

Implications of Seagrass Habitat Complexity for Benthic Biodiversity Conservation: Informing Coastal Management and Planning

Bimo Aji Nugroho*, Ermawaty Maradhy, Hardianto S. Umar

Department of Biology Education, Faculty of Teacher Training and Education, Universitas Borneo Tarakan
Jl Amal Lama No. 1, Tarakan City, North Kalimantan, 77115, Indonesia
Email: bimoajinugroho29@borneo.ac.id

Abstract

Seagrass meadows function as important ecosystem engineers, yet their role in maintaining benthic biodiversity is often overlooked. For this reason, we need to examine spatial variation in Mollusca community structure between seagrass-dominated and non-vegetated habitats. By understanding how seagrass affects the biodiversity of molluscs, we will obtain information on local coastal conservation strategies. We conducted a comparative analysis using the quadrat transect method at six coastal stations (three seagrass-dominated, three unvegetated). Mollusca abundance data, species diversity, and sediment characteristics were analyzed using the independent-samples t-test to assess habitat differences and Pearson correlation to evaluate benthic associations with sediment. The results show a significant difference: Mollusca abundance in seagrass vegetation is three times higher than in areas without vegetation. Seagrass vegetation supports species diversity by providing the organic material necessary for the survival of molluscs. Furthermore, sediment analysis shows that higher total organic material in vegetated areas correlates with the abundance of Molluscan. The findings indicate that the loss of seagrass habitat affects mollusk diversity. Preserving seagrass vegetation also protects the molluscs that inhabit it. This research remains local, so it cannot be directly applied because parameters still need further testing, especially hydrodynamics, canopy physical complexity, and predator interactions.

Keyword: mollusk, Seagrass Conservation, Marine Spatial Planning, Biodiversity

INTRODUCTION

Seagrass meadows are recognized as ecosystem engineers that play a fundamental role in the biophysical stability of coastal zones (Bos *et al.*, 2007; Cesbron *et al.*, 2016). The structural complexity of seagrass vegetation provides the capacity to attenuate wave hydrodynamics (Fourqurean *et al.*, 2012), stabilize benthic sediments, enhance water clarity, and protect shorelines from erosion (Ondiviela *et al.*, 2014). Ecologically, the three-dimensional complexity of seagrass canopies not only facilitates the mechanical trapping of fine particles and organic nutrient enrichment (Liu *et al.*, 2025) but also provides essential structural habitats serving as shelter from predators, stable substrates for spawning, and attachment surfaces for epiphytic growth (Borowitzka & Lethbridge, 1989; Orth *et al.*, 1984). Together, these physical and biogeochemical functions establish a critical foundation for benthic food webs, which directly sustains coastal biodiversity, particularly molluscan communities (Duffy, 2006). For coastal regions, the presence of seagrass represents more than mere vegetation; it serves as a primary indicator of ecosystem service capacity that underpins local food security and economic stability by providing essential habitats for species of high economic value (Nordlund *et al.*, 2018).

While the structural role of seagrass beds in supporting benthic communities compared to bare sediments is a widely recognized phenomenon globally, this ecological function varies significantly depending on specific environmental and geographical contexts (Benoit *et al.*, 2026). Increasing, the capacity of seagrass to maintain these vital protection mechanisms and resources is increasingly threatened by massive anthropogenic pressures, leading to a global decline in seagrass coverage. In Indonesia, this deteriorating condition ranges from moderate (30–59.9% canopy cover) to unhealthy (<30% cover) according to national environmental standards, reflecting a significant challenge in coastal governance (Decree of the State Minister for the Environment Number 200 of 2004 Concerning Standard Criteria for Damage and Guidelines for Determining the Status of Seagrass Beds, 2004). Such habitat degradation is projected to trigger ecological function failures, ultimately leading to a simplification of mollusca community structures. While the general impacts of losing habitat complexity on ecosystem resilience and marine productivity are well-documented,

*) Corresponding author
www.ejournal2.undip.ac.id/index.php/jkt

quantitative data capturing these contextual variations within specific local ecosystems remain limited. Therefore, examining these localized dynamics during the transition from vegetated to non-vegetated states is critical to filling regional data gaps and informing tailored coastal management strategies

