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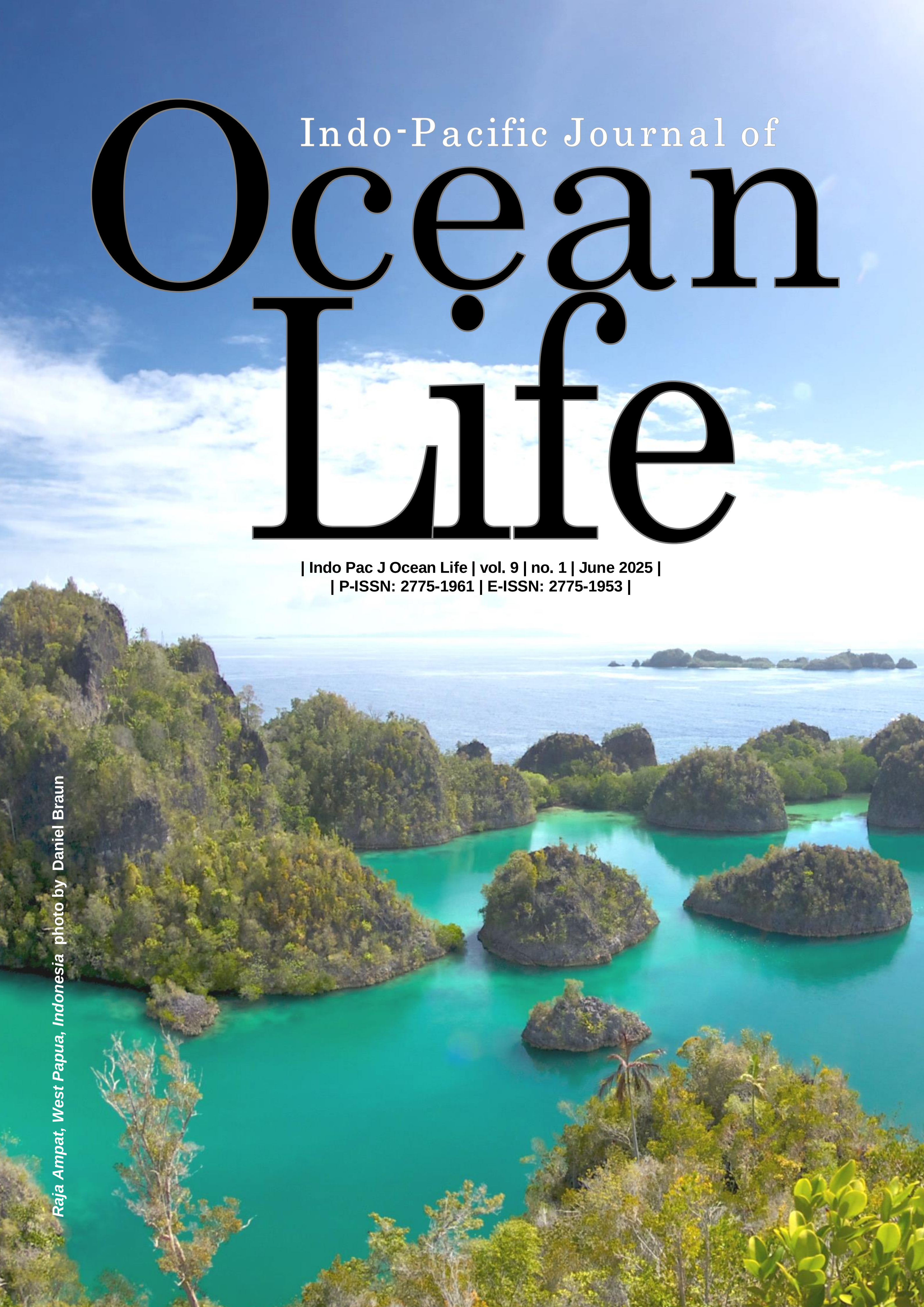

