses have not sufficiently linked wave steepness to practical risk indicators such as wave breaking potential. To address these gaps, this study presents a comprehensive analysis of wave steepness and its association with breaking risk on the Gold Coast, Australia, using data collected throughout 2023. Wave steepness, a dimensionless parameter defined as the ratio of wave height to wavelength, serves as a critical indicator for assessing wave stability and potential for breaking in coastal environments. Using the formula $S \approx \frac{2\pi H_s}{g T_p^2}$, we analyzed 17,520 observations of significant wave height (H_s) and peak period (T_p) to categorize waves into four distinct stability classes: gentle, moderate, steep, and breaking risk. Results indicate that only 0.34% of observations exceeded the critical breaking threshold of $S > 0.04$, with the maximum steepness of 0.0564 recorded on December 1, 2023. Significant seasonal variations were observed, with October exhibiting the highest mean steepness (0.0127) and June the lowest (0.0052). A strong negative correlation ($r = -0.78$) between peak period and wave steepness confirms the theoretical relationship between these parameters. The study also revealed that 69% of waves were classified as gentle ($S < 0.01$), 28% as moderate ($0.01 \leq S < 0.025$), 2.3% as steep ($0.025 \leq S < 0.04$), and only 0.3% posed a breaking risk. These findings provide valuable insights for coastal management, maritime safety, and engineering applications by establishing quantitative thresholds for wave breaking risk assessment in similar coastal environments.

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* Corresponding author
E-mail address: ahmetdurap@gmail.com (A. Durap)

Introduction

Wave steepness, a dimensionless ratio of wave height to wavelength, serves as a critical parameter in coastal engineering and oceanography (Zhongbiao Chen et al., 2014). It is essential for evaluating wave stability and the potential for wave breaking, influencing coastal processes such as sediment transport (Balas et al., 2024a) and shoreline erosion (Xie et al., 2024). Understanding wave behavior is also crucial for maritime safety and recreational activities in coastal areas (Petropoulos et al., 2022).

In coastal engineering, wave steepness is pivotal for designing and maintaining coastal structures (Chondros et al., 2024). Breakwaters, seawalls, and other protective measures must be engineered to withstand the forces exerted by waves, and wave steepness directly affects these forces (Al-Towayti et al., 2025). For instance, steeper waves exert greater pressure on coastal defenses, increasing the risk of structural damage or failure (Tang et al., 2020). Understanding wave steepness helps engineers optimize the design of these structures to ensure they can effectively mitigate coastal erosion and protect coastal communities.

Wave steepness plays a significant role in sediment transport, which in turn affects shoreline erosion (Yu et al., 2024). Steeper waves possess more energy and can mobilize larger volumes of sediment, leading to increased erosion rates (Schmelz et al., 2025). The direction and intensity of sediment transport (Uğurlu & Balas, 2024) are also influenced by wave steepness, with steeper waves often causing more significant alongshore and cross-shore sediment movement (Dionísio António et al., 2023). This understanding is critical for developing effective beach nourishment strategies and managing coastal sediment budgets.

Maritime safety is directly influenced by wave steepness, as steeper waves pose greater risks to vessels and offshore structures (Kwon et al., 2025). High wave steepness can lead to increased instability and potential capsizing of smaller boats, while larger ships may experience structural stress and reduced manoeuvrability (Tian et al., 2023). For recreational activities such as surfing and swimming, wave steepness determines the size and intensity of breaking waves, affecting the safety and enjoyment of these activities (Leatherman et al., 2024).

Wave steepness data can inform beach nourishment strategies by providing insights into sediment transport patterns (Husemann et al., 2024). Understanding how wave steepness affects sediment mobilization and deposition can help coastal managers develop more effective strategies for maintaining beach width and protecting shorelines from erosion.

Understanding wave energy dissipation is crucial for predicting wave behavior in coastal regions (De Vita et al., 2018). Wave breaking is a primary mechanism of energy dissipation, but other factors such as bottom friction and turbulence also play a role. The rate of energy dissipation affects wave height (Durap, 2024a), period, and steepness, influencing sediment transport and shoreline erosion.

Coastal protection structures, such as breakwaters and seawalls, are designed to mitigate the impacts of waves on shorelines (Vieira et al., 2024). The effectiveness of these structures depends on their ability to dissipate wave energy, reduce wave height, and alter wave direction. The design and placement of coastal protection structures require a thorough understanding of wave dynamics, sediment transport, and coastal morphology.

The classification of waves into stability categories based on steepness thresholds is a valuable tool for coastal management and safety assessments (Chondros et al., 2024; Durap & Balas, 2024). The identification of correlations between wave parameters, such as the negative correlation between peak period and wave steepness, can improve predictive models for wave breaking risk (Trizna, 2001).

The Gold Coast of Australia, a region celebrated for its extensive beaches and vibrant surf culture, experiences a diverse wave climate shaped by its exposure to the Pacific Ocean. This makes it an ideal location for investigating wave dynamics, yet detailed studies on wave steepness and its implications for breaking risk in this area remain scarce in terms of risk categorization and coastal management strategies.

(i) This study fills this research gap by conducting a comprehensive analysis of wave steepness and its relationship to breaking risk, utilizing data collected throughout 2023 from the Gold Coast. Our primary objectives are to:
(ii) Calculate wave steepness using significant wave height (Hs) and peak period (Tp) via the formula $S \approx \frac{2\pi H_s}{g T_p^2}$, and validate its applicability for the Gold Coast's unique wave climate,
(iii) Categorize waves into stability classes (gentle: S<0.01S<0.01; moderate: 0.01≤S<0.0250.01≤S<0.025; steep: 0.025≤S<0.040.025≤S<0.04; breaking risk: S≥0.04S≥0.04) to quantify breaking risk and inform coastal safety protocols,

(iv) Investigate seasonal variations in wave steepness, and explore the correlation between peak period and wave steepness, while emphasizing the need for accurate characterization of wave dynamics,

(v) Explore the correlation between peak period and wave steepness,

(vi) Assess deviations from classical wave models by comparing empirical data (e.g., C=Tz/Tp mean ≈ 0.58) with theoretical values (Pierson-Moskowitz: 0.86), deriving site-specific equations (e.g., Tp=1.78Tz) to improve local hazard assessments.

To achieve these goals, we employed the formula $S \approx \frac{2\pi H_S}{g T_p^2}$ to compute wave steepness from 17,520 observations of Hs and Tp. Waves were classified into four stability categories: gentle (S<0.01), moderate (0.01≤S<0.025), steep (0.025≤S<0.04), and breaking risk (S≥ 0.04). Our analysis revealed that only 0.34% of waves exceeded the critical breaking threshold of S>0.04, with notable seasonal fluctuations-October showing the highest mean steepness (0.0127) and June the lowest (0.0052). Additionally, a strong negative correlation (r=-0.78) was observed between peak period and wave steepness, reinforcing theoretical expectations.

Material and Methods

Dataset and Study Area

The study focuses on the coastal region of the Gold Coast, Australia, which is renowned for its dynamic coastal processes and significant recreational and economic importance (Figure 1). The dataset covering the year 2023 captures a wide range of wave conditions driven by local meteorological systems and oceanographic influences. To facilitate application of these findings to coasts with similar dynamics, key characteristics of the study area are: bathymetry near the measurement site features a gentle slope of approximately 1:50, with a sandy seabed dominant up to 20 m depth. Wave data were collected at a buoy located 2 km offshore (depth: 15 m), where prevailing winds are southeasterly (mean speed: 8 m/s) and wave direction is predominantly ENE (70% of observations). The local wave climate is characterized by mean significant wave heights (H_s) of 1.2–2.5 m and peak periods (T_p) of 8–12 s during non-storm conditions. These parameters align with fetch-limited, open-coast environments experiencing moderate wind-sea and swell mixing.

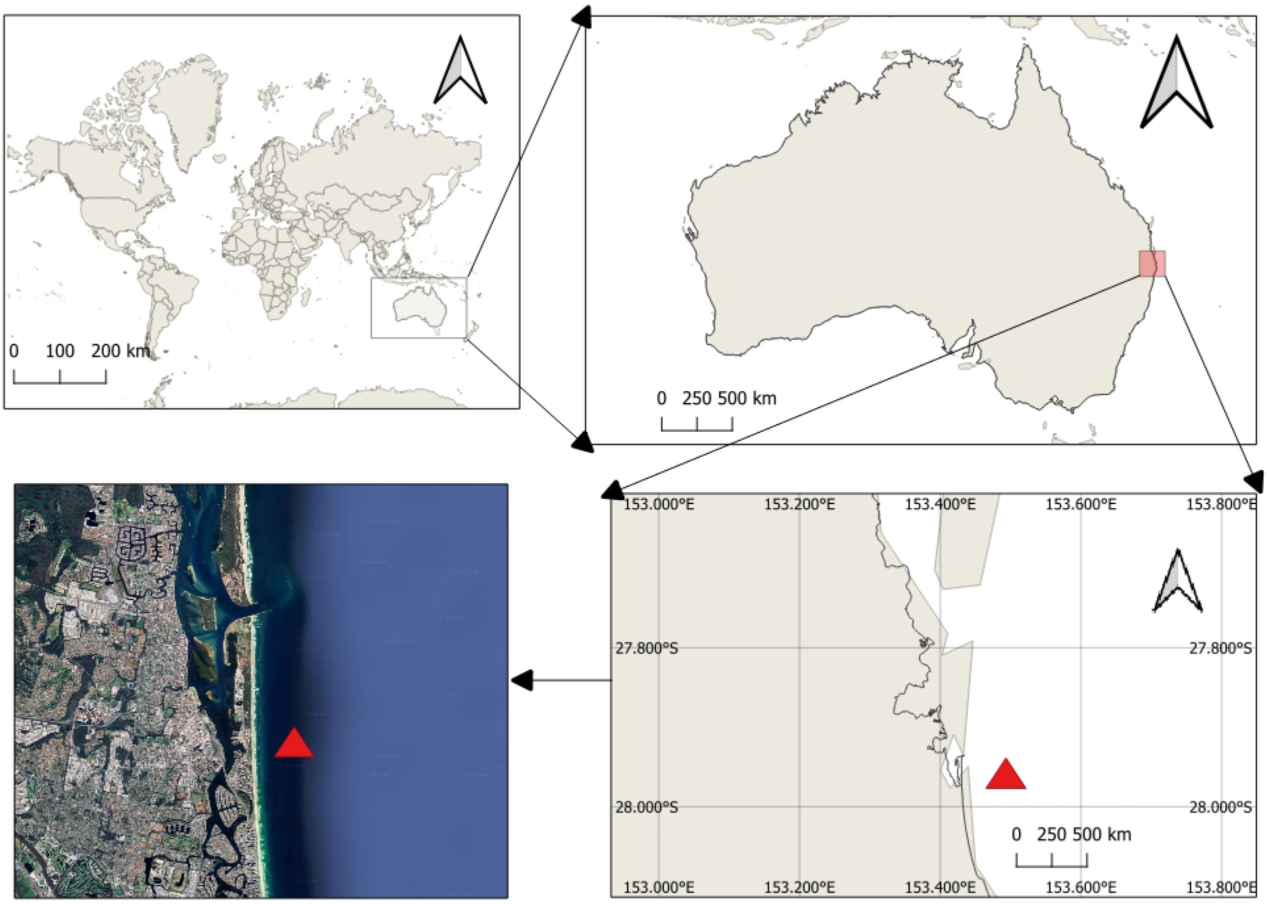

Figure 1. Study area

The geographical location and coastal configuration make the Gold Coast an ideal natural laboratory for investigating wave dynamics, particularly wave steepness and breaking potential.

The dataset used in this study, titled Gold_Coast_2023_Cleaned.csv, comprises 17,520 observations recorded at 30-minute intervals throughout 2023. The primary variables included in the dataset are:

Date/Time (AEST): Timestamp for each observation in Australian Eastern Standard Time, *Hs (m):* Significant wave height (in meters), representing the average height of the highest one-third of waves, *Hmax (m):* Maximum wave height observed, *Tz (s):* Zero-crossing period (in seconds), reflecting the time interval between successive wave troughs, *Tp (s):* Peak wave period (in seconds), the period associated with the most energetic frequency component of the wave spectrum, *Peak Direction (degrees):* Wave propagation direction in degrees, *SST(°C):* Sea surface temperature in degrees Celsius, *Wave Steepness (S):* A dimensionless measure calculated to evaluate wave stability and breaking risk (generated from the dataset).

Data Quality and Preparation

Prior to analysis, rigorous quality control steps (verification of data integrity, handling missing data, data calibration) were applied to the dataset to ensure reliability. All numeric columns were inspected to validate the absence of erroneous negative values, particularly in the wave period, which must remain positive. Observations with missing or incomplete values were either corrected or removed. The dataset was calibrated using standard meteorological and oceanographic measures, ensuring consistency across all parameters.

This combination of the comprehensive dataset and the established physical relationships enables a robust analysis of wave dynamics, providing significant insights into the coastal wave conditions at the Gold Coast over the study period.

Calculation of Wave Steepness

A key parameter analyzed in this study is the wave steepness, defined by the relationship between the significant wave height and the associated wavelength. In deep-water conditions, the wavelength (λ) is estimated using the peak wave period (T_p) with the dispersion relation:

$$\lambda \approx \frac{gT_p^2}{2\pi} \tag{1}$$

where: g is the acceleration due to gravity (9.8 m/s^2).

Thus, the wave steepness, represented by, S, can be approximated as the ratio of the significant wave height to the wavelength. The formula implemented based on the dataset is:

$$S \approx \frac{2\pi H_s}{gT_p^2} \tag{2}$$

In this equation: H_s is extracted from the “Hs (m)” column, $T_p$is extracted from the “Tp (s)” column, 2π is a constant derived from wave mechanics.

Results

Our analysis of the Gold Coast 2023 ocean wave data reveals several significant findings regarding wave steepness, its seasonal variability, and associated breaking risks. The first four rows generated values of S from Hs and Tp are given in Table 1.

Table 1. Generated S from raw dataset of Hs and Tp.

ID	Date/Time (AEST)	Hs (m)	Tp (s)	Wave Steepness
1	2023-01-01T00:00:00.000	1.702	10.526	0.0098488748
2	2023-01-01T00:30:00.000	1.694	10.526	0.0098025816
3	2023-01-01T01:00:00.000	1.827	10.526	0.0105722058
4	2023-01-01T01:30:00.000	1.669	11.111	0.0086676993
5	2023-01-01T02:00:00.000	1.866	10.0	0.0119636977

The corresponding time series plot (Figure 2) shows a relatively stable trend over the year, with intermittent spikes in steepness. Notably, the maximum recorded steepness of 0.0564 occurred on December 1, 2023, indicating short-term events that could be associated with storm conditions. Horizontal dashed lines thresholding the categories further highlight the boundaries between gentle, moderate, steep, and high-risk conditions.

Monthly statistics summarized in the study show clear seasonal patterns in wave steepness. For instance, October exhibits the highest average steepness (0.0127), while June experiences the lowest average (0.0052). These trends align with seasonal meteorological and oceanographic drivers in the region.

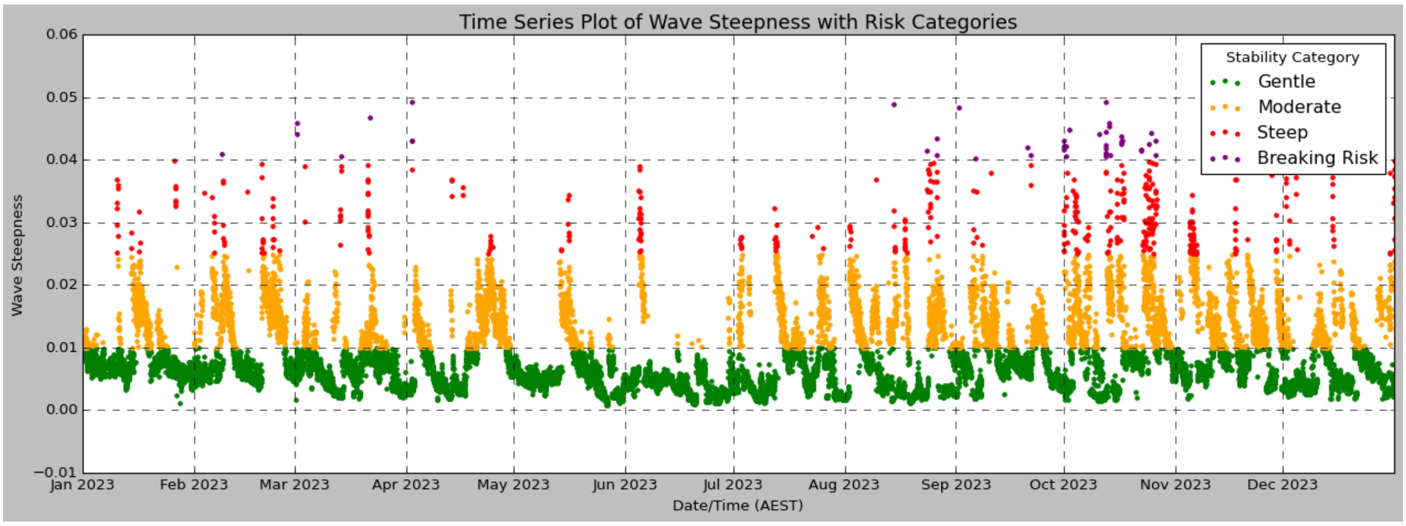

Figure 2. Time series plot of wave steepness with risk categories

The analysis reveals a comprehensive picture of local wave dynamics over the examined period. In summary, 60 potential breaking events (where S > 0.04) were identified—accounting for 0.34% of the total observation time—with the highest recorded wave steepness reaching 0.0564 on December 1, 2023, at 14:00.