Although seagrass meadows play an important ecological role, the specific dynamics of benthic community shifts during the transition from vegetated to non-vegetated states are often overlooked in local conservation assessments. Several studies have focus solely on seagrass health, there is a need to understand how this habitat fundamentally supports associated fauna. Therefore, this study aims to compare the structure of molluscan communities between seagrass-dominated habitats and open sediments, specifically examining how variations in biodiversity and abundance are related to sediment organic matter content. By evaluating the composition and diversity of species in these two different environments, this research provides important baseline data on the role of seagrass structures in maintaining coastal benthic biodiversity.

MATERIALS AND METHODS

The research took place from March to April 2025 at two coastal sites with differing habitat characteristics: Kapas Island ($1^{\circ}16'51.4''\text{N}$, $120^{\circ}48'08.2''\text{E}$) and Binar Beach ($1^{\circ}16'48.3''\text{N}$, $120^{\circ}48'40.1''\text{E}$) in Indonesia (Figure 1). Sampling locations were designated to capture macrobenthic community structures across differing coastal environments. Six observation stations were established using a purposive sampling approach based on the presence and absence of seagrass vegetation. Stations 1, 2, and 3 were located on Kapas Island within seagrass beds dominated by *Enhalus acoroides*, *Syringodium isoetifolium*, *Thalassia hemprichii*, and *Halodule pinifolia*. In contrast, Stations 4, 5, and 6 were situated along the mainland coast of Binar Beach, which is characterized by a non-vegetated, sandy-loamy substrate. This comparative design was utilised to clarify the functional significance of seagrass in influencing coastal habitats. The geographical separation creates inherent abiotic and biotic heterogeneities, which serve as a crucial baseline to illustrate how seagrass presence acts as an ecosystem engineer, fundamentally altering habitat components compared to open, unbuffered coastal systems.

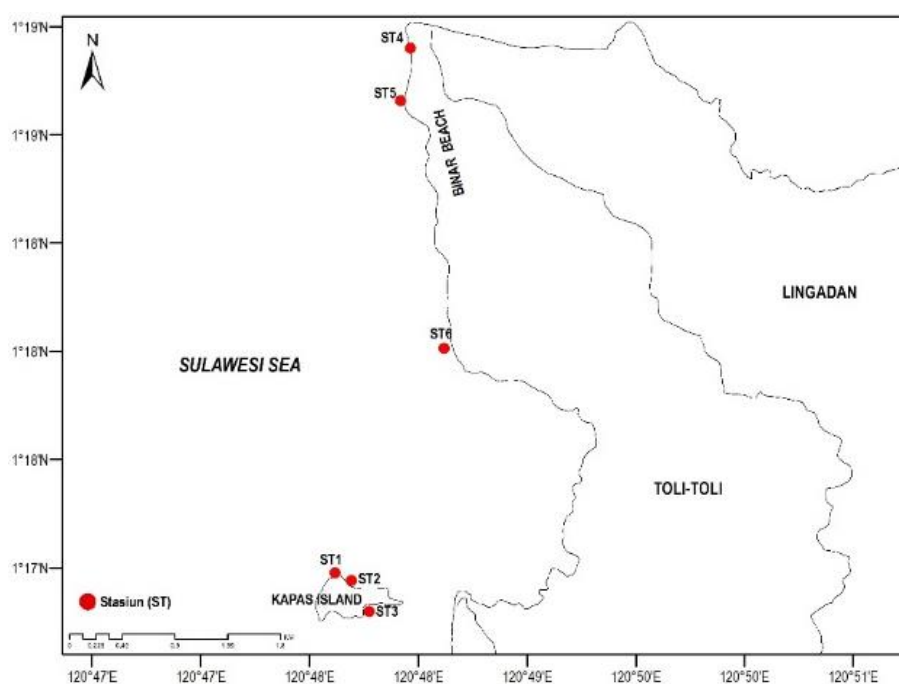


Figure 1. Map of sampling locations at Kapas Island and Binar Beach.