Raja Ampat, West Papua, Indonesia photo by Daniel Braun

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Introduction is about 600 words, covering the aims of the research and provide an adequate background, avoiding a detailed literature survey or a summary of the results. **Materials and Methods** should emphasize on the procedures and data analysis. **Results and Discussion** should be written as a series of connecting sentences, however, for a manuscript with long discussion should be divided into subtitles. Thorough discussion represents the causal effect mainly explains why and how the results of the research were taken place, and do not only re-express the mentioned results in the form of sentences. **Concluding** sentence should be given at the end of the discussion. **Acknowledgements** are expressed in a brief; all sources of institutional, private and corporate financial support for the work must be fully acknowledged, and any potential conflicts of interest are noted.

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Journal:

Saharjo BH, Nurhayati AD. 2006. Domination and composition structure change at hemic peat natural regeneration following burning; a case study in Pelalawan, Riau Province. Biodiversitas 7: 154-158. DOI: 10.13057/biodiv/d070213.

The usage of "et al." in long author lists will also be accepted:

Smith J, Jones M Jr, Houghton L et al. 1999. Future of health insurance. N Engl J Med 965: 325-329. DOI: 10.10007/s002149800025.

Book:

Rai MK, Carpinella C. 2006. Naturally Occurring Bioactive Compounds. Elsevier, Amsterdam.

Chapter in the book:

Webb CO, Cannon CH, Davies SJ. 2008. Ecological organization, biogeography, and the phylogenetic structure of rainforest tree communities. In: Carson W, Schnitzer S (eds.). Tropical Forest Community Ecology. Wiley-Blackwell, New York.

Abstract:

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

Proceeding:

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

Thesis, Dissertation:

Sugiyarto. 2004. Soil Macro-invertebrates Diversity and Inter-Cropping Plants Productivity in Agroforestry System based on Sengon. [Dissertation]. Universitas Brawijaya, Malang. [Indonesian]

Information from the internet:

Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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Diversity of soil macrofauna in the coastal karst area of Gunung Sewu, Paranggupito Sub-district, Wonogiri District, Indonesia

CALVIN LEVYANTO PRAMONO[1], GLORA RAMADHANI[1], JASMINE AISYAH ZAHRA[1], JUNIETA WAHYUNINGTYAS[1], GILANG DWI NUGROHO[2], MUHAMMAD INDRAWAN[1], AHMAD DWI SETYAWAN[1,3,♥]

[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia. Tel.: +62-271-669376, Fax.: +62-271-663375, ♥email: volatileoils@gmail.com

[2]Biodiversity Study Club, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

[3]Biodiversity Research Group, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

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Abstract. *Pramono CL, Ramadhani G, Zahra JA, Wahyuningtyas J, Nugroho GD, Indrawan M, Setyawan AD. 2025. Diversity of soil macrofauna in the coastal karst area of Gunung Sewu, Paranggupito Sub-district, Wonogiri District, Indonesia. Indo Pac J Ocean Life 9: 1-11.* As a region with unique characteristics of limestone formations and a complex drainage system, the karst region faces environmental challenges that affect its macrofauna diversity. This study aims to identify soil macrofauna and analyze the relationship between abiotic factors that influence their presence in agroforestry land in a coastal karst area of Gunung Sewu, a United Nations Educational, Scientific and Cultural Organization (UNESCO) Global Geopark, including Paranggupito Village, Gudangharjo Village, and Gunturharjo Village of Paranggupito Sub-district, Wonogiri District, Central Java, Indonesia, that was conducted in October 2024. To achieve the study's objectives, we measured abiotic factors, including physical and chemical elements of the environment, such as temperature, air humidity, soil humidity, light intensity, altitude, soil pH, and soil temperature. This study involved two types of plantation patterns in each village, namely woody and intercropping vegetation, with 18 research points divided into 2 stations in each area, each consisting of 3 sub-stations with 90 pitfall traps. Soil macrofauna samples were collected using the pitfall trap method, and data were analyzed using a diversity index and Pearson correlation between the diversity of soil macrofauna and its abiotic factors. The results showed that 16 different species were found in all three villages, and the sugar ant (*Camponotus consobrinus*) species dominated the intercropping vegetation, with a total of 347 individuals and 104 individuals in woody vegetation. The diversity of macrofauna at each station was relatively low. In contrast, the relationship between abiotic factors and diversity showed varying correlations, such as soil moisture, light intensity, and air humidity were negatively correlated by -0.59, -0.41, and -0.39, respectively, which means when the values increase, then the diversity tends to decrease and vice versa; In contrast, pH soil, soil temperature and air temperature were positively correlated by 0.79, 0.62, 0.78, respectively showing a moderately strong relationship whereas the soil values increase, the diversity also tends to increase. The discovery of soil macrofauna species in this study shows that macrofauna are able to survive in karst areas, which have an important role in maintaining soil health and fertility, so their existence must be maintained and preserved, highlighting their resilience and the importance of preserving their habitats to maintain soil health and fertility.