Figure 3 presents an integrated view of monthly trends and key correlations related to wave steepness. The top panel shows the monthly average steepness values, with notable seasonal variation. October records the highest average steepness (~0.0127), while June presents the lowest (~0.0052), consistent with calmer winter sea states and more energetic spring conditions in the southern hemisphere. Monthly statistics provide further detail on the variability of wave behavior (Figure 3):

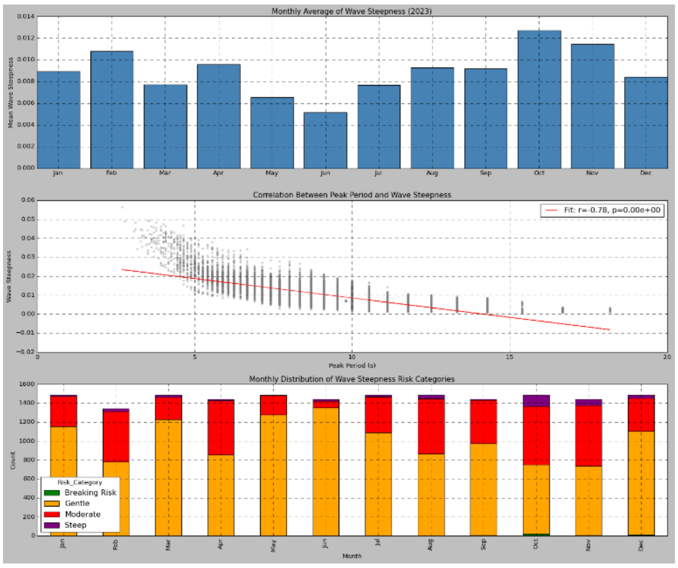

Figure 3. Monthly and correlation-based insights into wave steepness variability for 2023 at the Gold Coast

January: Mean steepness ≈ 0.00894, maximum ≈ 0.04002 (across 1488 records). February: Highest average steepness at about 0.01082 with a maximum of ≈ 0.04101 (over 1344 records)

March & April: Notable maximum values of ≈ 0.04689 and ≈ 0.04936, respectively. June: The lowest average steepness at ≈ 0.00516, with a maximum near 0.0390.

The middle panel illustrates the negative correlation between wave peak period (Tp) and wave steepness (S), with a Pearson correlation coefficient of −0.78 and a p-value below 0.001, indicating statistical significance. As expected, shorter-period waves are steeper, a key insight that supports theoretical models and justifies the use of steepness as a risk indicator.

Table 2. Monthly wave steepness statistics

Month	Mean	Max	Count
Jan	0.00893	0.0400	1488
Feb	0.01081	0.0410	1344
Mar	0.00772	0.0468	1488
Apr	0.00959	0.0493	1440
May	0.00655	0.0344	1488
Jun	0.00515	0.0389	1440
Jul	0.00769	0.0322	1488
Aug	0.00931	0.04901	1488
Sep	0.00921	0.04839	1440

These statistics reflect seasonal variability typical of the southern hemisphere, where summer months (December through February) tend to experience more energetic wave conditions compared to the generally calmer winter months (Table 2).

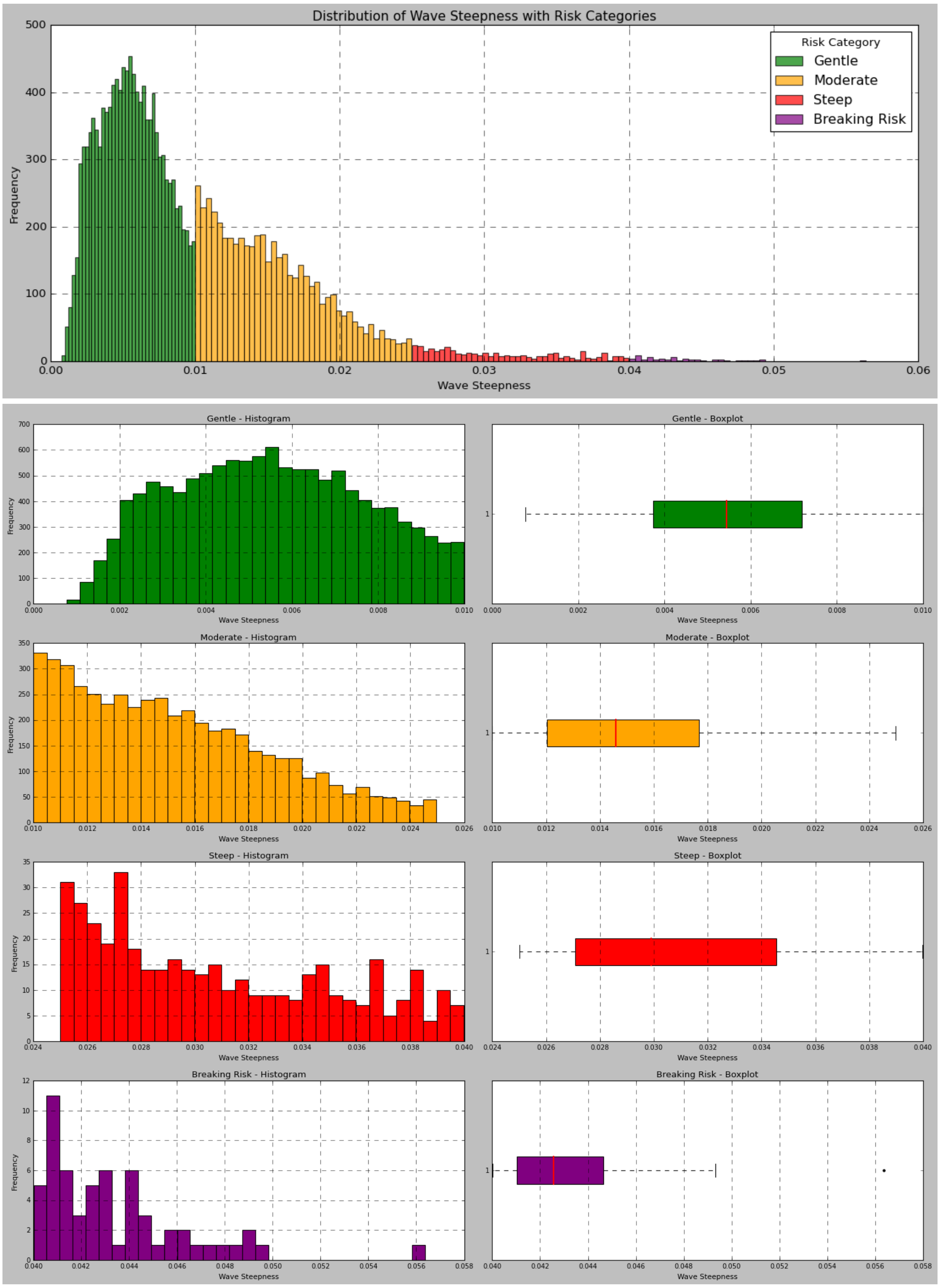

Figure 4. Wave steepness across the four defined risk categories—gentle, moderate, steep, and breaking risk

The bottom panel displays the monthly distribution of wave steepness classes, stacked by risk category. Across all months, the *gentle* and *moderate* classes dominate. However, October and November exhibit slight increases in the *steep* and *breaking risk* categories, reinforcing the conclusion that springtime (Australian season) generates higher-risk wave conditions. The visualization provides a granular look at temporal patterns in wave stability, offering valuable input for monthly or seasonal coastal hazard assessments.

The overall distribution by wave steepness category is also insightful: gentle: 12,099 instances, moderate: 4,952 instances, steep: 409 instances, breaking risk: 60 instances.

Figure 4 synthesizes wave steepness distributions across four risk classes: Gentle, Moderate, Steep, and Breaking Risk.

The aggregated histogram (top panel) confirms the predominance of low-steepness waves (Gentle, <0.01), which constitute ~69% of observations. Higher-risk categories diminish in frequency, with Breaking Risk events (steepness>0.04) representing just 2.3% of cases.

Individual category panels (lower section) reveal distinct statistical patterns. Gentle waves cluster tightly near zero (median = 0.003), while Moderate (0.01–0.02) and Steep (0.02–0.04) classes show progressively right-shifted distributions with rising medians (0.014 and 0.026, respectively). The Breaking Risk category exhibits the widest spread, with a median of 0.045 and outliers nearing the theoretical breaking limit (~0.056). Boxplots underscore incremental variability between classes, particularly in the Breaking Risk group, where the interquartile range (0.042–0.049) and outlier density reflect heightened instability.

Minimal overlap between adjacent categories and systematic median progression (Δ≈0.011–0.019 per class) validate the classification thresholds. This framework robustly isolates rare, high-impact breaking conditions, critical for coastal hazard assessments.

A correlation analysis (Figure 5) displays the relationships among key wave parameters, revealing a strong negative correlation between peak wave period (Tp) and wave steepness (r≈-0.78). This indicates that shorter peak periods are associated with higher steepness values, reinforcing the theoretical basis of our calculations based on the formula ($S \approx \frac{2\pi H_s}{gT_p^2}$).

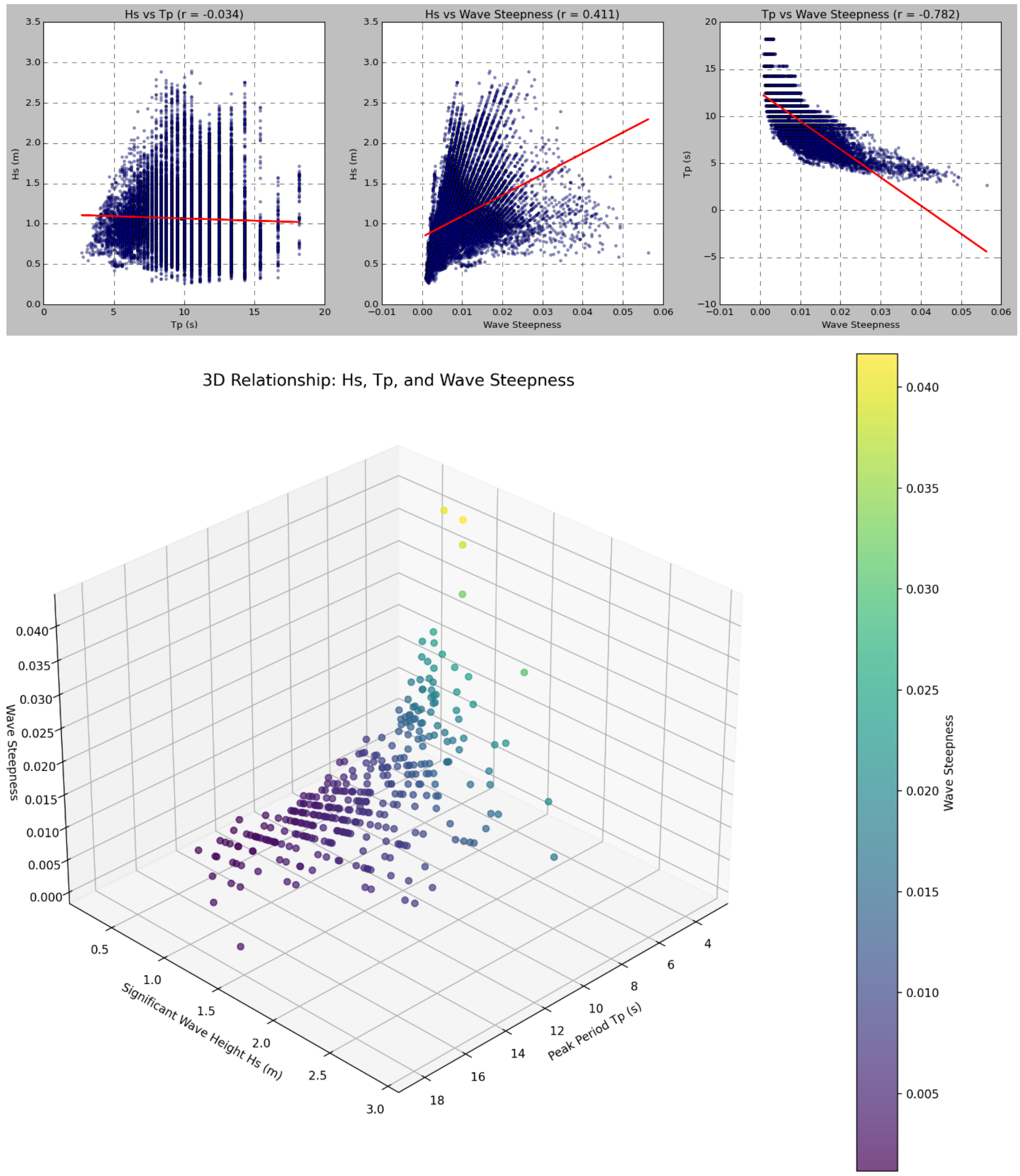

Figure 5. Correlation analysis

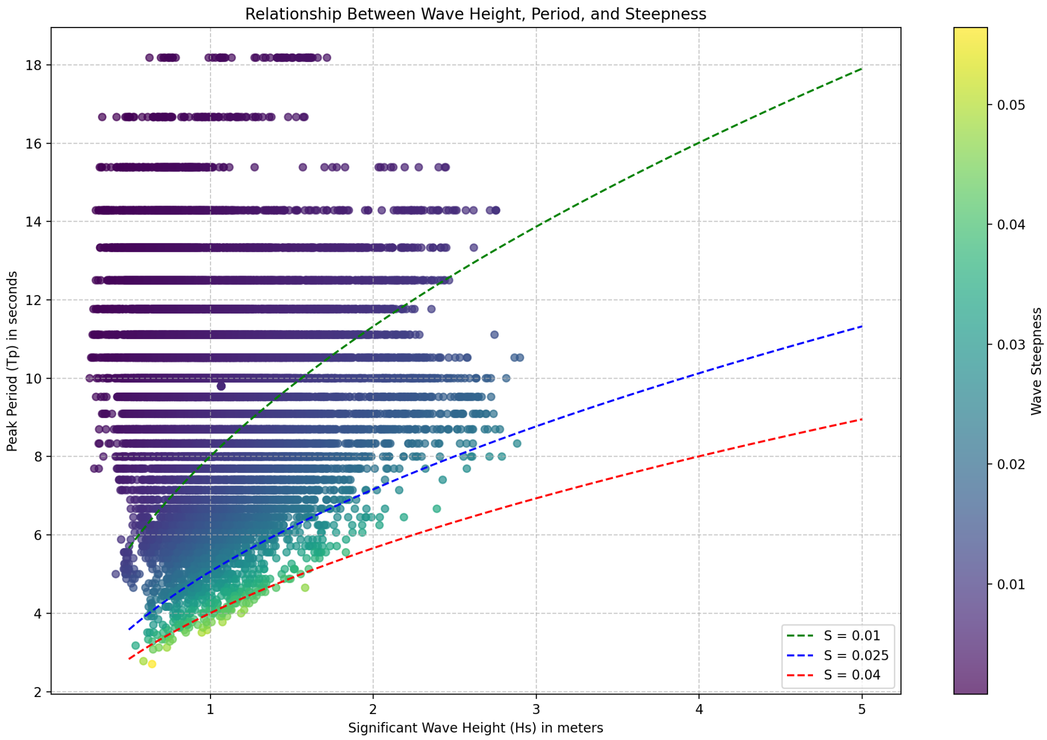

Figure 6. Variation of wave steepness with significant wave height and peak period

Additionally, the joint scatter plot (Figure 6) delineates the relationship between Hs and peak period Tp, with point colors representing wave steepness. Overlaid contour lines for constant steepness values (at thresholds of 0.01, 0.025, and 0.04) provide visual guides to interpret the wave conditions. This visualization confirms that for a given wave height, shorter peak periods lead to increased steepness, thereby enhancing the risk of wave breaking. The clustering of data points and the alignment with the contour lines support the theoretical expectations and suggest that variations in these parameters can be used to predict instances of high wave breaking risk.

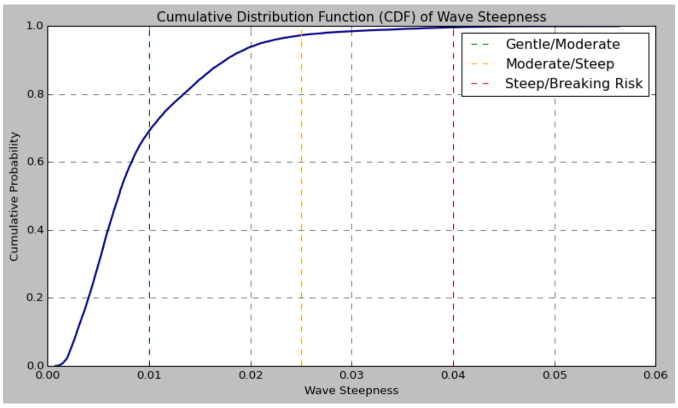

Figure 7. Cumulative distribution function (CDF) of wave steepness

Figure 7 illustrates the cumulative distribution function (CDF) of wave steepness. The CDF provides a probabilistic overview, showing the proportion of wave steepness values below specific thresholds. Vertical dashed lines demarcate critical steepness thresholds: gentle/moderate ($S \leq 0.01$, green), moderate/steep ($S \leq 0.025$, orange), and steep/breaking risk ($S \leq 0.04$, red), aligning with the contour lines from Figure 6. The curve indicates that approximately 40% of waves fall below the gentle/moderate threshold ($S \leq 0.01$), while the steep/breaking risk category ($S \leq 0.04$) encompasses about 90% of the data, reinforcing the earlier observation that shorter peak periods significantly increase steepness and breaking risk. This distribution further validates the predictive utility of Hs and Tp variations in assessing wave breaking potential.

Figure 8 presents the density distribution of wave steepness categorized into risk levels. The histogram reveals that the majority of waves (69.1%) fall within the gentle/moderate category ($S \leq 0.01$, green), with a significant portion (28.3%) classified as moderate/steep ($S \leq 0.025$, orange), and a smaller fraction (2.3%) reaching the steep category ($S \leq 0.04$, yellow). Notably, only 0.3% of waves enter the breaking risk zone ($S > 0.04$, red), consistent with the CDF analysis indicating that extreme steepness values are rare. The vertical dashed lines align with the thresholds identified in Figure 7, reinforcing the earlier findings that shorter peak periods, as observed in Figure 6, contribute to increased steepness and heightened breaking risk. This distribution underscores the infrequency of hazardous wave conditions while affirming the predictive relationship between wave parameters and breaking potential.