Sampling and sediment collection were conducted during low tide. To eliminate subjective selection bias, the initial positioning of the 50-meter transect at each station was established systematically parallel to the shoreline, ensuring it was positioned entirely within homogenous zones of either dense seagrass beds or completely bare sediments. Along each transect, five 0.5 × 0.5-meter plots (quadrats) were placed at fixed 10-meter intervals, resulting in a total of 30 plots across the six stations. Within each plot, a combined sampling protocol was utilized to capture both epibenthic and infaunal Mollusca (gastropods and bivalves), focusing strictly on the sedimentary compartment. First, visible surface epifauna within the quadrat were gathered through direct hand collection. Immediately following, the sediment within the entire plot area was excavated to a depth of 10 cm using a spade and sieved through a 1.0 mm mesh net to isolate the infauna (Liu *et al.*, 2025). Organisms strictly associated with the upper leaf structures of the seagrass canopy (e.g., canopy epiphytic molluscs) were not scraped or sampled, thereby ensuring a standardized and comparable sampling effort between the vegetated and non-vegetated habitats. Additionally, within the seagrass stations, habitat complexity was quantified by counting individual seagrass shoots inside each plot to determine shoot density. Biota samples were preserved in 70% alcohol. Seagrass density was assessed by counting the number of shoots per square meter within the same plots. Sediment samples for texture and organic matter analysis were collected with a 5 cm diameter, 15 cm depth sediment corer and stored in a cool box prior to laboratory transport.

Molluscan specimens were identified to the species level in the laboratory using taxonomic literature. We identified species through a literature review (Abbott & Dance, 1982; Carpenter & Niem, 1998) by carefully comparing morphological characteristics with published descriptions and verifying them against reference images from the World Register of Marine Species (<https://www.marinespecies.org>). Analysis of sediment characteristics involves determining texture (sand, silt, and clay fractions) using sieving methods (granulometry). The loss on ignition method was used to analyze total organic matter content (Erffemeijer & Koch, 2001). Sediment samples were dried at 105°C to constant weight and ashed at 550°C for 4 hours. The change in sample weight pre- and post-ashing was used to calculate the percentage of organic matter in the sediment (Short *et al.*, 2006).

The community structure of Mollusca was analyzed using ecological indices: total abundance (N), Margalef's species richness (d), Shannon-Wiener diversity (H'), and Pielou's evenness (J'), calculated with PRIMER 6.0 software. Hypothesis testing was conducted using Jamovi software version 2.6, with a significance level of $p < 0.05$. The Independent Samples T-Test compared community parameters and organic matter content between seagrass and coastal habitats following normality testing (Shapiro-Wilk Test). Pearson correlation analysis was conducted to assess the relationship between environmental factors and Mollusca. abundance. Quantitative data is presented as mean ± standard deviation (Mean ± SD).

RESULT AND DISCUSSION

The presence of seagrass species is related to the abundance and composition of molluscan species at each observation location (Table 1). Station 1 is dominated *Enhalus acoroides*, while Station 2 is dominated by *Halodule pinifolia*. Meanwhile, Station 3 has the highest seagrass density, particularly *Thalassia hemprichii* and *Halodule pinifolia*, with the highest accumulation of molluscan, totaling 146 individuals. From the data distribution, habitats rich in *Thalassia hemprichii* and *Halodule pinifolia* become heavily inhabited by molluscan. This phenomenon occurs because the relatively broad leaf morphology and the more effective root system trap sediments, provide an abundance of epiphytic food, and offer physical protection from predators and ocean currents (Kumar *et al.*, 2026).

Conservation status data shows that there is one molluscan species categorized as endangered, namely *Conus compressus* which is classified as vulnerable and is distributed across all stations. Most molluscan species in this study are classified as not evaluated, while species from the

genus *Conus* fall into the least concern category. The composition and abundance of molluscan in the seagrass bed area show differences compared to the non-seagrass area. The total abundance of molluscan found in the seagrass bed area from Station 1 to Station 3 reached 384 individuals, while in the non-seagrass coastal area from Station 4 to Station 6, there were only 141 individuals. Some species, such as *Barbatia virescens*, are even found exclusively in seagrass areas. This difference proves that the structure of seagrass beds serves as a habitat that provides foraging grounds, spawning sites, and protective areas that are not optimally available on open coastal substrates without seagrass.