Keywords: Coastal, intercropping, karst, pitfall trap, vegetation, woody

INTRODUCTION

Karst is known as an area with a landform composed of limestone with a distinctive morphological and hydrological arrangement (Aprilia et al. 2021). In geology, the term karst represents the physiognomic phenomenon of dissolved carbonate rocks, for example, the development of carbonic acid salts (Anjum et al. 2014). The typical hydrological characteristics found in karst areas are rock formations that are easily dissolved and have good secondary porosity, for instance, limestone, marble, and gypsum (Prihatanto et al. 2022). Aside from its uniqueness, the karst area faces many challenges, including water availability, high physical, chemical, and biological heterogeneity or variation, and sensitivity to environmental changes that influence the suitability of agricultural systems (Wang et al. 2019). The choice of plants in karst regions depends on their ability to adapt to limiting factors in the environment, such as scarce water resources and nutrient-poor soil that lacks essential elements like nitrogen and phosphorus (Liu et al. 2021).

An agricultural system is an ecosystem with unique characteristics and often faced with limited resources in water, soil, and land (Pretty and Bharucha 2014). For sustainable reasons, an agricultural system requires a population or social resources (Anjum et al. 2014). The existence of irrigation as a substitute for natural rainfall is an example of maintaining the stability of the water supply and overcoming drought in karst areas. It has already happened in a coastal karst area of Paranggupito Sub-district, located at the southern tip of Wonogiri District, Central Java, Indonesia, which has been designated as an area that is highly vulnerable to drought by the Wonogiri Regional Disaster Management Agency (Widjajadi 2019). Research by Wang et al. (2019) showed that there is a positive correlation between the density of soil macrofauna and soil water content which decreases due to drought. For this reason, the agricultural system in Paranggupito must implement a strategy to help with the adaptation of macrofaunas. In the study of Wardani et al. (2021), forms of short-term and medium-term adaptation strategies that can be applied to the agricultural system are presented, such as planning planting times, selecting superior drought-tolerant plant varieties, implementing intercropping systems, economic adaptation, empowering farmers, and utilizing sloping land.

Soil macrofauna plays a key role in maintaining soil quality and agricultural productivity. Abiotic factors like temperature, humidity, and soil pH influence the metabolism and activities of these organisms (Masebo et al. 2024). Optimal soil temperature can boost macrofauna activity in digging, digestion, and reproduction (Dacal et al. 2022). Adequate soil moisture supports their mobility and enhances aeration, while a neutral pH promotes higher diversity (Chamorro-Martínez et al. 2022). Favorable abiotic conditions improve soil quality through aeration, decomposition, and nutrient cycling, whereas poor conditions can cause stress or death in macrofauna, harming soil ecosystem health (Rajwar et al. 2021). Soil macrofauna are soil-dwelling organisms larger than 2 mm (Gongalsky 2021) and often serve as soil health indicators in agricultural systems. Their diversity and abundance can reflect soil quality and the health of nutrient-cycling micro-ecosystems. Soils rich in macrofauna are typically more fertile, with improved texture and greater support for plant growth (Bufebo et al. 2021; Coelho et al. 2021).