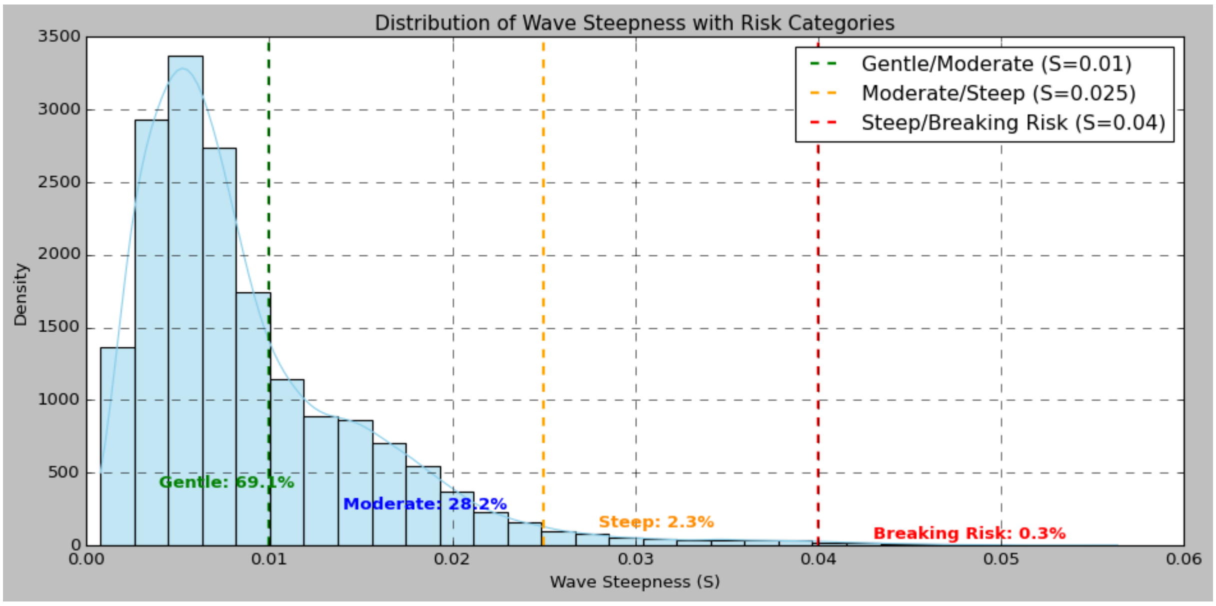

Figure 8. Distribution of wave steepness with risk categories

Discussion

Our analysis of wave steepness in the Gold Coast region, utilizing a dataset of 17,520 observations from 2023, revealed that only 0.34% of waves exceeded the critical breaking threshold of S > 0.04. This suggests that wave conditions in this region were predominantly stable throughout the year, with a maximum recorded steepness of 0.0564 on December 1, 2023. However, seasonal variations were apparent, with October exhibiting the highest mean steepness (0.0127) and June the lowest (0.0052). These results align with the theoretical framework of wave breaking in deep water, where steepness values exceeding approximately 0.04 indicate a propensity for breaking. The observed maximum steepness of 0.0564 further corroborates this threshold, reflecting conditions where breaking becomes probable. Breaking wave height, a crucial parameter, can be estimated using time-exposure images from coastal video monitoring systems (Andriolo et al., 2020). These systems provide a practical way to overcome the difficulties associated with direct wave measurements.

The observed seasonal peaks in wave steepness (e.g., October's mean of 0.0127) suggest periods of heightened coastal vulnerability. Since wave steepness is closely associated with wave runup, steeper waves likely contribute to elevated swash zone dynamics, increasing the risk of beach erosion and overwash during storms (Durap, 2023). This underscores the need for steepness-based early warning systems. October, a transitional month in the Southern Hemisphere Spring, often experiences weather shifts that generate more energetic wave fields, potentially driven by increased wind activity or distant storm systems (Balas et al., 2024b; Durap, 2025b). Conversely, June, occurring during the austral winter, corresponds to a period of typically calmer seas, consistent with reduced wave energy. Identifying meteorological conditions associated with seasonal patterns can improve understanding of wave dynamics (Morley et al., 2018). These temporal patterns emphasize the need to account for seasonality when assessing wave-related risks for coastal management and safety planning in this region. The influence of extreme weather events, such as tropical cyclones, can significantly affect coastal hydrodynamics (Zhong et al., 2024).

A key finding of this study is the strong negative correlation (r = -0.78) between peak period (Tp) and wave steepness, which reinforces the theoretical relationship encapsulated in the formula $S \approx \frac{2\pi H_s}{gT_p^2}$. The visual representation in Figure 9 reinforces the statistically significant and theoretically grounded relationship between peak period and wave steepness. The marginal histograms on both axes show the distribution of peak periods and steepness values, respectively, while the regression line clearly illustrates a downward trend. The correlation coefficient (r=– 0.78) is statistically significant (p<0.001) and supports the expected inverse relationship from deep-water wave theory. Notably, the coefficient of determination (R^2=0.61) implies that over 60% of the variance in wave steepness can be explained by variations in peak period alone, making this a robust predictor. The extremely low standard error (0.0000) further enhances confidence in the reliability of the regression line. These findings emphasize the practical importance of monitoring wave period alongside wave height for early warning systems and coastal risk assessments.

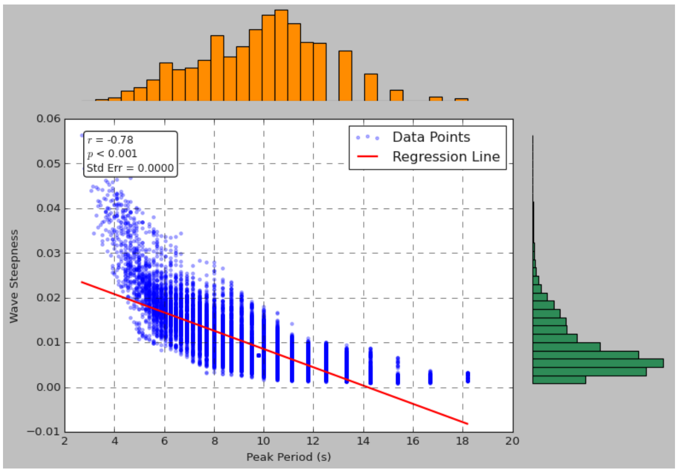

Figure 9. Scatter plot showing the correlation between peak period (Tp) and wave steepness, with marginal histograms

This inverse relationship indicates that, for a given significant wave height (Hs), shorter peak periods result in steeper waves, thereby elevating the likelihood of breaking. This underscores the importance of considering both wave height and period as interdependent parameters when evaluating wave stability and breaking potential, rather than relying solely on wave height as a standalone metric. Machine learning techniques can be used to predict wave data, offering a way to estimate the best possible route for maritime autonomous surface ships by predicting weather changes (Domala et al., 2022).

The classification of waves into four stability categories—gentle ($S < 0.01$), moderate ($0.01 \leq S < 0.025$), steep ($0.025 \leq S < 0.04$), and breaking risk ($S \geq 0.04$)—offers a practical tool for interpreting wave conditions. With 69% of waves classified as gentle, 28% as moderate, 2.3% as steep, and only 0.3% posing a breaking risk, this framework provides actionable insights for coastal stakeholders. For example, periods with elevated frequencies of steep or breaking-risk waves, such as those observed in October, may necessitate heightened precautions for maritime activities, including surfing, fishing, or small vessel navigation. Wave peel tracking can also be used to assess surf amenity and analyze breaking waves, providing a quantitative method for evaluating surfing breaks (Thompson et al., 2021).

These findings carry significant implications for coastal engineering and management along the Gold Coast. The predominance of stable wave conditions suggests that the region is generally well-suited for water-based recreational and economic activities. However, the occasional occurrence of steep waves—particularly during high-steepness months—highlights the importance of designing coastal structures, such

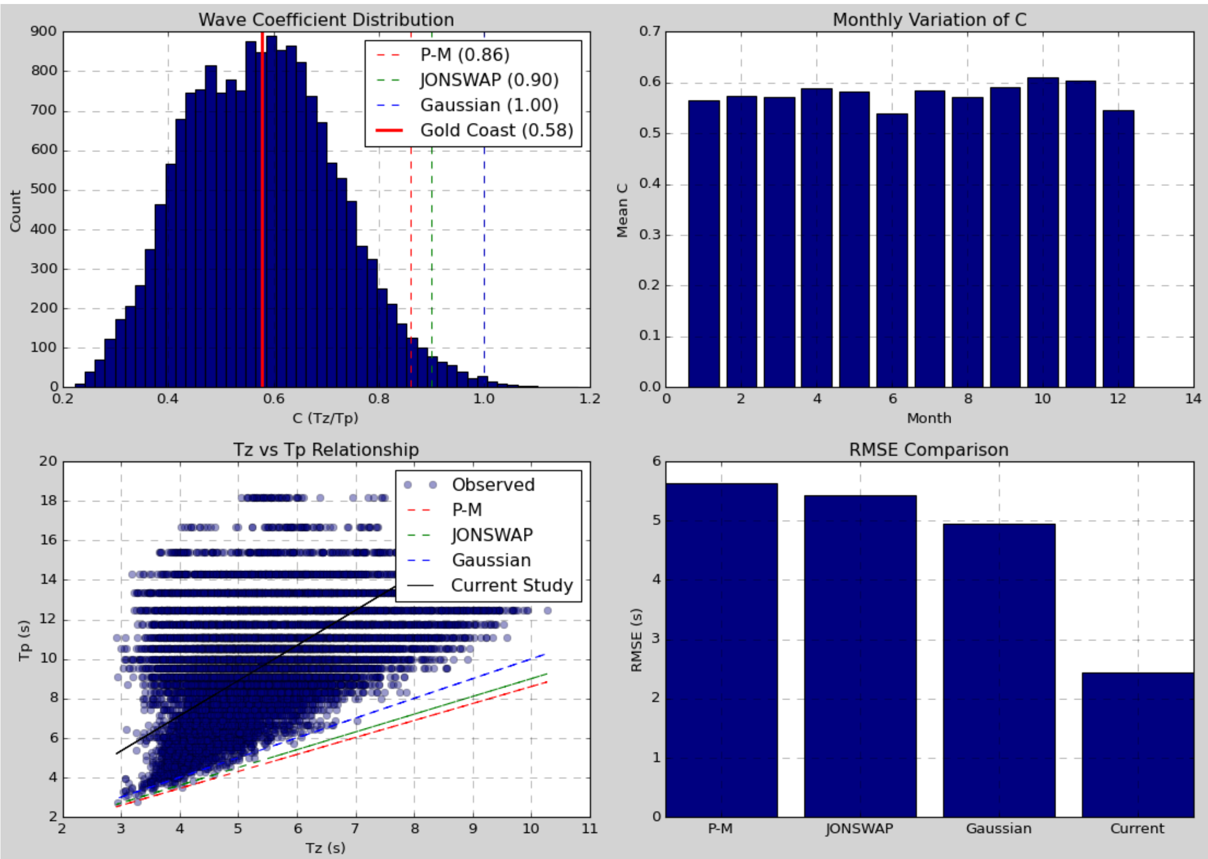

Figure 10. Analysis of wave period characteristics at the Gold Coast

as breakwaters and seawalls, to withstand the forces exerted by these events. Floating platforms are economically viable for harvesting wind energy in deeper waters (Buyruk et al., 2024; Durap, 2025a), offering an alternative for countries with steep continental shelves (Pascual et al., 2021). Moreover, wave steepness influences sediment transport and erosion dynamics, with steeper waves capable of mobilizing greater sediment volumes. Understanding the frequency and distribution of steep waves can thus inform beach nourishment strategies and erosion mitigation efforts, enhancing the resilience of the Gold Coast's iconic shorelines (Durap, 2024b).

To support such engineering applications, accurate characterization of wave dynamics is essential. As shown in Figure 10, the distribution of the wave coefficient $C=Tz/Tp$ is heavily skewed toward lower values, with a mean around 0.58, which is significantly lower than the classical values suggested by the Pierson–Moskowitz (0.86), JONSWAP (0.90), and Gaussian (1.0) models (Ahn, 2021). This deviation reflects the unique wave climate of the Gold Coast. Monthly variations in C (top-right panel) also suggest seasonal consistency with slight peaks in Australia spring. The Tz–Tp relationship (bottom-left) shows a moderate correlation (r = 0.42), and the locally derived equation Tp = 4.716 + 0.941Tz (or Tp = 1.78Tz), which demonstrates improved predictive accuracy (RMSE = 2.25 s) over traditional models. This site-specific relationship reflects the unique wave environment of the Gold Coast and provides a more reliable tool for coastal design and hazard assessment.

From a maritime safety perspective, this refined understanding of local wave dynamics is crucial for identifying periods of elevated wave steepness, which is essential for issuing targeted warnings to mariners and recreational users. Although the overall incidence of breaking-risk waves is low (0.3%), rare yet extreme events—such as the December maximum of 0.0564—underscore the necessity for real-time monitoring and forecasting systems. Technologies such as wave glider-based platforms with towed hydrophone arrays offer autonomous, real-time monitoring capabilities, contributing to safer navigation and better detection of marine hazards (Premus et al., 2022). Furthermore, coastal management strategies must also incorporate considerations of non-linear surges and extreme wind-wave interactions, particularly in light of projected mean sea level rise scenarios, to mitigate long-term risks to coastal infrastructure and ecosystems (Tran et al., 2024).

Conclusion

This study presents a detailed investigation into wave steepness and its implications for breaking risk along the Gold Coast of Australia, drawing on a comprehensive dataset of 17,520 wave observations recorded throughout 2023. By integrating significant wave height (Hs) and peak period (Tp) to compute wave steepness (S), we classified waves into four stability categories: gentle, moderate, steep, and breaking risk. Our analysis revealed that only 0.34% of waves surpassed the critical breaking threshold of $S > 0.04$, with the highest steepness of 0.0564 recorded on December 1, 2023. Seasonal patterns emerged, with October showing the highest mean steepness (0.0127) and June the lowest (0.0052). Furthermore, a robust negative correlation (r = -0.78) between peak period and wave steepness was identified, aligning with theoretical predictions.

These findings offer critical insights for coastal management, maritime safety, and engineering design. The predominance of stable wave conditions—69% gentle and 28% moderate—indicates that the Gold Coast generally supports safe conditions for maritime and recreational activities. However, the presence of steep and breaking-risk waves, particularly in high-steepness months like October, highlights the need for targeted monitoring during these periods. By establishing quantitative thresholds for breaking risk, this study provides a practical tool for assessing wave conditions, which can be adapted to other coastal regions with similar dynamics.

The significance of these results lies in their contribution to a deeper understanding of wave behavior in the Gold Coast. The strong negative correlation between peak period and wave steepness underscores the necessity of evaluating both wave height and period to fully assess wave stability, rather than focusing solely on height-based metrics. This holistic approach enhances the accuracy of wave risk predictions, benefiting applications such as coastal erosion control, infrastructure planning, and safety protocol development.

Accurate characterization of wave dynamics is critical for engineering applications, particularly in regions like the Gold Coast with distinct wave climates. Our analysis reveals that the wave coefficient (C=Tz/Tp) exhibits a mean value of 0.58 (Figure 10), markedly lower than classical theoretical values (Pierson-Moskowitz: 0.86; JONSWAP: 0.90; Gaussian: 1.0). This deviation underscores the limitations of generic models in capturing local hydrodynamic conditions. Seasonal trends in C further highlight variability tied to Australian spring peaks, aligning with observed steepness fluctuations. The derived empirical relationship Tp=1.78Tz (RMSE=2.25s) outperforms traditional formulations, offering enhanced predictive accuracy for coastal hazard assessments. These findings advocate for site-specific wave parameterization in engineering design, particularly for breakwaters, sediment transport models, and maritime safety systems sensitive to period-steepness interactions.

Despite its contributions, this study is constrained by its single-year scope, which limits its ability to capture long-term trends or interannual variability influenced by climatic factors like El Niño or La Niña. To address this, future research should prioritize multi-year data collection to elucidate decadal patterns in wave steepness. Additionally, integrating bathymetric data and shallow-water wave transformation models could improve breaking risk assessments in nearshore zones, where wave dynamics are further complicated by seabed interactions.

In summary, this research lays a data-driven groundwork for understanding wave steepness and breaking risk in the Gold Coast, delivering actionable insights for coastal stakeholders. By incorporating these findings into planning and safety frameworks, and through ongoing monitoring and expanded studies, the region can better adapt to evolving wave conditions, ensuring the sustainable management of its valuable coastal environment.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Funding

Not applicable.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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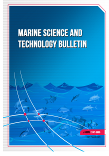

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RESEARCH ARTICLE

Hidden engineering in molecular silence: Examination of biomineralization structure in the shell of *Magallana gigas* (Thunberg, 1793) species using X-ray diffraction (XRD)

Harun Yıldız[1] • Dilek Şenol Bahçeci[2] • Bayram Kızılkaya[1*]

[1] *Çanakkale Onsekiz Mart University, Faculty of Marine Sciences and Technology, Department of Aquaculture, Çanakkale, Türkiye*
[2] *Çanakkale Onsekiz Mart University, Çanakkale Vocational School of Technical Sciences, Department of Clothing Manufacturing Technology, Çanakkale, Türkiye*

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ABSTRACT

This study was conducted using X-ray diffraction (XRD) analysis to determine the mineralogical composition of the shell structure of *Magallana gigas* (Pacific oyster). The analyses revealed that the shell is predominantly composed of calcium carbonate ($CaCO_3$), with the structure predominantly found in the crystalline calcite phase. XRD patterns were thoroughly evaluated in the 20°–80° 2θ range, and high-intensity diffraction peaks specific to the calcite phase were detected, particularly in the 40°–49° and 60°–78° regions. Signals related to the aragonite phase were limited and of low intensity. The biomineralization process plays a central role in organisms' adaptation to environmental factors and structural protection. Marine mollusks like *M. gigas* provide physical protection and gain resilience to chemical variability in their habitats through biomineralization mechanisms that govern shell formation. The dominance of calcite in the shells is demonstrated comprehensively by our XRD data, as the preferential formation of the calcite phase in this species' shell structure is favored for its advantages in long-term environmental stability and biological energy efficiency. Additionally, the obtained data make significant contributions to understanding the biochemical and environmental interactions involved in shell formation in marine organisms. In this regard, the study makes significant contributions for future research on the formation, function, and ecological importance of biogenic minerals.