Table 1. Abundance of seagrass and molluscan species and IUCN conservation status

Seagrass	IUCN	St 1	St 2	St 3	St 4	St 5	St 6
<i>Enhalus acoroides</i>	LC	30	20	21	0	0	0
<i>Syringodium isoetifolium</i>	LC	12	13	23	0	0	0
<i>Thalassia hemprichii</i>	LC	21	11	31	0	0	0
<i>Halodule pinifolia</i>	LC	14	25	30	0	0	0
Bivalvia							
<i>Pinna muricata</i>	NE	1	2	1	0	0	1
<i>Barbatia virescens</i>	NE	2	1	3	0	0	0
<i>Malleus malleus</i>	NE	3	4	2	1	2	0
<i>Isognomon ehippium</i>	NE	1	3	0	2	0	2
<i>Pinctada nigra</i>	NE	1	2	1	0	1	3
Gastropoda							
<i>Nerita incerta</i>	NE	4	3	2	1	0	2
<i>Nassarius pullus</i>	NE	1	2	3	1	1	1
<i>Monetaria moneta (f) icterina</i>	NE	2	4	5	1	3	2
<i>Dolicholatirus lancea</i>	NE	1	6	2	2	1	0
<i>Clypeomorus batillariaeformis</i>	NE	2	5	9	1	2	3
<i>Gibberulus gibberulus</i>	NE	8	2	4	2	1	0
<i>Siphonaria laciniosa</i>	NE	4	7	2	1	3	2
<i>Planaxis sulcatus</i>	NE	4	10	6	1	2	1
<i>Siphonaria normalis</i>	NE	5	2	4	1	0	2
<i>Nerita exuvia</i>	NE	5	7	10	2	0	4
<i>Mauritia arabica</i>	NE	4	5	2	1	2	3
<i>Amplidrupa clathrata</i>	NE	6	2	5	1	2	1
<i>Lyncina vitellus</i>	NE	5	3	10	1	0	3
<i>Lambis millepeda</i>	NE	2	4	8	1	1	1
<i>Conomurex luhuanus</i>	NE	4	8	1	1	4	2
<i>Tylothais aculeata</i>	NE	3	5	2	1	4	2
<i>Lambis lambis</i>	NE	3	5	2	5	0	1
<i>Canarium incisum</i>	NE	6	2	9	1	2	3
<i>Conus compressus</i>	VU	3	2	5	1	1	0
<i>Lentigo lentiginosus</i>	NE	2	3	8	2	0	2
<i>Vasum turbinellus</i>	NE	3	2	6	1	4	2
<i>Conomurex luhuanus</i>	NE	3	7	8	2	5	0
<i>Conus miles</i>	LC	3	1	3	5	3	1
<i>Cypraea tigris schilderiana</i>	NE	2	1	2	1	0	1
<i>Conus marmoreus</i>	LC	3	4	5	1	2	0
<i>Ergalatax margaritcola</i>	NE	6	2	8	2	1	2
<i>Conus litteratus</i>	LC	4	5	7	1	2	0
<i>Lambis chiragra</i>	NE	8	3	1	0	0	1

Note: Not Evaluated (NE); Least Concern (LC); Vulnerable (VU); ST 1,2 and 3 seagrass meadow habitat; ST 4,5 and 6 coastal habitat without seagrass

The Independent-Samples T-Test showed significant differences in the proportion of Mollusca individuals between seagrass ecosystems (Kapas Island) and unvegetated beaches (Binar Beach). The average individual abundance (N) at the seagrass station (Kapas Island) was 136.3 ± 9.6 ind./station, which was significantly higher than at the unvegetated Binar Beach station (45.0 ± 7.0 ind./station) (Table 2). Furthermore, Kapas Island exhibited a higher species richness ($S = 29.3 \pm 1.5$) and a Shannon-Wiener diversity index of $H' = 3.12 \pm 0.04$, indicating a highly diverse community ($H' > 3.0$). In contrast, Binar Beach recorded lower values ($S = 13.7 \pm 1.5$; $H' = 2.30 \pm 0.15$). Pielou's Index (J') showed no significant differences ($P > 0.05$), indicating stable evenness in both habitats.