Soil macrofauna influences biological processes that support soil fertility and agricultural productivity. Soil macrofauna often found include earthworms, ants, termites, beetles, centipedes, and several types of insects and other arthropods (Coleman et al. 2024). Soil macrofauna is able to decompose organic matter, such as dead plant and animal remains (Gongalsky 2021). This decomposition process accelerates the formation of humus, an important part of fertile soil. In addition, these organisms have a role in supporting nutrient cycles, improving soil structure, and improving the soil's ability to absorb and store water (Anitha et al. 2020). Prabowo et al. (2024) researched the vegetation characteristics of the Wonogiri karst region. However, little research has been carried out on soil macrofauna in the Wonogiri karst area. Therefore, this research is essential to identify soil macrofauna and understand their relationship with abiotic factors, especially in the agroforestry land of coastal karst area in Wonogiri District, Central Java, Indonesia, as those macrofaunas play a critical role in terms of soil health and nutrient cycling of agroforestry practices in an ecologically fragile region.

MATERIALS AND METHODS

Study area

The study was conducted in October 2024 in the agroforestry land in the coastal karst area of Gunung Sewu, a United Nations Educational, Scientific and Cultural Organization (UNESCO) Global Geopark, of Paranggupito Sub-district, Wonogiri District, Central Java, Indonesia, including three villages/stations, i.e., Paranggupito Village, Gudangharjo Village, and Gunturharjo Village (Figure 1). Wonogiri has a fairly wide variety of habitats, ranging from reservoir waters, rivers, and forests to agricultural land. This diversity provides a variety of environments that support a diversity of microfauna, allowing more profound observation and analysis of diverse microfauna species.