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* Corresponding author
E-mail address: bayram342001@yahoo.com (B. Kızılkaya)

Introduction

The evolution of biomineralization in mollusks represents a key development in the history of life over approximately 500 million years, marking the beginning of the production of hard structures such as shells, skeletons, or exoskeletons by organisms. This biological mechanism is known as biomineralization, and it has not only supported the structural integrity of organisms but also enabled them to effectively protect their soft tissues from external factors. In this way, organisms have been able to adapt to environmental changes and challenges, laying the foundation for the emergence of evolutionary diversity and adaptation strategies (Marin et al., 2007; Murdock, 2020; Louis et al., 2022). The importance of biomineralization lies not only in making organisms more resistant to environmental stress factors but also in paving the way for increased diversity at the ecosystem level (Gilbert, 2022). Living organisms can develop different strategies in the process of mineral production. These strategies range from passive external biological mineralization (also known as organomineralization) processes, which are influenced by environmental conditions, to biogenic mineralization that are directed by the organism internal biochemical mechanisms and occur in a more controlled manner. These processes play a significant role in the formation, organization, and biological functionality of the mineral structure, directly affecting the ability of organisms to gain environmental adaptation and structural resilience (Weiner & Dove, 2003; Dupraz et al., 2009; Louis et al., 2022; Chen et al., 2019: Qin et al., 2024). The growth process of hard biological structures such as shells and skeletons is largely determined by environmental factors and the organism physiological condition. The development of these structures can slow down or even come to a complete halt due to fluctuations in environmental variables such as temperature, food availability, and pH levels, or due to a slowdown in the organism metabolic activities. This demonstrates how closely the calcification mechanism is related to the vital balance of living organisms (Iglikowska et al., 2018; Figuerola et al., 2021; Ehrlich et al., 2021; Campodoni et al., 2021; Louis et al., 2022). The hard tissues produced by many organisms not only provide structural durability but also serve various biological functions depending on the species and location. For example, shells provide physical protection against external factors, while bones support the body structure and enable movement in vertebrate animals. On the other hand, otoliths found in certain fish species play a role in balance and hearing by being located in the inner ear. This diversity demonstrates how versatile biomineralized tissues are in terms of their adaptation in the evolutionary process (Louis et al., 2022). Marine bivalves actively regulate to synthesize a wide variety of mineral types, such as silica, bioapatite, iron oxides, and hydroxides. However, the most commonly produced mineral component in the shell mineralization is $CaCO_3$ deposition system. This component can appear in three different crystal forms (polymorphs). While calcite and aragonite are the most commonly encountered forms, vaterite can be produced more rarely. These polymorph selections may vary depending on the organism genetic traits and environmental conditions (Skinner & Jahren, 2003; Louis et al., 2022). Shells make up a significant portion of the total weight of bivalve organisms, typically ranging 56-61%. Approximately 94% of the structural composition of a shell is made up of $CaCO_3$. This indicates that shells are largely mineralized and durable structures. Marine organisms use shells, which are hard external structures, to provide protection and structural support. These shells are typically formed by the aggregation of $CaCO_3$ crystals, which are covered by a thin organic membrane. This structure enhances the protection of organisms against external factors and increases their chances of survival (Hamester et al., 2012; Ituen, 2015; Mititelu et al., 2022; Kızılkaya et al., 2024).

Material and Methods

Sample Collection and Preparation

In this study, samples were collected in 2015 from Bandırma, Turkey, to examine the mineralogical composition of the shell structure of *Magallana gigas* (Pacific oyster). The samples were taken from the local marine environment and prepared for analysis under laboratory conditions. The collected *M. gigas* shells were initially washed with clean water to remove marine water and external contaminants. This process aimed to clean the shells of dirt, algae, and other organic residues. Care was taken during the cleaning process to ensure that the mineral structure of the shells was not damaged and their natural surfaces were preserved. After cleaning, the shells were ground to obtain a homogeneous texture. The grinding process was carefully carried out in the laboratory to ensure the samples were reduced to an appropriate powder size. This step is necessary to obtain fine powder samples for XRD analysis. The ground samples were homogenized to ensure they could be analyzed in the XRD device. This ensured that the data obtained from the mineralogical analysis would be accurate and reliable.

X-Ray Diffraction (XRD) Analysis

In this study, XRD analysis technique was used to determine the mineralogical composition of the shell structure of *M. gigas*. The shell samples were analyzed using the PANalytical Empyrean XRD device located at the Central Laboratory of Çanakkale Onsekiz Mart University. This device is equipped with an advanced diffraction system to ensure high precision and accuracy for mineralogical analyses. XRD is a widely used technique for determining the internal structure and mineral composition of samples. The PANalytical Empyrean device used in this study has the capacity to detect different mineral phases in samples with various diffraction angles and high-resolution features. Located at the Central Laboratory of Çanakkale Onsekiz Mart University, this device provides an ideal environment for examining diffraction patterns in the 20°–80° 2θ range. The analyses were conducted on the powdered forms of the samples. Before being analyzed in the XRD device, the powdered samples were properly released and homogenized.

Results and Discussion

XRD examination of bivalve shell structure reveals which calcium carbonate form (calcite, aragonite) these organisms prefer. In this way, the biomineralization process, adaptations to environmental conditions and changes in shell structure can be understood. In addition, XRD data provide a scientific basis for the evaluation of shells for biotechnological and environmental applications. The shells of marine organisms such as *M. gigas* are composed of $CaCO_3$ polymorphs crystals formed as a result of biogenic mineralization. Calcite and aragonite are the two most commonly found polymorphs in these processes. According to XRD analysis results, the higher concentration of calcite in this oyster species reflects the organism biological response to environmental conditions (such as temperature, ion concentration, pH, etc.). This provides important data for understanding the role of environmental factors on shell mineralogy. XRD analysis allows for detailed information about the crystal structure of the material. This method is widely used, especially in determining the crystal phases of biogenic $CaCO_3$ deposition minerals. Organisms are known to form these phases through a process called biomineralization. In this process, the organism directs calcium and carbonate ions to produce specific crystal structures through particular proteins and organic compounds. The formation of crystal phases is known to depend on environmental factors (such as temperature, pH, magnesium/calcium ratio) and the genetic structure of the organism. In particular, aragonite forms more easily at higher magnesium concentrations and may be preferred when rapid shell formation is required.

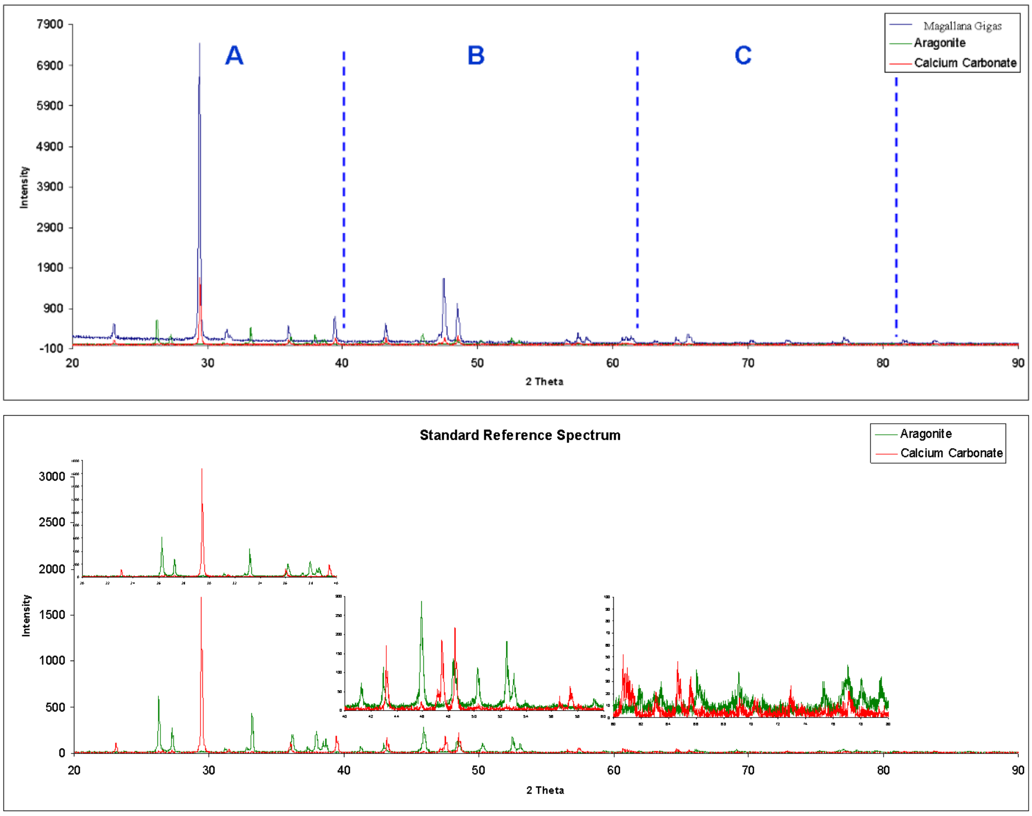


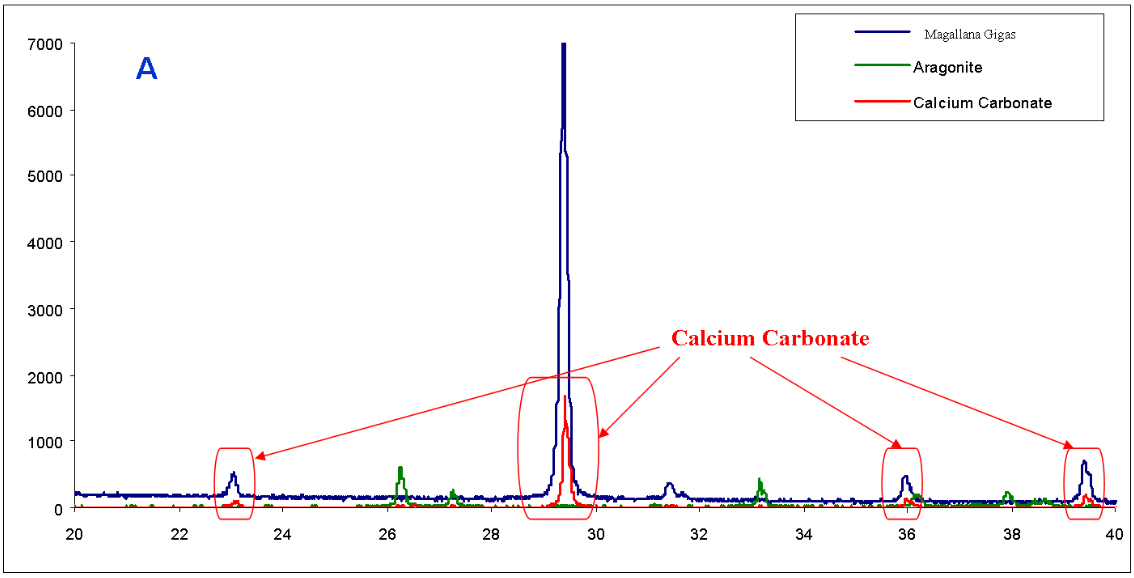
Figure 1. XRD spectra (20°–90° 2θ) of *Magallana gigas*, $CaCO_3$ and aragonite

Such analyses are crucial for understanding the different crystal phases of biogenic $CaCO_3$. Aragonite, with its properties such as high resolution and biocompatibility, has potential for use in environmental applications, biomaterial production, and particularly in the biomedical field. The use of shells obtained from species like *M. gigas* as a natural source of aragonite is therefore noteworthy. Additionally, these types of analyses contribute to the industrial utilization of shell waste and the development of appropriate methods for recycling processes.

In this study, the mineralogical composition of the shell structure of *M. gigas*, a bivalve mollusk species, was investigated using XRD method. The results obtained from the analysis and the reference materials are shown in Figure 1. In Figure 1, the XRD spectrum has been divided into three regions (20-40° 2θ, Figure 2; 40-60° 2θ, Figure 3; and 60-80° 2θ, Figure 4) to allow for a detailed interpretation. The *M. gigas* sample (blue line) was compared with two different standard reference materials: aragonite (green line) and $CaCO_3$ deposition (red line, calcite form). Through this comparison, the crystal forms that make up the shell structure were attempted to be determined. In the analysis of crystal structures, not only the position of the peaks but also their shape (sharpness, width), and intensity provide important technical data. Sharp, symmetrical, and high-intensity peaks indicate that the crystals within the sample are highly ordered, that is, crystallized. Peak width can allow for the calculation of nanocrystal sizes, which can provide information about the structural quality of biomineralization products. Additionally, the content of the amorphous phase can be evaluated by the increase in the background level and the formation of broad peaks. When the XRD pattern of the shell is examined, it can be seen that the pattern of the *M. gigas* sample (blue line) largely aligns with the $CaCO_3$ polymorphs pattern (red line). A particularly dense peak is observed in the 2θ range of approximately 26°–30°. The peaks in this region directly overlap with the crystal planes characteristic of $CaCO_3$. Similarly, other significant peaks in the 30°–50° range are also found to match with the aragonite and $CaCO_3$ phases. Notwithstanding, while there are some limited similarities between the specific peak points of aragonite in the calcite form (green line) and the *M. gigas* shell, the intensity of these overlaps is low. In particular, the peak around 2θ ≈ 29.4°, characteristic of calcite, overlaps with $CaCO_3$, making it difficult to distinguish. In contrast, considering the overall pattern, it can be inferred that the aragonite content is quite low. The sharp and high-intensity peaks observed in the obtained XRD pattern indicate that the crystal structure of the shell is well-ordered and highly crystalline. This suggests that the *M. gigas* shell has undergone a biogenically regulated crystallization process and possesses a homogeneous phase content. It can be concluded that the shell is predominantly composed of the $CaCO_3$ phase, with a smaller proportion of amorphous or other crystalline phases. Based on the XRD analysis, it has been determined that the mineralogical composition of the *M. gigas* shell is largely in the form of the $CaCO_3$ phase.

In Figure 2, the XRD analysis of the shell sample of the *M. gigas* species was examined by enlarging the 2θ values between 20° and 40°. This detailed spectral analysis enables a more precise and thorough evaluation of the crystal phases present in the shell structure. This range is particularly critical for distinguishing the main crystal forms of $CaCO_3$ polymorphs, namely the aragonite and calcite phases. These phases are commonly found together in biogenic-origin materials, and phase determination by XRD is a fundamental step in mineralogical characterization. In XRD analysis, the 20°–40° 2θ range is one of the critical regions for the mineralogical characterization of biomineralization products. This range contains characteristic diffraction signals that allow for the differentiation of biogenic $CaCO_3$ phases, such as aragonite, calcite, and sometimes vaterite. During the biomineralization process, organisms synthesize one or more of these phases in accordance with environmental and biological control factors. The type of synthesized mineral can vary depending on many parameters, such as the growth environment, ion concentration, temperature, pH level, and biological templating. The most striking diffraction peak in the analyzed region is located at approximately 29.4° 2θ and shows a very high intensity. This peak represents a common reflection plane for both the sample and calcite phases, and by itself, it is not sufficient for phase differentiation. Notwithstanding, the other characteristic signals observed along with this main peak, particularly those that align with the diffraction patterns specific to $CaCO_3$ phases, indicate that $CaCO_3$ is the dominant structure in the *M. gigas* shell. Notably, diffraction peaks around approximately 23°, 26.2°, and 29.5° 2θ are characteristic reflections of $CaCO_3$ crystal phases. These signals are clearly detected in both the reference aragonite and calcite patterns as well as in the *M. gigas* sample. The high degree of overlap of these peaks with the sample further confirms that the shell is predominantly composed of $CaCO_3$ mineral. Additionally, the high intensity, sharpness, and symmetry of the peaks observed in the diffraction pattern reveal that the shell material has a highly crystalline structure. The narrow width of the peaks and the smooth termination of their bases suggest that the crystal sizes are regularly and homogeneously distributed, with very limited amorphous content. These features indicate that the shell mineralization in *M. gigas* shells occurs in a highly controlled manner, optimizing the crystalline structure to enhance the mechanical strength of the shell. As a result, the detailed XRD analysis performed in the 20°–40° 2θ range demonstrates that the mineralogical composition of the *M. gigas* shell is predominantly $CaCO_3$ deposition -based. These detailed analyses in this range are important not only for phase identification but also for understanding the formation conditions of biogenic calcium carbonates and the mechanisms of biocrystallization. This mineralogical structure provides valuable insights into both environmental adaptation processes and potential biomaterial applications.

Figure 3 presents the XRD analysis of the *M. gigas* shell sample in the 40°–60° 2θ range, which provides significant information for determining the crystal phases present in the sample. In this range, characteristic diffraction peaks related to $CaCO_3$ polymorphs, such as aragonite and calcite, can be examined in more detail. This specific range is particularly critical for identifying the different crystal structures (polymorphs) of $CaCO_3$. In the examined region, particularly in the 40°–49° 2θ range, two prominent peaks are observed in the *M. gigas* sample. These peaks represent characteristic diffraction signals of $CaCO_3$ deposition phases and strongly align with the reference $CaCO_3$ patterns. This indicates that the calcite phase is predominantly present in the sample, and a significant portion of the shell structure is composed of this crystal form. Comparisons with reference $CaCO_3$ patterns clearly show a strong correlation between these two peaks and the calcite phase. Additionally, within the 42°–44° and 50°–58° 2θ ranges, some minor peaks characteristic of aragonite is also detected. Although these peaks are of low intensity, they confirm that aragonite is present in trace amounts in the sample. While some peaks related to aragonite are present in the same region, they are much lower in intensity and weaker when compared to the *M. gigas* sample. This suggests that the aragonite content is quite limited. Interestingly, the contribution of this phase remains secondary in the overall mineralogical structure of the sample, leading to the conclusion that the dominant phase is still calcite.