The marked difference in molluscan abundance between the two sampling locations reflects the environmental contrast the study was designed to test: Kapas Island's small-island setting represents a thriving, natural seagrass ecosystem, while the coastal sandy habitat serves as a non-seagrass control. The results show that the seagrass ecosystem on Kapas Island provides better habitat support for Mollusca than the open, unvegetated coastal substrate (Figure 2). This disparity is primarily driven by seagrass structural complexity, which dampens hydrodynamic currents (Fonseca et al., 2019; Risandi et al., 2023) and mitigates predation pressure (Valdez et al., 2020). Furthermore, the dense seagrass meadow offers diverse microhabitats that families such as Strombidae and Conidae use for shelter and to forage on leaves and epiphytic growth (Table 2). Conversely, the significantly lower diversity and abundance recorded in the sandy coastal habitats devoid of vegetation emphasize that unreinforced substrates fail to provide the essential physical protection and ecological niches sustained by seagrass meadows.

Table 2. Variation in the community structure of mollusca in seagrass and coastal habitats.

Station	Habitat	N	S	d	J'	H'
St. 1	KI	126	29	5.81	0.92	3.12
St. 2	KI	145	31	06.03	0.91	3.15
St. 3	KI	138	28	5.48	0.92	03.08
Average		136.3 ± 9.6	29.3 ± 1.5	5.77 ± 0.28	0.92 ± 0.01	3.12 ± 0.04
St. 4	BB	45	15	3.68	0.90	2.45
St. 5	BB	38	12	03.02	0.86	2.15
St. 6	BB	52	14	3.29	0.87	2.30
Average		45.0 ± 7.0	13.7 ± 1.5	3.33 ± 0.33	0.88 ± 0.02	2.30 ± 0.15
T-Test (P-value)		0.0001**	0.002**	0.001**	0.051	0.004**

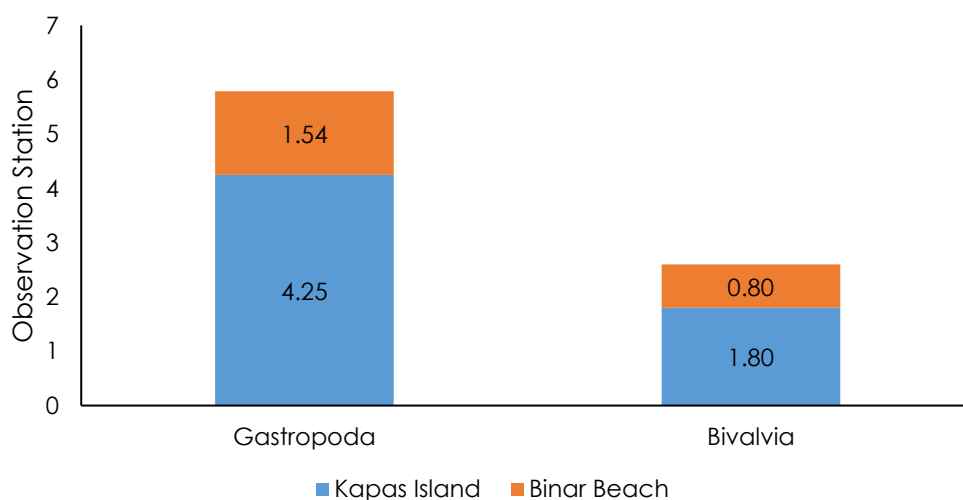


Figure 2. Spatial comparison of community parameters between Kapas Island and Binar Beach.

The substrates differ fundamentally in both habitats. Seagrass bed habitats are dominated by sandy sediment with total organic matter content of $1.95 \pm 0.37\%$ (Table 3). In comparison, the Binar Beach habitat is dominated by muddy sand with an organic matter content of $1.62 \pm 0.33\%$. Although the mean organic matter is higher in the seagrass habitat, overlapping standard deviations suggest caution in interpreting these differences.