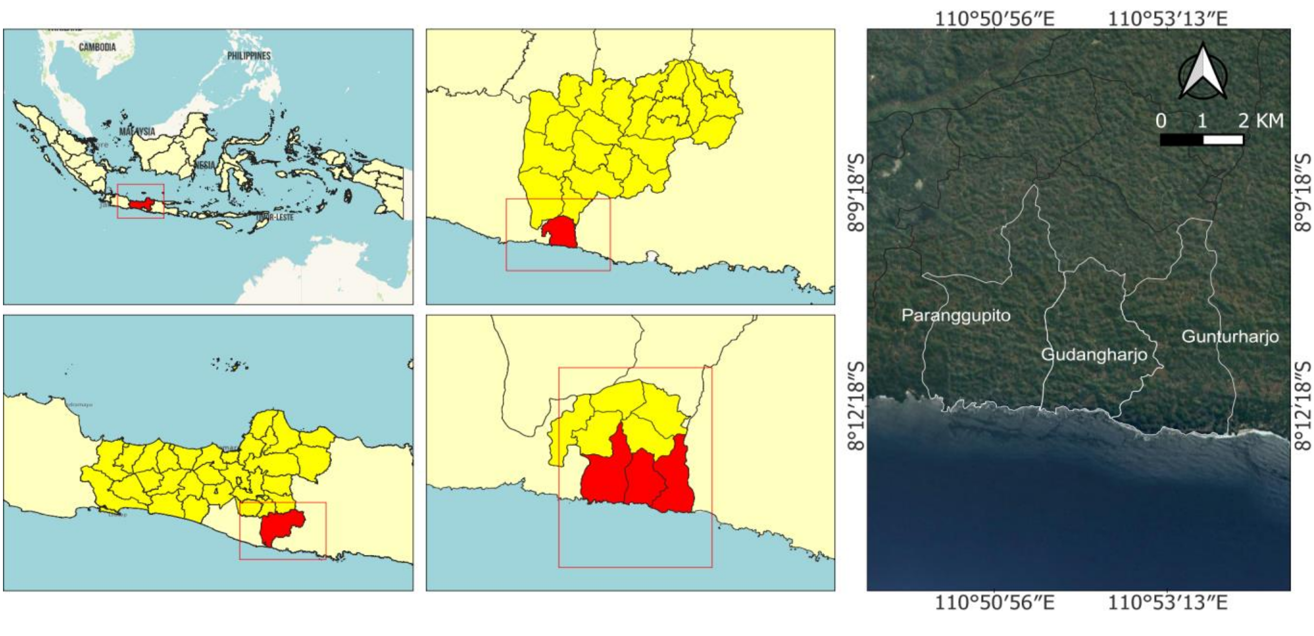

Figure 1. Research location in the coastal karst area of Gunung Sewu, i.e., Paranggupito, Gudangharjo, and Gunturharjo villages of Paranggupito Sub-district, Wonogiri District, Central Java, Indonesia

Figure 2. Research locations in the coastal karst area of Paranggupito Sub-district, Wonogiri District, Central Java, Indonesia. A. Woody vegetation; B. Intercropping vegetation

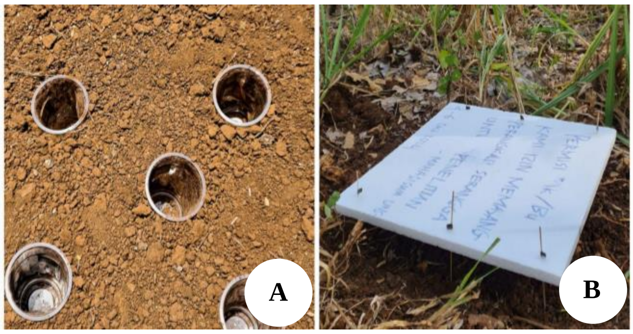

Figure 3. A. Installation of plastic cups; B. Pitfall trap shade

The location is part of the Gunung Sewu Karst area, which is spread across five districts: Eromoko, Pracimantoro, Giritontro, Paranggupito, and Giriwoyo Districts. This area is dominated by limestone hills with hilly contours, and there are natural limestone caves scattered in various locations resulting from the process of dissolving limestone by rainwater. Each station in one village represents 2 sampling points based on different vegetation, namely woody and intercropping vegetation (Figure 2). Station 1 is located in Paranggupito Village, mainly in woody vegetation with coordinates 8.09'55" S-110.051'9" E and in intercropping vegetation with coordinates 8.09'53" S-110.051'8" E. Then, station 2 is located in Gudangharjo Village, in woody vegetation with coordinates 8.010'16" S-110.052'16" E and intercropping vegetation with coordinates 8.010'15" S-110.052'14" E. The last station is located in Gunturharjo Village in woody vegetation with coordinates 8.012'20" S-110.054'02" E and intercropping vegetation with coordinates 8.010'55" S-110.052'38" E.

The research area has 2 stations in each village that are distinguished based on the type of plantation pattern (woody vegetation and intercropping vegetation) as in Figure 2, with each having 3 sub-stations (5 pitfall traps every sub-station), so the total number of stations is 18 points with 90 cups of pitfall traps. This is because vegetation management in different agroforestry systems can affect the diversity of soil macrofauna (Masebo et al. 2024). The tools used in this study included 500 mL plastic cups, stirrers, hoes, foam tape, styrofoam, scissors, rulers, smartphones, tweezers, plastic clips, jerry cans, and satay skewers. Enviro-meter tools, such as ITuin Soil Testers, Alla France Soil Thermometers, Krisbow AS803 Lux Meter, and NTL-HM370 Hygro Thermometer were used to determine the abiotic conditions in the research area. The materials used were liquid detergent, distilled water, shrimp paste, and 70% alcohol.

Procedures

Environmental factor measurement

Environmental parameter measurements were carried out at each trap installation point at three different times, namely morning (07.00-08.00), afternoon (12.00-13.00), and evening (16.00-17.00), to represent the environmental conditions of observation (Ahmad et al. 2024). The environmental conditions of the study were based on the abiotic factors measured: air temperature, air humidity, soil humidity, light intensity, soil pH, and soil temperature.