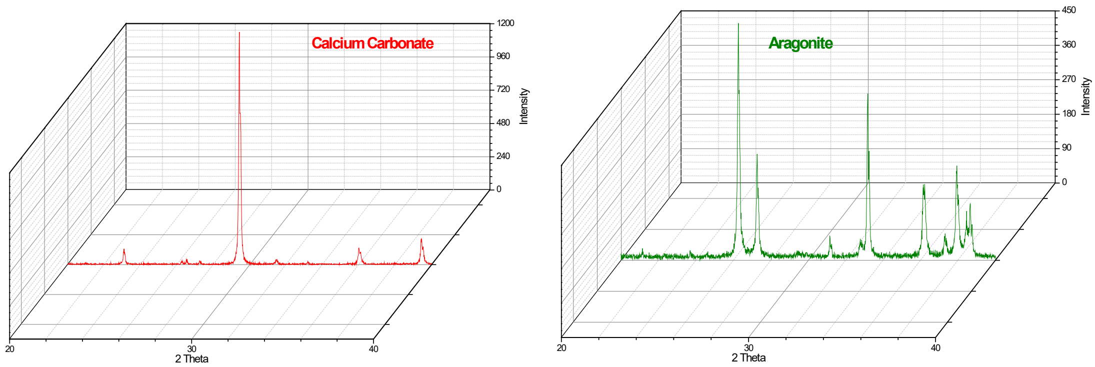


Figure 2. Comparative XRD spectra in the 40°–60° 2θ range

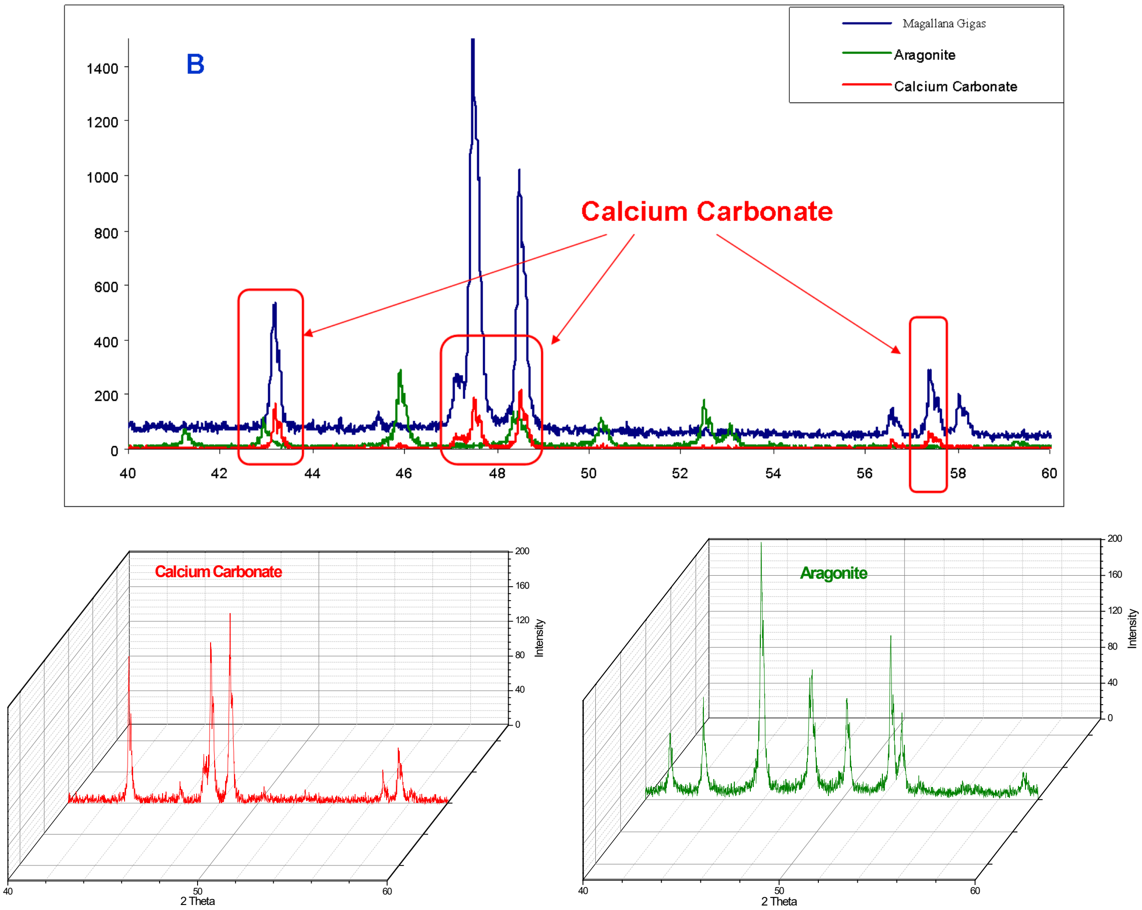


Figure 3. Comparative XRD spectra in the 40°–60° 2θ range

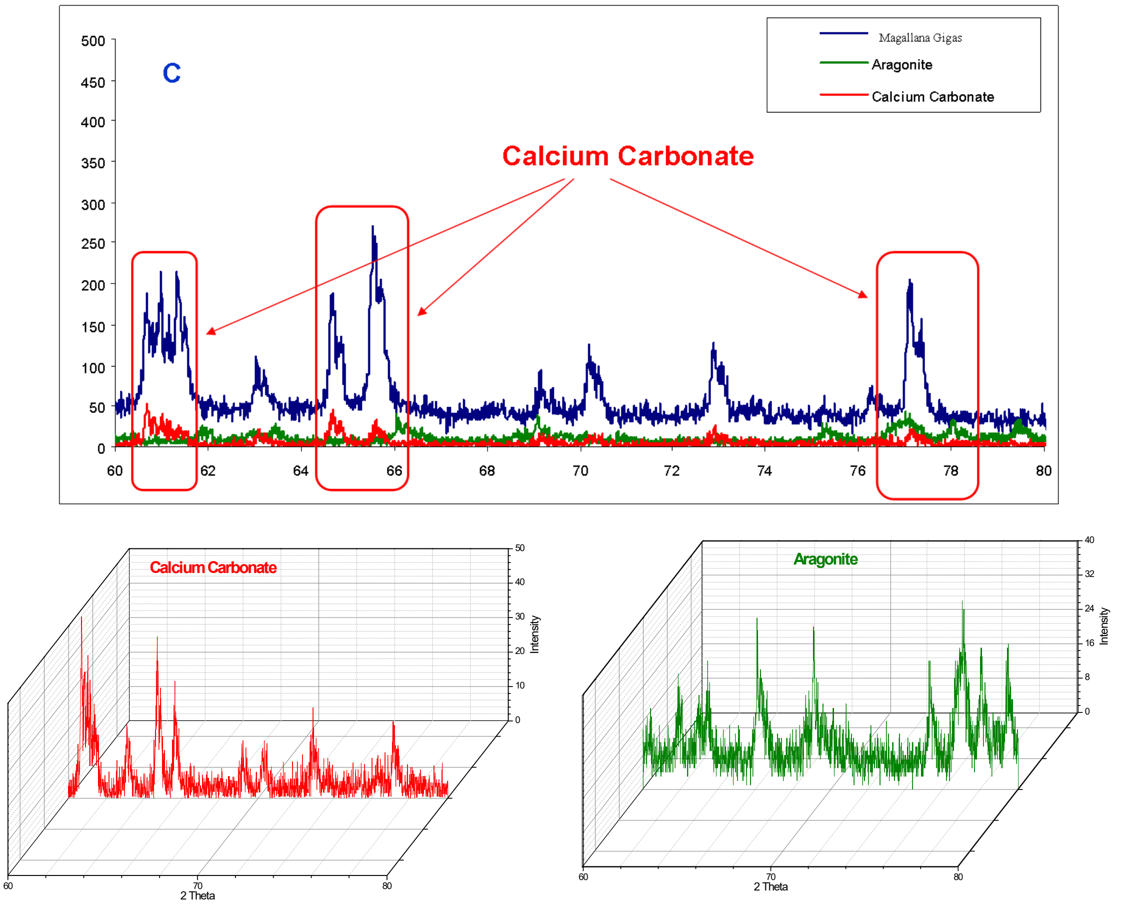


Figure 4. Comparative XRD spectra in the 60°–80° 2θ range

In Figure 4, XRD analysis of the *M. gigas* shell sample, the 60°–80° 2θ range was zoomed in on, providing significant insights into the mineralogical structure of the shell. The diffraction peaks observed in this range particularly confirm the presence of crystal phases of $CaCO_3$. The intense and distinct peaks found in the regions marked with red boxes on the graph reflect characteristic signals of $CaCO_3$, specifically the calcite form. These peaks are concentrated at approximately 61–62°, 65–66°, and 77.5–78° 2θ values. These peak points indicate that the crystals in the *M. gigas* shell are highly ordered and highly crystallized. Moreover, the signals in these regions are stronger and more distinct compared to the aragonite phase (green), indicating that the calcite phase is dominant in this range. Additionally, there is a high degree of overlap between the general $CaCO_3$ (red line) pattern and the sample. Consequently, this analysis shows that the mineral composition of the *M. gigas* shell consists of a high percentage of $CaCO_3$, which is predominantly in the crystalline calcite form. This structure contributes to the shell durability and provides insights into the direction of calcification.

The preference for $CaCO_3$ phases in the shells of marine organisms like *M. gigas* can be explained by biological, environmental, and physical reasons. It is well-known that these organisms use their shells as protective structures against environmental influences. The crystal phases of $CaCO_3$, especially aragonite and calcite, are particularly suitable for providing this protection. The use of $CaCO_3$ in this form can also provide energy efficiency for the organism. Biological systems require less energy to form these structures, which can be advantageous for survival (Reddy, 2013; Muhammad Mailafiya et al., 2019). Additionally, $CaCO_3$ crystals isolate the organism internal structure from the chemical effects of the external environment, regulate ion exchange, and can act as a buffer against environmental changes such as salinity. While aragonite has a denser and harder structure, calcite is more stable and durable (McCauley, 1981; Hossain & Ahmed; 2023). These crystal phases enhance the mechanical strength of the shell, providing resistance against cracking and breaking. As a result, this detailed XRD analysis shows that the shell structure of *M. gigas* is largely composed of $CaCO_3$. This suggests that the crystalline formation of these biogenic structures is directly shaped by environmental conditions and the organism's biomineralization mechanisms. The selection of $CaCO_3$ phases in the shell structure of *M. gigas* offers numerous advantages, such as maintaining structural integrity, resisting environmental conditions, and making biological processes energy-efficient. It is proposed that this represents an evolutionary adaptation resulting from an evolutionarily optimized biomineralization strategy.

Conclusion

This study provides important insights into how biogenic materials are optimized through natural processes by characterizing the mineralogical structure of *M. gigas* shells. The results obtained serve as a valuable resource for biomaterial research and the understanding of marine organisms' adaptation mechanisms. In this study, the mineralogical composition of the shell of *M. gigas* was examined in detail using XRD methodology. Biomineralization is a complex process in which organisms integrate inorganic and organic components to produce optimized structures. In the case of *M. gigas*, shell mineralogy reflects both the organism's survival strategy and its environmental interactions. Research in this field offers significant implications for materials science and ecology.

The mineralogical composition of the *M. gigas* shell was analyzed using XRD, and the data obtained revealed that the shell is largely composed of $CaCO_3$, with the calcite phase being dominant. Detailed examinations of the XRD spectra in the 20°-80° 2θ range showed high-intensity and sharp characteristic peaks specific to calcite (e.g., 29.4°, 39.4°, 43.2°, and 47.5°), indicating that the shell has a highly crystalline structure. Additionally, peaks corresponding to the aragonite phase (e.g., 26.2° and 45.9°) were detected at low intensity, suggesting that this mineral is present in limited quantities within the shell structure. The narrow and symmetrical nature of the peaks supports the idea that the crystal sizes are homogeneously distributed and that the amorphous phase is minimal. The high intensity and sharpness of the peaks observed in the analyzed regions indicate that the crystalline structure of the *M. gigas* shell is highly crystallized. This regularity in crystal structure is directly related to the material mechanical strength properties. It can be inferred that this provides a significant clue in understanding how the shell structures of marine organisms' function as natural defense mechanisms. The findings show that the shell is predominantly composed of crystalline forms of $CaCO_3$, particularly aligning with the characteristic peaks of the calcite phase. The low intensity of signals from the aragonite phase suggests that this mineral is present in a secondary capacity in the shell structure. The sharp, symmetrical, and high-density peaks observed in the XRD analysis further confirm the shell's highly crystalline and homogeneous structure. These findings suggest that the biomineralization process of *M. gigas* occurs through a controlled and optimized strategy. Thus, it can be concluded that the $CaCO_3$ polymorphs of the *M. gigas* shell is a well-regulated and optimized mechanism.

The fact that the mineralogical composition of the shell is predominantly made up of calcite is considered to provide an evolutionary advantage in terms of mechanical durability, environmental adaptation, and energy efficiency for *M. gigas*. The stable structure of calcite enhances the shell's resistance to external physical and chemical influences, while also allowing the biological production process to require less energy. As a result, this study has detailed the mineralogical composition of the *M. gigas* shell using XRD data and highlighted the importance of this structure in terms of biological resilience and environmental adaptation. The findings contribute to the understanding of biomineralization mechanisms and the field of biomaterials research. In future studies, a more detailed examination of the physical properties of this mineralogical structure (such as hardness, fracture resistance, etc.) and its relationship with environmental factors could provide further insights into the evolutionary and functional significance of these biomineralized shells.

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Compliance With Ethical Standards

Authors' Contributions

HY: Conceptualization, Investigation, Writing- original draft
DŞB: Investigation, Data curation, Formal analysis, Writing – review & editing
BK: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing
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Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability

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

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Generative AI (e.g., ChatGPT 4.0, DeepSeek) was used for grammatical review of the introduction and discussion sections. The authors validated all outputs and assume full responsibility for the content.

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RESEARCH ARTICLE

School engagement and occupational readiness in maritime vocational education: A structural equation modeling approach

Gözde Gürerk Başkol[1*] • Güldem Elmas[2]

[1] *İstanbul University - Cerrahpaşa, Institute of Graduate Studies, Department of Maritime Transportation and Management Engineering, 34320, İstanbul, Türkiye*

[2] *İstanbul University - Cerrahpaşa, Faculty of Engineering, Department of Maritime Transportation and Management Engineering, 34320, İstanbul, Türkiye*

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ABSTRACT

According to the most recent national data from the Ministry of National Education, only 40.46% of graduates remain employed in the maritime sector, indicating critically low retention. This study investigates the psychological mechanisms that influence students' intention to remain in the maritime profession after graduation. Data were collected from 366 students enrolled in maritime vocational high schools and analyzed using Structural Equation Modeling (SEM). The model tested two latent constructs: School Engagement and Occupational Readiness. Results revealed that school engagement significantly predicted occupational readiness ($\beta = 0.568$, $p < .001$). The model is theoretically grounded in Bloom's taxonomy, Career Construction Theory, and the concept of Vocational Self-Concept, which together provide a robust framework for understanding how school-based experiences influence students' perceptions of occupational readiness and alignment with the sector. Findings indicate that students' perceptions of their school experience, particularly in terms of the adequacy of vocational knowledge, skills, and attitudes, play a pivotal role in shaping their professional orientation. The model demonstrated strong internal reliability and construct validity, offering a psychometric framework to understand how educational commitment evolves into perceived occupational preparedness. Addressing a notable gap in Turkish maritime education research, this study empirically tests how school engagement influences psychological readiness using a theory-informed SEM design. Such strategies are especially critical for fostering better alignment between students and the maritime profession, potentially supporting future improvements in retention.

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* Corresponding author
E-mail address: gozdebaskol@gmail.com (G. Gürerk Başkol)

Introduction

Maritime vocational education in Türkiye plays a strategic role in supplying qualified personnel for the national economy and guiding youth toward employment. According to Ministry of National Education (MEB) data, only 40.46% of graduates work in the maritime field, while 37.7% transition into unrelated sectors (MEB, 2020). In the existing literature, maritime vocational education is primarily examined through the lens of technical competencies, language instruction, or internship practices, whereas psychological dimensions that may develop during schooling, such as vocational identity formation and sectoral commitment, have received comparatively limited attention. Structural models that explain the interrelations between internal variables like school engagement, occupational readiness, and vocational identity remain scarce. Yet understanding not only students' cognitive outcomes but also their perceived fit and sense of belonging within the profession is critical to addressing long-term sectoral retention.

This study is based on the assumption that post-graduation retention in the maritime sector is shaped not only by external conditions, but also by the psychological and structural experiences students acquire during their education. Accordingly, the central research question investigates how students' levels of school engagement, occupational readiness, and vocational identity relate to their intention to remain in the sector. To examine these relationships, SEM was employed. The theoretical framework integrates Bloom's taxonomy of cognitive, affective, and psychomotor domains, Bandura's Social Cognitive Theory, and Lave & Wenger's Situated Learning Theory. The proposed model aims to holistically explain the student's educational journey along a trajectory of engagement, readiness, identity, and retention.

Specifically, school engagement and occupational readiness emerge as key drivers of students' professional orientation. Prior theoretical frameworks suggest that these constructs may contribute to vocational identity development and long-term sectoral retention (Super, 1980; Allen & Meyer, 1990; Eccles & Wigfield, 2002; Savickas, 2005).

Literature Review

Research on maritime vocational education in Türkiye identifies persistent structural and pedagogical issues that affect student commitment and long-term sectoral retention. Field selection is often guided by family influence rather than intrinsic motivation (Fidan & Nas, 2019), and graduates continue to face significant challenges in terms of practical readiness and English proficiency, which hinder international employability (Başkol, 2019; Saray, 2020). Although Turkish programs comply with Standards of Training Certification and Watchkeeping (STCW), instructional quality remains questionable due to the widespread absence of seafaring certification among teachers (Öztürk et al., 2020). Misalignment between vocational curricula and industry needs is another well-documented concern (MEB, 2021a; Kılıç, 2022).