Pearson correlation analysis indicated a moderate positive relationship ($r = 0.59$) between sediment organic matter content and total Mollusca abundance (Figure 3). The coefficient of determination ($R^2 = 0.35$) shows that organic matter availability contributes to 35.2% of the variation in Mollusca population density. This value indicates that organic matter is not the only factor.

The presence of seagrass is widely recognised as an ecosystem engineer that affects sediment characteristics by reducing current velocity and facilitating the deposition of fine particles (Krause et al., 2025; Liu et al., 2025). In this study, the physical function was demonstrated through the differences in environmental parameters between the two habitats. Seagrass-dominated habitats such as *Enhalus acoroides* in Kapas Island recorded a higher average Total Organic Matter (TOM) content ($1.95 \pm 0.37\%$) compared to the unvegetated Binar Beach ($1.62 \pm 0.33\%$) (Figure 4). In addition to

Table 3. Physicochemical characteristics of sediments and seagrass density at each observation station

Station	Habitat	Sediment Characteristics	Organic Matter (%)	Seagrass Density (ind/m ²)	Abundance of Mollusca (ind/m ²)
St 1	KI	Sand	1.55	120	114
St 2	KI	Sand	2.29	145	124
St 3	KI	Sand	2.00	110	146
Average $\pm$ SD			1.95 ± 0.37	125 ± 18	136 ± 10
St 4	BB	Clayey sand	1.94	0	44
St 5	BB	Clayey sand	1.28	0	49
St 6	BB	Clayey sand	1.65	0	48
Average $\pm$ SD			1.62 ± 0.33	0	45 $\pm$ 7

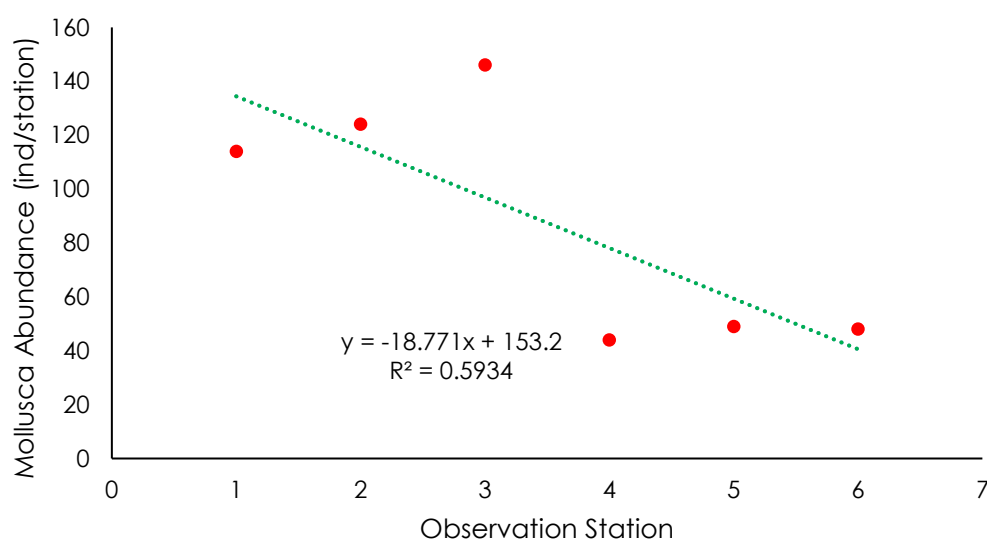


Figure 3. Linear regression relationship between total organic matter (TOM) content in sediments and total abundance of Mollusca.

Organic matter analysis also showed that the total phosphorus (P total) content in Kapas Island was much higher, ranging from 18.93 to 22.60 mg/kg (Figure 5). Phosphorus is a limiting nutrient in coastal ecosystems that triggers primary productivity (Liu *et al.*, 2025), both in seagrass beds and the epiphytes that grow on them (Cai *et al.*, 2024). The structure of seagrass vegetation on Kapas Island facilitates the accumulation of phosphorus and organic matter, in contrast to Binar Beach, where the sandy clay substrate lacks vegetation.