Preparation of attractant solution

The attractant solution attracts soil macrofauna to the installed trap. It is made by mixing detergent liquid (25 mL), 70% alcohol (50 mL), and distilled water (75 mL) in a ratio of 1: 2: 3 for 1 cup of pitfall trap. The mixture is stirred until it becomes a homogeneous solution and stored in a clean jerrycan before being poured into the pitfall trap.

Pitfall trap making

The sampling method used was a pitfall trap (Figure 3). The pitfall trap method is a simple trap made by digging the ground and then submerging a plastic cup so that the lip of the plastic cup is parallel to the ground surface to obtain samples of macrofauna that are active on the ground surface (Heddle et al. 2023). The plastic cup contains an attractant solution in the form of a mixture of detergent, alcohol, and distilled water to kill and preserve the sample so that the specimen is not easily damaged (Rahmawati et al. 2024). Liquid detergent is added to eliminate the tension on the water surface so that the sample does not float on the solution (Graux et al. 2024). This study placed 5 plastic cups by random simple sampling with an attractant solution of 150 mL at each sub-station so that the total pitfall traps installed were 90. The trap's inside was baited with shrimp paste attached to the plastic cup's wall to increase the attraction of incoming macrofauna. The top of the trap is shaded with styrofoam with skewers as supports (Figure 3) to prevent water, pollutants, or other vertebrates from entering the trap (Gardarin and Valantin 2021). Pitfall traps are installed in the morning (07.00-08.00) and evening (18.00-19.00) and then observed after 24 hours in the hope of being able to represent the ecological conditions of each category of soil macrofauna (nocturnal and diurnal).

Table 1. Macrofauna community structure value criteria

Index	Range	Category
Biodiversity (H')	H' ≤ 2	Low diversity
	2 < H'≤ 3	Moderate diversity
	H ≥ 3	High diversity

Source: Ulfah et al. (2019)

Identification of soil macrofauna

The soil macrofauna samples obtained will be observed and measured using a ruler, tweezers, and a smartphone telephoto camera at the family, genus, and species level with key guidelines from the book, namely Insect Determination Key (Lilies 1991) and An Introduction to the Study of Insects (Borror et al. 1989), then a scientific study by Peritika et al. (2012), Sembiring et al. (2021) and Rahmawati et al. (2024). The number of samples for each species was counted manually to determine the dominant species of certain trapped macrofauna.

Data analysis

Diversity index

Soil macrofauna sample data is used to calculate the Shannon-Wiener diversity index (Putro et al. 2023) by comparing the high and low diversity of macrofauna species in each area with the formula:

$$H' = -\sum_{i=1}^{s}(Pi)(\text{In}Pi)$$

Where: Pi: ∑ni/N; H': Shannon-Wiener diversity index; Pi: Number of individuals of a species/total number of all species; ni: Number of individuals of the i-th species; N: Total number of individuals. Macrofauna community structure value criteria can be seen in Table 1.

Pearson correlation

Furthermore, a Pearson correlation analysis was carried out to determine the relationship between the soil macrofauna diversity index and various environmental factors variables such as soil moisture, pH, soil temperature, light intensity, air temperature, and air humidity. Many abiotic factors indirectly affect the reproduction of soil macrofauna, including changes in rainfall, temperature, humidity, and air direction (Peritika et al. 2012; Safitri 2016). One method is used to determine the relationship status between a variable and another variable. One of the popular correlation techniques is the Pearson correlation. This correlation technique involves one dependent variable and one independent variable. The Pearson correlation coefficient measures the extent of the linear relationship between two variables. However, suppose the relationship between the two variables is non-linear. In that case, the Pearson correlation coefficient results will not accurately represent the strength of the relationship between the two variables, even though they have a strong relationship (Safitri 2016). The Pearson correlation coefficient value is between -1.0 and 1. A value of 1 indicates a positive correlation, while -1 represents a negative correlation, and a value of 0 signifies no correlation (Windarto 2020). The formula for determining Pearson correlation is shown as follows:

$$r = \frac{\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{[(\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2)(\frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2)]^{\frac{1}{2}}}$$