Sectoral Retention and Vocational Mismatch in Maritime Education

A substantial body of both national and international research highlights a persistent misalignment between maritime vocational education and actual employment outcomes in the maritime sector. For instance, the most recent data from the Ministry of National Education (MEB, 2020) reveal that only 40.46% of maritime vocational high school graduates in Türkiye are employed in the sector, while 37.7% transition into unrelated professions. This issue appears to stem not only from labor market dynamics but also from fundamental structural shortcomings within the educational system.

According to the MEB's E-Mezun 2020 report, 74.02% of vocational high school graduates who actively sought employment were able to find their first job within six months after graduation. However, 87% of these employed graduates earned wages at or below the minimum wage level (MEB, 2020). This pattern is not merely an economic outcome but also reflects a psychological adaptation to structural labor market constraints. As suggested by Gitlin (2001), individuals may choose to accept precarious or underpaid jobs primarily to avoid the stigma and uncertainty of unemployment. In this context, the high rate of employment should be interpreted with caution, as it may mask deeper issues of vocational mismatch and systemic inefficiencies within the training-to-work transition. Further insight is offered by Kablay's (2021) qualitative and descriptive case study, which reveals that 95% of students were assigned to vocational programs involuntarily due to low academic performance. Most did not intend to pursue a career in their trained field and expressed disappointment during internships, indicating a lack of identification with their area of study.

Moreover, findings from the MEB (2021b) also follow a descriptive format, showing that only 4.7% of vocational graduates secure employment in the public sector, and employers have become increasingly reluctant to hire vocationally trained individuals. According to the same report and supported by Kablay (2021), 47.1% of graduates believe their training does not contribute meaningfully to their professional lives.

This concern is echoed in Yılmaz's (2018) survey-based descriptive study of 652 Turkish seafarers, where 59.8% of respondents under the age of 24 stated they would leave maritime work if land-based alternatives were available. For those aged 25–44, the figure rises to 68%. Among support staff, only 35% regarded their training as sufficient preparation for their occupational duties.

A study by Karaoğlu et al. (2023), which conducted a descriptive content analysis of 21 associate degree programs in Türkiye and Northern Cyprus, found that maritime education curricula often fail to include essential topics such as logistics, foreign trade, and maritime English. This curricular inadequacy is considered a central factor contributing to low sectoral retention.

Additionally, Yorulmaz et al. (2022) identified inadequate training, professional burnout, and dissatisfaction as key human factors contributing to turnover in port operations. Although the study includes analytical weighting through AHP, its foundational findings reflect recurring descriptive concerns about maritime workforce challenges.

Lastly, Güzel's (2021) doctoral dissertation at Istanbul Technical University presents a mixed-methods assessment but includes strong descriptive elements when reporting institutional deficiencies. The study states that despite the increasing number of maritime training institutions, graduates still face substantial challenges in securing internships and employment. Türkiye's share of global maritime employment remains below 1%, and 40% of institutions fall short of meeting basic quality standards.

Taken collectively, these findings suggest that sectoral retention is shaped not merely by market conditions but also by a complex interplay of factors, including voluntary program selection, curriculum quality, guidance systems, and the psychological development of professional identity.

Research Gap and Contribution

Recent studies on vocational orientation have increasingly emphasized psychological dimensions such as institutional support, career motivation, and identity development (Yıldırım et al., 2022; Melović et al., 2022; Senbursa, 2023; Yıldız, 2023). However, in the field of maritime vocational education, most existing research tends to focus on topics evaluated primarily at the applied level, relying heavily on descriptive analysis. There is a notable lack of theory-driven studies that test causal relationships among psychological constructs. Existing research often emphasizes themes such as curriculum adequacy (Karaoğlu et al., 2023), internship satisfaction (Kablay, 2021), employment mismatch (Yılmaz, 2018; Yorulmaz et al., 2022), and institutional deficiencies (Güzel, 2021), but rarely investigates how school-based psychological experiences shape post-graduation sectoral retention.

This growing emphasis on the psychosocial aspects of vocational orientation has revealed a theoretical gap in addressing the widely observed employment mismatch in maritime vocational education.

In response to this gap, the present study tests the relationship between maritime vocational high school students' school engagement and their occupational readiness within a theory-informed system framework constructed through Structural Equation Modeling (SEM). This approach offers a comprehensive structure for explaining the interrelations among psychological variables that influence sectoral retention. To the best of the authors' knowledge, no prior study has tested a theoretical SEM model linking these two constructs specifically within the context of maritime vocational education.

Material and Methods

Population and Sample

This study focused on 10th to 12th-grade students enrolled in Maritime Vocational High Schools in Türkiye during the 2023–2024 academic year. The target population comprised 8,390 students from Deck Management and Marine Engineering tracks. Cluster sampling was applied to select students from Istanbul, Izmir, Muğla, and Antalya, which are the regions with the highest concentration of maritime students. After excluding incomplete responses, the final sample consisted of 366 students. Grade-level distribution is presented in Table 1.

Sample adequacy was assessed through multiple criteria. Based on Comrey & Lee (1992), a sample of 300 is "good" for multivariate analysis; Hair et al. (2010) further recommends 5–10 participants per item for factor analysis. With 28 items, the sample size meets both criteria. Additionally, power analysis using RMSEA thresholds (MacCallum et al., 1996) confirmed adequacy: for 289 degrees of freedom, a sample of 250–400 ensures 0.80 power at $\alpha = 0.05$, detecting RMSEA between 0.05 and 0.08. Therefore, the sample is statistically sufficient for CFA and SEM procedures used in this study.

Table 1. Research population and sample

Variable	Categories	N	%
Research Population	All maritime high school students (Türkiye)	8390	100.0
Sample	Students from 4 selected provinces	366	4.36
Grade Level	10th Grade	117	32.0
	11th Grade	156	42.6
	12th Grade	93	25.40

Instrument Development

The measurement instrument used in this study is a structured questionnaire composed of 28 items designed to assess students' perceptions of their maritime vocational education, school engagement, occupational readiness, and career aspirations. (See Appendix A, Table A1 for the complete item list.) The instrument includes both multiple-choice items for demographic and descriptive purposes and 5-point Likert-type scale items for latent construct measurement. The questionnaire was developed through a hybrid process that combined item adaptation from national sources with original item development based on established educational theories. Specifically, 11 items (Items 1–11) were adapted from the 2020 "E-Mezun" Research Report published by the Turkish Ministry of National Education. This national report presents the most recent large-scale data available on vocational education graduates' employment outcomes and sectoral alignment in Türkiye. Although the E-Mezun report is not a psychometric scale, it provides policy-relevant and thematically structured content regarding students' experiences, including satisfaction with vocational education, perceptions of internships, readiness for employment, and career planning. These themes were reworded into student-centered Likert-type items and restructured to reflect the perspectives of current students enrolled in vocational programs rather than graduates recalling past experiences. The remaining 17 items were newly developed to address areas not fully covered by the adapted content and to align with the specific theoretical and contextual scope of the present study. Item construction was guided by Bloom's Taxonomy of Learning Domains (Bloom et al., 1956), Social Cognitive Career Theory (Lent et al., 1994), and Situated Learning Theory (Lave & Wenger, 1991). These items aimed to capture cognitive, emotional, and behavioral indicators of school engagement, professional identity, and career readiness in the maritime vocational education context. To ensure the content validity and clarity of the questionnaire items, expert opinions were obtained from five professionals with over ten years of experience working with maritime vocational students. The expert panel included: (1) a school counselor specialized in psychological guidance, working in a maritime high school for more than a decade; (2) a senior deck instructor who is also a licensed first-class captain and a teacher; (3) a vocational teacher of deck operations; (4) a vocational teacher in maritime engineering (machinery); and (5) a university lecturer holding a PhD in maritime transportation and management engineering. This diverse panel provided feedback from both practical and academic perspectives, ensuring the instrument's appropriateness for the target population. Based on expert feedback, minor revisions were made to improve item clarity and eliminate redundancy. Content Validity Index (CVI) values for all items exceeded the accepted threshold of .80 (Polit & Beck, 2006), supporting the overall content validity of the instrument. This process ensured that the final instrument reflects both contextual relevance and theoretical integrity within the maritime vocational education domain.

Data Collection and Preliminary Screening

Data were collected online via Google Forms during the 2023–2024 academic year to ensure accessibility and efficiency. Participation was voluntary and anonymous; informed consent was obtained digitally. The study adhered to all ethical standards and involved no intervention. The aim was to explore students' perceptions of how well maritime vocational education prepares them for sectoral employment.

Before conducting multivariate analyses, the dataset was screened for missingness and normality. Little's MCAR test confirmed that missing data were random ($p = 0.984$), supporting the use of the Expectation-Maximization (EM) algorithm for imputation. One item (m12) with excessive missing values was excluded. Item m16 was reverse-coded to ensure directional consistency. As shown in Table 2, skewness and kurtosis values indicated that most items exhibited acceptable distribution characteristics, confirming the dataset's suitability for EFA, CFA, and SEM.

Table 2. Skewness and kurtosis ranges and distribution interpretations of items

Skewness / Kurtosis Range	Items	Interpretation
Skewness between -1 and +1 Kurtosis between -1 and +1	m4, m8, m9, m10, m11, m13, m14, m17, m18, m21, m22, m23, m11, REGR factor 1	Normal distribution, excellent skewness and kurtosis.
Skewness between ±1 and ±2 Kurtosis between -1 and +2	m1, m2, m7, m15, m16, m19, m20, m24, REGR factor 2	Mild to moderate positive skew, acceptable kurtosis.
Skewness > +2 Kurtosis > +2	m6	Substantial positive skewness and kurtosis; non-normal distribution.
Special Note	m16 was reverse-coded before analysis.	

Table 3. Eigenvalues, explained variance, and item loadings for each factor

Factor	Eigenvalue	% of Variance	Cumulative %	Items (and Loadings)
1	5.986	42.76%	42.76%	m1 (0.884), m2 (0.869), m3 (0.839), m4 (0.832), m5 (0.827), m8 (0.784), m9 (0.773), m10 (0.753)
2	2.036	14.54%	57.30%	m6 (0.845), m7 (0.822), m19 (0.756), m20 (0.742), m21 (0.715), m22 (0.694)

Exploratory Factor Analysis (EFA)

An exploratory factor analysis (EFA) was conducted on 24 Likert-type items, excluding nominal and categorical variables. The Kaiser-Meyer-Olkin (KMO) value of 0.895 and significant Bartlett's Test ($\chi^2 = 2468.437$, df = 91, $p < 0.001$) confirmed the data's suitability for factor analysis (Hair et al., 2010). An iterative procedure removed items with low factor loadings (< .40) or cross-loadings (> .30). Based on the eigenvalue > 1 criterion and Scree Plot inspection (Kaiser, 1960; Cattell, 1966), a two-factor structure was retained, explaining 57.30% of the total variance,42.76% by Factor 1 and 14.54% by Factor 2. This exceeds the 50% benchmark considered adequate in perception and behavior studies (Worthington & Whittaker, 2006; Tabachnick & Fidell, 2013). All retained items (See Appendix A, Table A2 for the item list.) loaded strongly onto their respective factors (0.694–0.884), exceeding the 0.60 threshold recommended for large samples (Stevens, 2002). Promax rotation was applied, assuming factor correlation. As illustrated in the scree plot (Figure 1) and detailed in Table 3, a two-factor structure emerged, explaining 57.30% of the total variance. This structure provided empirical support for proceeding to Confirmatory Factor Analysis (CFA).

Confirmatory Factor Analysis (CFA) Process

Confirmatory Factor Analysis (CFA) was conducted using AMOS 30 software to test the construct validity of the measurement model. During the transition from EFA to CFA, items m1, m4, m6, and m7 were removed to enhance clarity and avoid cross-loadings, resulting in a more coherent structure. Initially, a two-factor structure based on Exploratory Factor Analysis results was specified (CFA1), which demonstrated strong fit indices (see Table 4). The residual covariances identified in this model enhanced theoretical coherence; however, the overall structure also required balancing with the principle of parsimony.

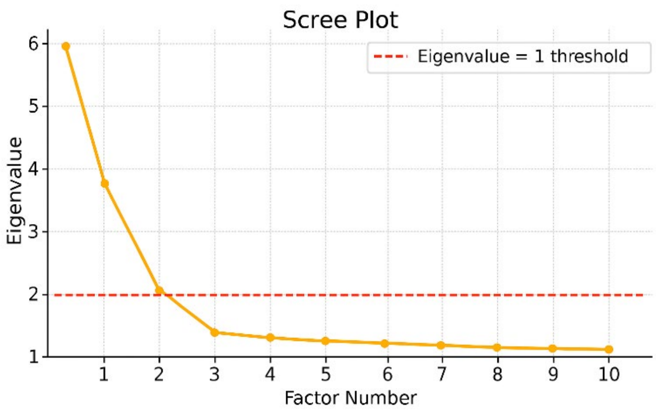

Figure 1. Scree plot indicating the two-factor solution based on eigenvalues

Therefore, a more parsimonious alternative model (CFA2) was developed by retaining only theoretically justifiable residual covariances based on item content and semantic similarity. The CFA2 model also achieved satisfactory fit indices, offering a defensible and efficient measurement structure (see Table 4).

Table 4. Fit indices of CFA models

Model	χ2/df	RMSEA	CFI	TLI	SRMR
CFA 1	2.342	0.066	0.935	0.923	0.0434
CFA 2	2.771	0.070	0.967	0.950	0.0457

Two sets of error covariances were specified in CFA2. The first involved items md8 ("I find the professional knowledge/theory we acquire beneficial"), md9 ("I find the professional skills/practice we acquire beneficial"), and md10 ("I find the professional attitudes, work habits, and values we acquire beneficial"). These items reflect Bloom's cognitive, psychomotor, and affective domains, respectively. Their conceptual proximity, common phrasing, and sequential presentation may have led to residual correlations between their error terms (e8, e7, e12), which are considered localized measurement dependencies rather than structural misfit (Brown, 2015; Kline, 2016). The second group of residual covariances involved items m19 and m21, which assess students' perceived readiness for professional life. These items are conceptually aligned and presented consecutively. High modification indices suggested by AMOS and content similarity justified the specification of residual covariances between their corresponding error terms (e1–e2). CFA2 was adopted as the final measurement model for SEM (Figure 2). All retained items loaded strongly onto their respective factors (Table 5), based on methodological guidelines by Hair et al. (2010), Kline (2016), and Brown (2015), ensuring clarity and minimizing cross-loadings.

Construct Validity, Reliability Assessment and Discriminant Validity Assessment Fornell–Larcker Criterion

The model's convergent validity and composite reliability were assessed using Average Variance Extracted (Eq. 1) and Composite Reliability (Eq. 2):

$$AVE = \frac{\sum(\lambda_i^2)}{n} \quad (1)$$

$$CR = \frac{(\sum \lambda_i^2)}{\sum \lambda_i^2 + \sum \varepsilon_i} \quad (2)$$

where λ_i denotes the standardized factor loading for item i, and ε_i denotes its corresponding error variance in Table 5) values calculated from the Confirmatory Factor Analysis (CFA) results. According to Fornell & Larcker (1981), AVE values above 0.50 indicate acceptable convergent validity. Additionally, Hair et al. (2010) recommend CR values greater than 0.70 to demonstrate sufficient internal consistency. For the School Engagement factor, the AVE value was slightly below the threshold (0.459), but the high CR value (0.843) compensates for this, indicating acceptable convergent validity as suggested in the literature (Hair et al., 2010; Malhotra & Dash, 2011).

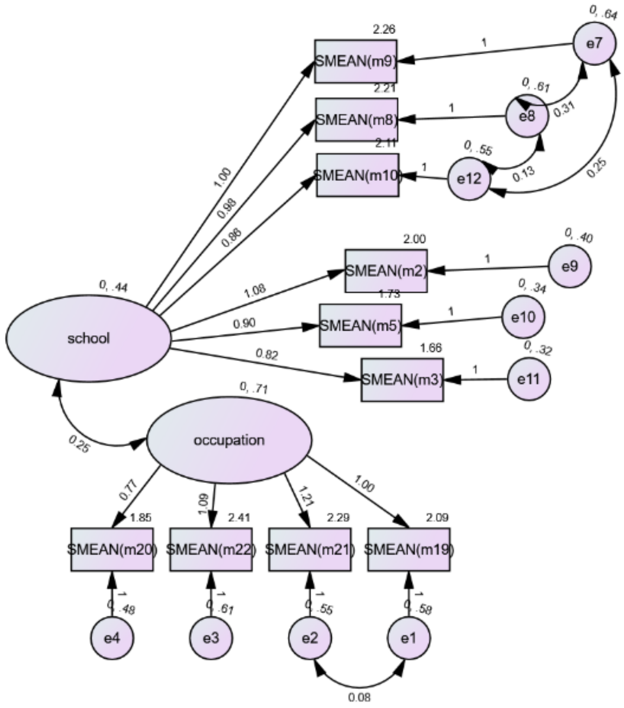

Figure 2. Standardized CFA path diagram representing the final model

Discriminant validity was evaluated using the Fornell–Larcker criterion, which requires the square root of the AVE for each construct ($\sqrt{AVE_i} > r_{ij}$, where $\sqrt{AVE_i}$ denotes the square root of the Average Variance Extracted for construct i, and r_{ij} is the correlation coefficient between constructs i and j.) to exceed the correlation with any other construct (Fornell & Larcker, 1981). As shown in Table 6, the model meets these thresholds for both constructs.

Model Development through Structural Equation Modeling

Structural Equation Modeling (SEM) was conducted using IBM SPSS AMOS v30 to test the consistency of the factor structure with the theoretical model. The latent-variable relationships were modeled based on the previously confirmed factor structure, and three SEM models were tested sequentially following the guidelines of Kline (2016) and Byrne (2010).

Table 5. Standardized loadings, error variances, and squared loadings of CFA model items

Factor	Item	Std. Loading (λ)	Error Variance (ε)	Squared Loading (λ^2)
Occupational Readiness	md19	0.743	0.577	0.552
Occupational Readiness	md21	0.811	0.547	0.658
Occupational Readiness	md22	0.763	0.607	0.582
Occupational Readiness	md20	0.685	0.477	0.469
School Engagement	md5	0.718	0.639	0.516
School Engagement	md3	0.694	0.610	0.482
School Engagement	md2	0.751	0.605	0.564
School Engagement	md9	0.640	0.339	0.410
School Engagement	md8	0.639	0.320	0.408
School Engagement	md10	0.613	0.546	0.376

Note: All standardized loadings are significant at $p < .001$.