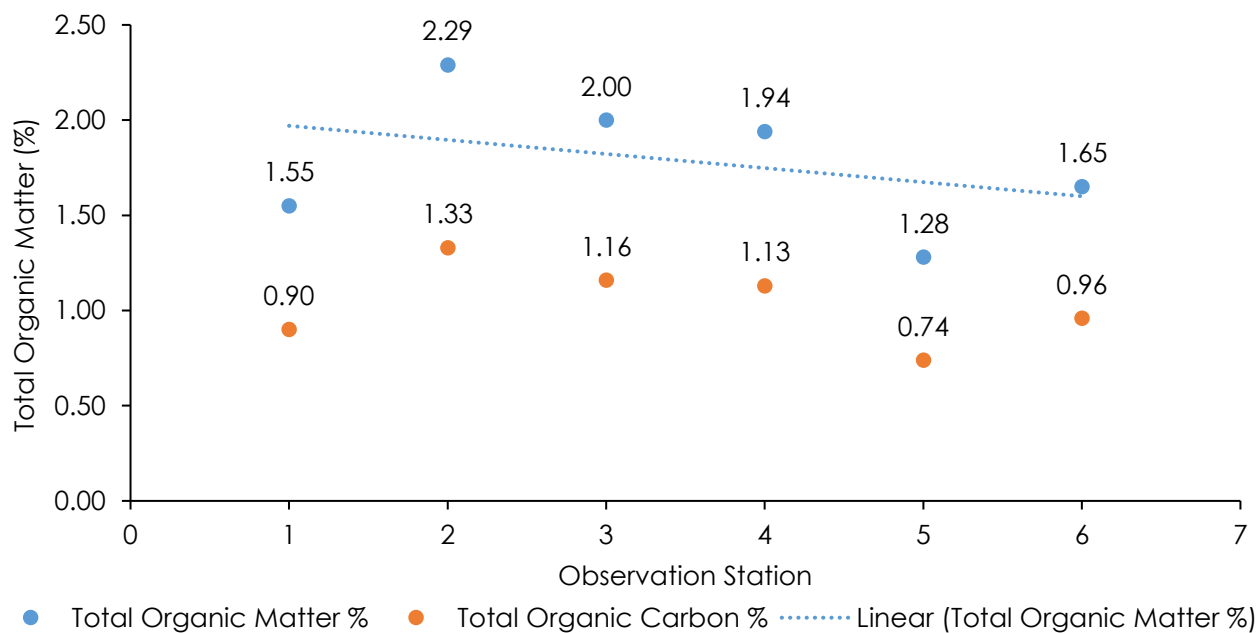


Figure 4. Analysis of Total Organic Matter and Total Organic Carbon

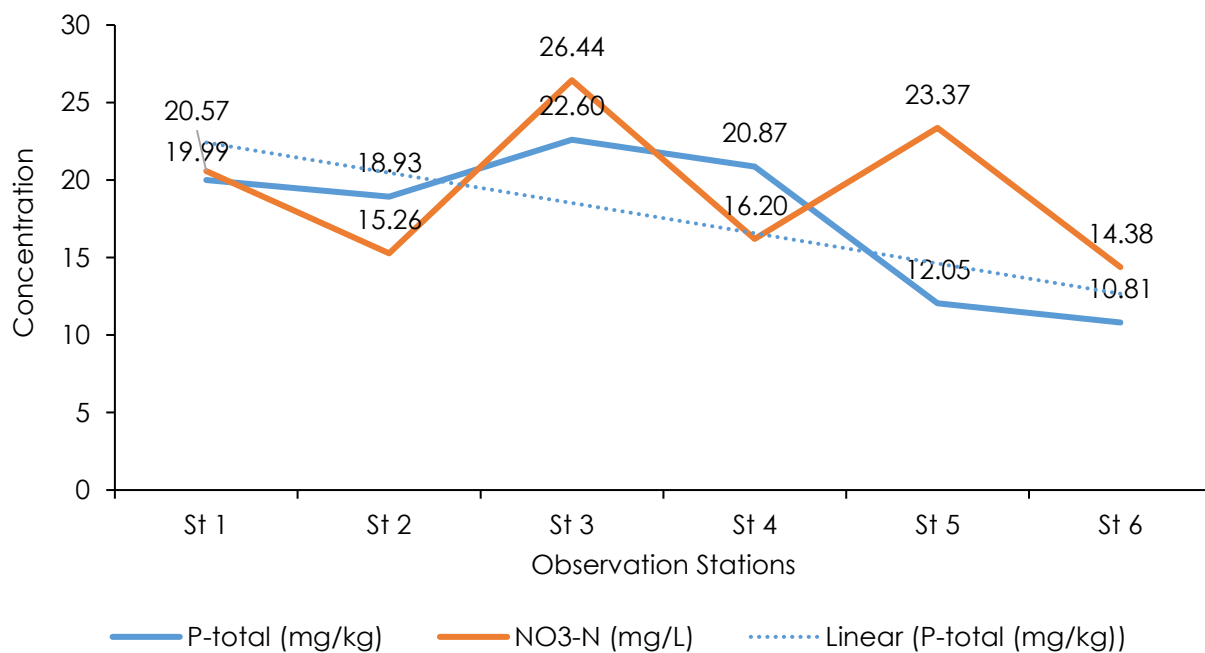


Figure 5. Analysis of total P and NO₃-N

The nutrient-rich, organic-matter-laden sediment on Kapas Island spatially coincides with higher Mollusca abundance, which is three times higher (136.3 individuals/station) than at Binar Beach (45.0 individuals/station). Statistically, correlation analysis shows a moderate positive relationship ($r = 0.59$) between TOM content and Mollusca abundance, with a coefficient of determination ($R^2 = 35.2\%$). This indicates that about one-third of the variance in Mollusca abundance among habitats can be explained by sediment organic matter availability. Organic matter accumulation supports benthic communities by providing abundant food resources (Tsikopoulou *et al.*, 2021), as evidenced by the presence of families such as Strombidae in vegetated areas. Conversely, the unvegetated environment at Binar Beach recorded much lower abundance, reflecting its low capacity to retain organic matter because the absence of a seagrass canopy removes a natural barrier (Salinas *et al.*, 2020).

Although organic matter is an important driver, it should be noted that most of the abundance variance (around 64.8%) remains unexplained by the parameters in this study. The unmeasured variance is likely influenced by a combination of other environmental and biological factors not assessed in this study, such as the physical ability of seagrass to dampen hydrodynamics (Soto *et al.*, 2023), predator-prey dynamics (Lennox *et al.*, 2025), and the provision of crucial physical protection for Mollusca (Villanueva *et al.