Table 6. Construct validity, reliability, and discriminant validity results based on the Fornell–Larcker criterion

Construct	AVE	CR	$\sqrt{AVE}$	Inter-Construct Correlation	Discriminant Validity
School Engagement	0.459	0.843	0.678	0.451	Met
Occupational Readiness	0.565	0.803	0.752	0.451	Met

Results

Construct Validity and Reliability Results

The School Engagement factor represents students' perceptions of their cognitive, affective, and psychomotor development. Items m2, m3, and m5 assess institutional support and satisfaction, while m8, m9, and m10 evaluate the adequacy of vocational knowledge, skills, and attitudes. These dimensions align with Bloom's taxonomy and the construct showed high reliability (CR = .843). Although the AVE value was slightly below the conventional threshold (.459), it was deemed acceptable in line with Hair et al. (2010) and Malhotra & Dash (2011), given the high CR.

The Occupational Readiness factor measures students' psychological preparedness, including career fit, future orientation, and proactive behaviors (items m19–m22). This structure is grounded in Career Construction Theory (Savickas, 2005) and Vocational Self-Concept (Super, 1980), and satisfies all validity criteria (CR = .803; AVE = .565).

SEM Analysis Findings

To assess the alignment between the theoretical model and observed data, three structural equation models (SEM1, SEM2, SEM3) were tested. As shown in Figure 3, model fit improved across stages, with SEM3 demonstrating excellent fit (Hu & Bentler, 1999). Minor modifications were made based on modification indices, all below the threshold of 10. All path coefficients were statistically significant, and the final model is presented in Figure 4, with fit indices in Table 7. Residual covariances were limited and conceptually justified. Items m8, m9, and m10 were linguistically similar and shared overlapping theoretical domains (Bloom), while m19–m22 reflected a cohesive vocational self-image. These were identified through modification indices (MI < 10) and align with best modeling practices (Byrne, 2010; Brown, 2015).

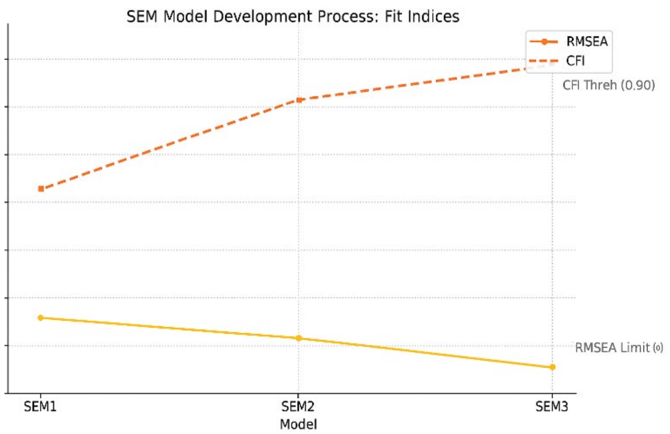

Figure 3. Fit indices across SEM model development stages (SEM1–SEM3)

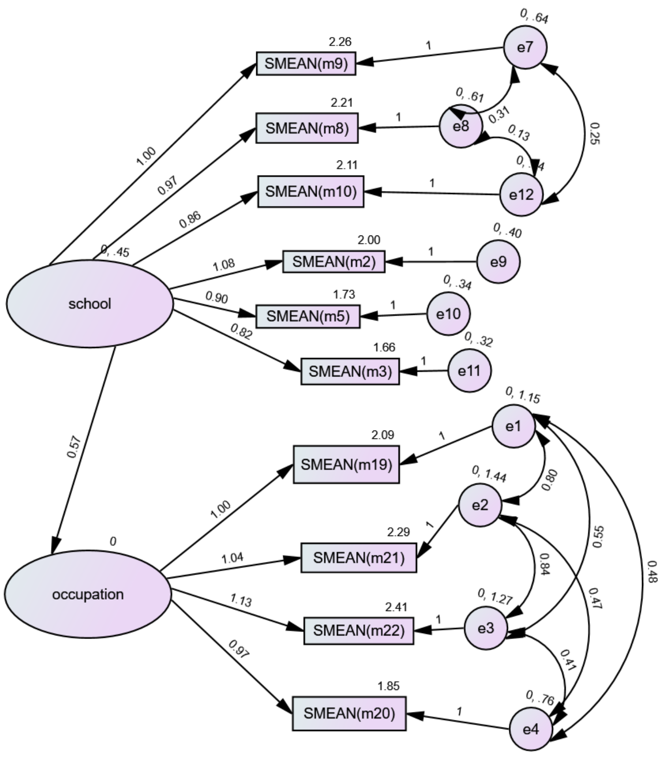

Figure 4. Final structural equation model with standardized path coefficients

Table 7. Model fit indices and recommended thresholds

Fit Index	Value	Acceptable Threshold (Hu & Bentler, 1999; Kline, 2016)
χ^2/df	2.065	< 3 (acceptable)
CFI	0.983	> .90 (good fit)
TLI	0.97	> .90 (good fit)
RMSEA	0.054	< .06 (excellent)
PCLOSE	0.348	> .05 (good fit)
Hoelter (.05)	265	> 200 (acceptable)

A unidirectional path was modeled from School Engagement to Occupational Readiness ($\beta = .568$, $p < .001$). Observed variables m2, m3, m5, m8, m9, and md10 loaded onto School Engagement, while m19, m20, m21, and m22 loaded onto Occupational Readiness. Factor loadings ranged from .617 to .750 for School Engagement and .690 to .810 for Occupational Readiness, consistent with the previously confirmed CFA structure and supporting the measurement model's validity. SEM3 was retained as the final model due to its statistical adequacy and theoretical structure (see Figure 4).

The path from School Engagement to Occupational Readiness was both statistically significant ($\beta = .568$, $p < .001$) and theoretically consistent. Students who perceive their schooling as meaningful and supportive are more likely to feel ready for a maritime career. The final model displayed excellent fit indices (see Table 7). The SEM results empirically validate the hypothesized pathway from school engagement to occupational readiness, reinforcing the study's theoretical framework.

Discussion

This study was designed in response to a structural problem in Türkiye's maritime vocational education: although thousands of students graduate annually, only 40% remain in the sector (MEB, 2020). While existing research typically focuses on curriculum or technical skills, (e.g., Kılıç, 2022; Karaoğlu et al., 2023) the psychological experiences of students during their education, such as vocational identity and sectoral commitment, remain largely underexamined in the Turkish maritime education context (Güzel, 2021; Yıldız, 2023). Our study addresses this gap by applying a structural equation model (SEM) that incorporates psychosocial constructs to explain how school engagement predicts occupational readiness.

The constructs assessed in the model reflect both institutional and psychological aspects of student experience, forming a comprehensive foundation for understanding career readiness in maritime education.

Theoretical Contribution and Policy Implications

To the best of the authors' knowledge, this model is among the first empirical efforts in Türkiye to statistically explain how school engagement influences psychological preparedness and long-term sectoral retention in maritime vocational education. It bridges the gap between vocational training and employment outcomes. While previous studies have explored institutional barriers or student dissatisfaction descriptively (e.g., Yorulmaz et al., 2022; Yıldız, 2023), few have adopted a validated theoretical model that quantitatively links school engagement to long-term sectoral commitment.

These findings suggest several actionable directions for policy, including the implementation of psychological readiness assessments during student enrollment, the development of engagement-focused pedagogical strategies, and the promotion of student–profession alignment mechanisms throughout the educational process. These measures may help vocational education move beyond graduation metrics toward sustaining a skilled and committed maritime workforce.

Conclusion

This study was grounded in a well-documented national challenge: the low sectoral retention rate among graduates of maritime vocational high schools in Türkiye, with only 40.46% employed in the maritime industry despite years of specialized training. Recognizing that this pattern cannot be fully explained by labor market conditions or individual choices alone, we aimed to explore the internal psychological mechanisms formed during schooling that influence post-graduation career outcomes.

Using SEM, we developed and validated a theory-informed model that revealed a significant predictive pathway from School Engagement to Occupational Readiness. The findings indicate that students' perceptions of their school experience, including the perceived adequacy of vocational knowledge, skills, and attitudes, appear to play a significant role in shaping their confidence and motivation for entering the maritime sector. These results move beyond conventional explanations and emphasize that dropout from the profession often originates from misalignments experienced during schooling, not only after graduation.

Practically, the study underscores the need for pre-enrollment diagnostic tools to assess students' psychological and motivational readiness. Improving student–program matching at the outset may reduce the number of graduates who later leave the field due to incompatibility or lack of self-efficacy. In addition, pedagogical reforms that enhance school engagement, including practices such as mentoring, hands-on simulations, and industry-linked curricula may contribute meaningfully to building students' occupational readiness.

The model also contributes significantly to the literature by empirically linking educational experience with long-term vocational behavior through latent psychological constructs. In contrast to existing studies that focus on surface-level curriculum or internship quality, our study proposed a validated mechanism that policy-makers and educators may consider when designing interventions. Maritime vocational training programs, could benefit from being restructured to cultivate not only technical competence but also professional identity emotional alignment, and perceived sectoral fit.

In sum, this research reconceptualizes vocational education not merely as a skill-transmission process, but as a formative ecosystem that builds occupational identity and sectoral commitment. The transition from School Engagement to Career Readiness should be viewed as a critical juncture in the long-term retention of maritime professionals. The study presents a theory-informed model that seeks to bridge education and employment, contributing to a broader understanding of workforce sustainability in vocational contexts.

Limitations and Further Research Directions

The study was limited to vocational maritime schools in four coastal provinces of Türkiye, which may restrict generalizability to other regions or educational contexts. Data collection relied on an online survey, potentially excluding students without adequate internet access. Future studies should employ broader and more diverse samples and consider longitudinal or intervention-based research designs to validate and extend the current findings.

This study empirically examined how vocational maritime high school students' school engagement predicts their occupational readiness. Future research may consider extending this validated pathway based on well-established theoretical frameworks such as Career Construction Theory (Savickas, 2005), Organizational Commitment Theory (Allen & Meyer, 1990), and Expectancy-Value Theory (Eccles & Wigfield, 2002). These frameworks collectively may support a potential developmental pathway, such as School Engagement → Career Readiness → Vocational Identity → Sectoral Retention. Such a proposed sequence could be explored in future research to offer deeper insights into not only how students respond to education, but also how they construct professional identities and develop long-term sectoral commitment. Accordingly, longitudinal designs, intervention-based experimental studies, and cross-cultural validations are recommended for future research to empirically test this extended sequence.

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Compliance With Ethical Standards

Authors' Contributions

GGB: Conceptualization, Data curation, Formal analysis, Writing – original draft

GE: Supervision, Writing – review & editing

All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

This study was approved by the Istanbul University-Cerrahpaşa Social and Human Sciences Research Ethics Committee with decision number 2022/338 and was conducted in accordance with the 1964 Declaration of Helsinki and its subsequent amendments or comparable ethical standards.

Funding

Not applicable.

Data Availability

All results are fully presented in the manuscript. However, the raw data are not publicly available but can be provided by the corresponding author upon reasonable request.

AI Disclosure

Generative AI (ChatGPT 3.5) was used for grammatical review of the introduction and discussion sections. The authors validated all outputs and assume full responsibility for the content.

Supplementary Materials

Supplementary data to this article can be found online at https://doi.org/10.33714/masteb.1697022

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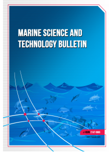

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RESEARCH ARTICLE

First record of *Calyptotheca alexandriensis* (Cheilostomatida, Lanceoporidae) from Ras Juddi (Pasni) Makran coast, Northern Arabian Sea

Qadeer Mohammad Ali[1] • Ateeqa Baloch[1] • Quratulan Ahmed[1*] • Paul D. Taylor[2] • Levent Bat[3]

[1] *The Marine Reference Collection and Resources Centre, 75270, Karachi, Pakistan*
[2] *Sciences, Natural History Museum, London SW7 5BD*
[3] *Sinop University, Fisheries Faculty, Department of Hydrobiology, 57000, Sinop, Türkiye*

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ABSTRACT

The available information regarding bryozoans in coastal areas of Pakistan is limited. This research paper presents the first record of *Calyptotheca alexandriensis* from Ras Juddi (Pasni) along the Makran coast, and the second record globally of this species. This species was first reported in the Eastern Harbor of Alexandria, Egypt, as a distinctive deep orange erect foliaceous bryozoan and was observed abundantly on various hard substrates, such as rocks, ropes, metal pipes supporting marina piers, and ship hulls. The discovery adds a new record of the family, Lanceoporidae, and genus, *Calyptotheca*, to the bryozoan fauna of Pakistan, expanding its known distribution to the Northern Arabian Sea. The present specimens were collected during December 2021–October 2022 and subjected to detailed taxonomic analysis using light microscopy and scanning electron microscopy (SEM). This study contributes to the understanding of bryozoan biodiversity in the region and highlights the potential for further discoveries along the unexplored coastal areas of Pakistan.

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* Corresponding author
E-mail address: quratulanahmed_ku@yahoo.com (Q. Ahmed)

Introduction

Calyptotheca alexandriensis Abdel-Salam, Taylor & Dorgham, 2017 is a bryozoan belonging to the family Lanceoporidae within the order Cheilostomatida. Cheilostomes are the dominant order of living bryozoans, highly diverse, abundant and including species with a wide variety of colony-forms.

Family Lanceoporidae comprises 4 genera, of which *Calyptotheca* contains at least 61 living species according to Bock (2024) a fossil record extending back to the Oligocene (Guha & Gopikrishna, 2007) while Anonymous (2025) documented 58 living species and 4 fossil records. The genus *Calyptotheca* exhibits a global distribution, occurring in both tropical and temperate marine waters (Bock, 2025). These species are found in various regions, including the Mediterranean, the North Atlantic and the North Pacific, with a significant concentration in the Indo-West Pacific in which the most diverse area is Southeast Asia through Papua New Guinea and the Torres Strait, with thirteen species that are unknown elsewhere. (Cumming & Tilbrook, 2014; Bock, 2024).

Fourteen species of *Calyptotheca* have been recorded from the Indian Ocean, including *C. anceps* (MacGillivray, 1879), *C. australis* (Haswell, 1881), *C.hastingsae* (Harmer, 1957), *C. inclusa* (Thornely, 1906), *C. lata* (MacGillivray, 1883), *C. nivea* (Busk, 1884), *C.perpendiculata* (Tilbrook, 2006), *C.porelliformis* (Waters, 1918), *C. subimmersa* (MacGillivray, 1879), *C. triangula* (Hincks, 1881), *C. triangula* (Canu & Bassler, 1928), *C. triquetra* (Harmer, 1957), *C. variolosa* (MacGillivray, 1869), *C. wasinensis* (Waters, 1913) (Florence et al., 2007; Ostrovsky et al., 2011; Boonzaaier, 2017; Sanjay et al., 2021; National Oceanic & Atmospheric Administration, 2024; Anonymous, 2025).

Calyptotheca alexandriensis was first reported in the Eastern Harbor of Alexandria, the Mediterranean Sea, Egypt, as a distinctive deep orange erect foliaceous bryozoan by (Abdelsalam et al., 2017). It was abundantly observed on various hard substrates, such as rocks, ropes, metal pipes supporting marina piers, and ship hulls.

Available information regarding bryozoans in coastal areas of Pakistan is limited. Research on this group has primarily been conducted by Karim (1970), Menon (1973), Ahmed et al. (1978), Haq et al. (1978), Javed (1990), Javed & Tirmizi (1993), Javed & Mustaquim (1995), Ali (2006), Baig (2014), Aslam et al. (2019) and Kazmi et al. (2022). A total of 32 species, 21 genera and 17 bryozoan families have been recorded from the coast of Pakistan. The family Lanceoporidae has never been recorded in the coastal areas of Pakistan. The current study present the first record of *C. alexandriensis* found at Ras Juddi (Pasni) along the Makran coast, Balochistan. It expands the distribution of *C. alexandriensis* to the Northern Arabian Sea.

Material and Methods

Colonies of *Calyptotheca alexandriensis* were collected from the intertidal zone at Ras Juddi, Makran coast (25°13’25” N 63°30’15” E) (Figure 1) between December 2021 and October 2022.

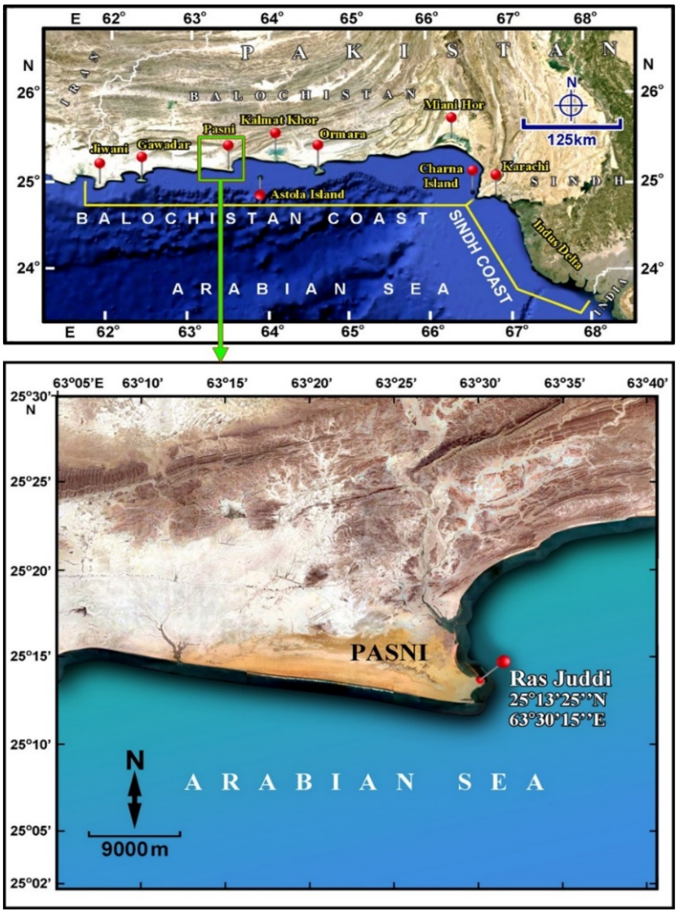

Figure 1. Map of the study area map, Ras Juddi, Makran coast (25°13’25” N 63°30’15” E)

The samples were initially preserved in situ using 5% formaldehyde solution in seawater and were subsequently transferred to 70% alcohol for further analysis. For taxonomic study, the specimens were cleaned and processed in a weak sodium hypochlorite (domestic bleach) solution to remove excess organic material, resulting in clearer images of the skeletal structures. They were rinsed with distilled water and dried. Microscopic observations and photographic imaging were performed using a stereo-zoom microscope (Wild 181300, Switzerland) at 10×50 magnification and along with an upright microscope (Nikon LABOPHOT-2) at 10x4 and 10x10 magnifications. Specimen fragments were imaged using a JSM

6380A (JEOL Japan) at the Centralized Science Lab, University of Karachi, for Scanning Electron Microscopy (SEM). Morphometric measurements, such as length and width of zooids, orifices and ovicells, were made directly from digital SEM images. The specimens were cataloged (MRC&RC-UOK-BRY-14) and deposited in the Museum of the Marine Reference Collection and Resource Centre, University of Karachi.

Results

Systematics

Order Cheilostomatida Busk, 1852
Suborder Flustrina Smitt, 1868
Superfamily Smittinoidea Levinsen, 1909
Family Lanceoporidae Harmer, 1957
Genus Calyptotheca Harmer, 1957
Species Calyptotheca alexandriensis Abdel-Salam, Taylor & Dorgham, 2017 (Figures 2-3; Table 1)

Material examined: Catalogue no (MRC&RC-UOK-BRY-14) Ras Juddi, Pasni, Makran Coast, Balochistan (25°13’25” N 63°30’15” E), 6 specimens, December 4, 2021; January 31, 2022; April 18, 2022; August 12, 2022, and October 27, 2022, intertidal zone.

Description: Colonies erect, foliaceous, about 9-14 cm, live specimens with dark orange to red colonies, fading to light brown and yellow in alcohol (Figure 2A-C). Autozooids sub-rectangular, about twice longer than wide, separated by thin and well-defined furrows (Figure 2D, 3A-B). Frontal shield moderately convex, densely large subcircular, pseudopores; in center and decreasing toward the edge of the frontal shield; calcification around the pseudopores in the shape of a polygonal network. Marginal areolar pores not distinct from pseudopores. Zooids vary in size, measuring between 480–616 µm in length and 300–421 µm in width. Primary orifice subcircular to oval, wider than long with a broad U-shaped sinus marked by a pair of condyles (Figure 3C-D). Primary orifice measuring 150–207 µm long by 165–200 µm wide. Condyles are small, rounded, and non-serrated, projecting distomedially (Figure 3D). Some orifices are covered by closure plates, with an unevenly granular surface. Ovicells hyperstomial, globose, wider than long, with smaller, more closely spaced pseudopores (Figure 2D, 3E). Ooecium 427–576 µm long by 375–429 µm wide. Orificial dimorphism not distinctive. Suboral avicularia oriented disto-laterally (Figure 3C-D) and present almost all zooids, all avicularia facing the same direction on a frond, either left or right; plane of the avicularium steeply inclined to the colony frontal surface; small in size, about 52.2–92.7 µm long by 33.7–49.2 µm wide; opesia semicircular; pivotal bar complete, more or less straight, longer than opesia; rostrum arch-shaped, with a hook-like distal end.

Habitat: Colonies were found under the rocks, attached to hard substratum.

Distribution: Eastern Harbor, Alexandria (Mediterranean Egypt) and recently Pakistan (Northern Arabian Sea).

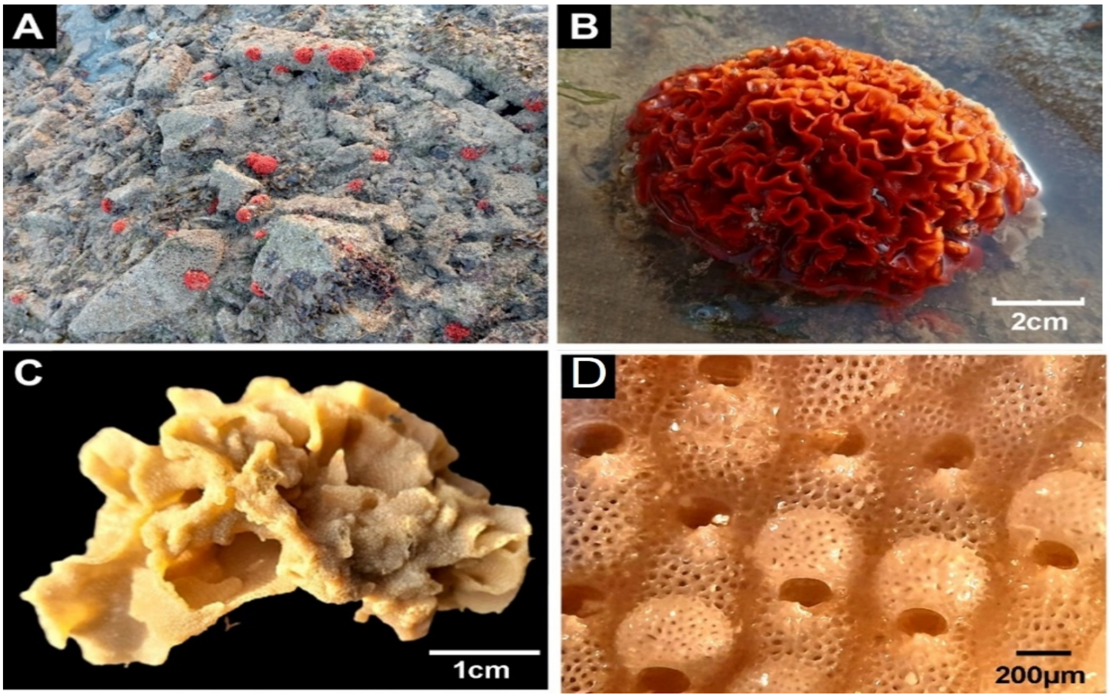

Figure 2. General views of *Calyptotheca alexandriensis.* **(A)** Distribution of colonies in the rocky zone of low tidal areas, **(B)** A fresh specimen exhibiting a leafy colony shape and a deep orange color, **(C)** The preserved specimen displays a pale brown and yellow coloration, **(D)** Zooids with ovicells

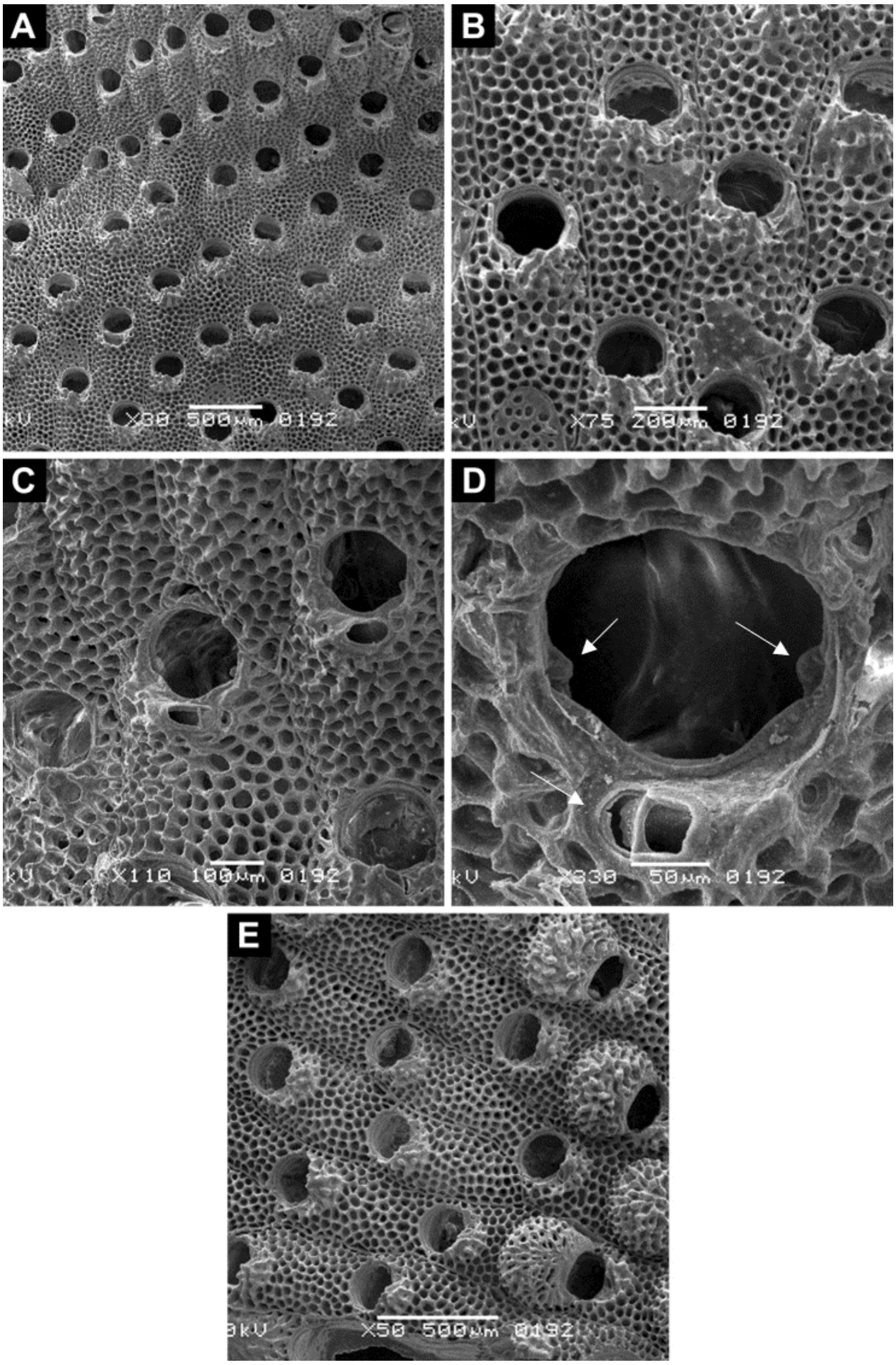

Figure 3. *Calyptotheca alexandriensis.* **(A–B)** General views of zooids without operculum,**(C–D)** Primary orifice, condyles and suboral avicularium,**(E)** Group of zooids, some with complete ovicells

Discussion

This research represents the first documented occurrence of *C. alexandriensis* at Ras Juddi, Pasni along the Makran coast. It was found during monitoring surveys conducted between December 2021 and October 2022. Therefore, this study significantly contributes to the bryozoan fauna of Pakistan by introducing a new species, *C. alexandriensis* (Harmer, 1957).

The specimens from Pakistan closely match the description of *C. alexandriensis,* as outlined by Abdelsalam et al. (2017) for the species found in Alexandria, Egypt. One striking feature is the distinctive deep-orange, erect, foliaceous colony form. Additionally, zooid-level characteristics, such as the broad sinus, evenly pseudoporous frontal shield, and notably the transversely oriented suboral avicularium, distinguish *C. alexandriensis* from other known species of *Calyptotheca*.

Table 1. Comparative Measurements (in µm) of *Calyptotheca alexandriensis* from Ras Juddi (Pakistan) and Alexandria (Mediterranean Egypt)

Character	Location	Mean	Range	SD	N
Zooid length	Pakistan	567.8	480616	52.8	15
	Mediterranean Egypt	560	460-650	60.0	12
Zooid width	Pakistan	351	300-421	49.8	15
	Mediterranean Egypt	320	270-350	30.0	12
Orifice length	Pakistan	182.4	150-207	20.5	10
	Mediterranean Egypt	130	110-140	10.0	10
Orifice width	Pakistan	188.1	165-200	14.0	10
	Mediterranean Egypt	170	170-180	10.0	10
Ooecium length	Pakistan	505.4	427-576	59.2	7
	Mediterranean Egypt	260	250-270	10.0	10
Ooecium width	Pakistan	407.4	375-429	27.8	7
	Mediterranean Egypt	350	330-370	20.0	10

Note: SD: standard deviation; N: number of determinations

When comparing the given values for the two specimens, variations in the size and measurements in the morphological structures were seen. Specimens from Mediterranean Egypt and the present specimens exhibit insignificant differences in the dimensions of their zooids, primary orifices, and ovicells. The present specimens exhibit larger zooids, with length ranging from 480-616 µm and width from 300-421 µm, compared to Mediterranean Egypt specimen's zooid length of 460-650 µm and width of 270-350 µm. The primary orifices in our specimens are also larger, measuring 150-207 µm in length and 165-200 µm in width, while those in the Mediterranean Egypt specimens measure 110-140 µm in length and 170-180 µm in width. Similarly, the ovicells of our specimens are larger, measuring between 427 and576 µm in length and 375 to 429 µm in width. In contrast, the ovicells from the Mediterranean Egypt specimen are smaller, with lengths ranging from 250 to 270 µm and widths from 330 to 370 µm. These differences underscore the variability in morphological features between the two specimens.

Conclusion

The first documented occurrence of *Calyptotheca alexandriensis* along the Makran coast at Ras Juddi represent a significant contribution to the bryozoan fauna of Pakistan. This discovery not only introduces the family Lanceoporidae and the genus *Calyptotheca* to the region but also extends the known distribution of *C. alexandriensis* to the Northern Arabian Sea.

The recent discovery of *C. alexandriensis* in the Arabian Sea, following its initial identification in the eastern Mediterranean (Abdelsalam et al., 2017), raises important questions about the species' origins. This finding suggests that the species likely entered the Mediterranean Sea through the Suez Canal, rather than migrating from the Atlantic. However, the precise location of the species' origin remains uncertain.

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Compliance With Ethical Standards

Authors' Contributions

QMA: Conceptualization
AB: Investigation, Data curation, Writing – original draft
QA: Supervision, Writing – review & editing
PDT: Validation, Taxonomic identification and reviewing
LB: Writing – review & editing
All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Funding

Not applicable.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

AI Disclosure

The authors confirm that no generative AI was used in writing this manuscript or creating images, tables, or graphics.

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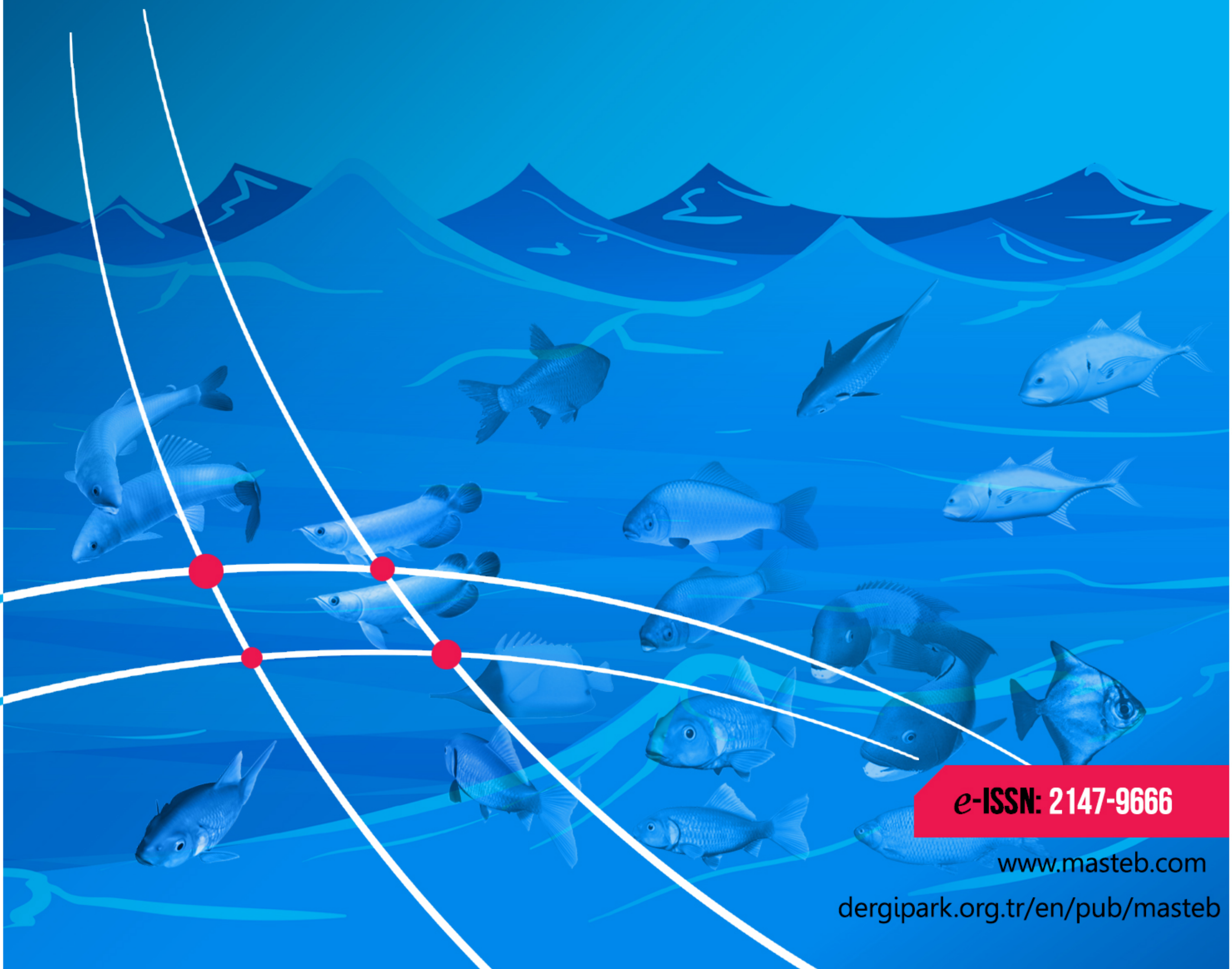

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