*, 2023). The loss of seagrass meadows in the future not only risks reducing nutrient retention capacity by 15–40% (Ren *et al.*, 2024) but also eliminates the environmental stability necessary for benthic communities to thrive. These results emphasise that the presence of seagrass ecosystems is crucial for the sustainability of the local coastal ecosystem structures on Kapas Island. Although this study has limitations in spatial scale and the number of parameters, the data produced can be relied upon as baseline data for initial conservation studies.

CONCLUSION

This study indicates that seagrass meadows at Kapas Island are associated with a significantly higher abundance of Mollusca averaging 136.3 individuals/station and superior species diversity ($H' > 3.0$) compared to the unvegetated habitats of Binar Beach (45.0 individuals/station). These findings suggest that the presence of seagrass may function as a critical habitat driver for benthic communities. While a positive correlation exists between total organic matter and Mollusca abundance ($r = 0.35$), the coefficient of determination ($R^2 = 12.4\%$) suggests that organic matter enrichment is only one of several factors influencing these communities. The majority of the variance in abundance remains unexplained, likely due to unmeasured variables such as canopy structural complexity and hydrodynamic damping. Given the localised scale and taxonomic focus of this research, these results should be viewed as a preliminary baseline. Further studies with broader spatial replication and functional trait analysis are essential to fully elucidate the mechanistic links between seagrass architecture and coastal biodiversity services.

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