Where: r: Pearson coefficient; n: Number of pairs of the stock; $\sum xy$: Sum of products of the paired stocks; $\sum x$ = Sum of the x scores; $\sum y$ = Sum of the y scores; $\sum x^2$ = Sum of the squared x scores; $\sum y^2$ = Sum of the squared y scores.

RESULTS AND DISCUSSION

Soil macrofauna are a group of animal organisms that live in and/or on the surface of the soil with large sizes, usually more than 2 mm (Zhou et al. 2022). Soil macrofauna plays an important role in the soil ecosystem by helping the decomposition process, loosening the soil, and increasing air and water circulation (Handayani and Winara 2020). Installing pitfall traps is carried out to determine the density or abundance of soil macrofauna, especially active insects above the soil surface.

Table 2 shows that the sugar ant (*Camponotus consobrinus* (Erichson, 1842)) species dominate the soil macrofauna in Gunturharjo Village, with a total of 54 individuals in intercropping vegetation land and 229 individuals in woody vegetation land. In woody vegetation land in Gudangharjo Village, the dominant soil macrofauna species are *C. consobrinus*, with a total of 49 individuals, and *Odontoponera* sp., with a total of 32 individuals. *Camponotus consobrinus* also dominates intercropping vegetation land in Gudangharjo with 42 individuals. In addition, the *Odontoponera* sp. species has a total of 15 individuals, which is quite significant compared to other species. *Camponotus consobrinus* species still dominates in Paranggupito Village in intercropping vegetation land with a total of 76 individuals. Meanwhile, in soil macrofauna in woody vegetation land, there are no species that dominate significantly because the difference number of individuals between species is very small; the most individuals found are the *Odontoponera* sp. species, with a total of 3 individuals.

Based on Table 3, the number of soil macrofauna individuals in Gunturharjo Village and Paranggupito Village was more inland with intercropping vegetation. Meanwhile, soil macrofauna in Gudangharjo Village was mostly found on land with woody vegetation. Gunturharjo Village has the largest total number of individuals among the other 2 villages, namely 299 individuals. Based on species diversity, macrofauna in intercropping vegetation land are more diverse in Gudangharjo and Paranggupito Villages. In Gunturharjo Village, the number of species between woody vegetation land and intercropping vegetation land showed balanced results. Overall, the number of species in Gunturharjo Village was the largest among the three villages, namely 9 different species.

Table 2. Identification of soil macrofauna diversity in the coastal karst area of Gunung Sewu, Paranggupito Sub-district, Wonogiri District, Indonesia

Village	Vegetation	Ordo	Species	Number of individuals
Gunturharjo	Woody	Hymenoptera	*Odontoponera* sp.	3
		Hymenoptera	*Dolichoderus* sp.	4
		Hymenoptera	*Camponotus consobrinus* (Erichson, 1842)	54
		Coleoptera	*Harpalini* sp.	4
		Orthoptera	*Teleogryllus emma* (Ohmachi & Matsuura, 1951)	1
	Intercropping	Hymenoptera	*Camponotus consobrinus* (Erichson, 1842)	229
		Arthropoda	Arthropods species	1
		Arthropoda	*Tegenaria* sp.	1
		Hemiptera	*Leptocorisa oratoria* (Fabricius, 1794)	1
		Lepidoptera	*Eressa confinis* (Walker, 1854)	1
Gudangharjo	Woody	Hymenoptera	*Odontoponera* sp.	32
		Hymenoptera	*Camponotus consobrinus* (Erichson, 1842)	49
		Diptera	*Musca domestica* (Linnaeus, 1758)	5
	Intercropping	Hymenoptera	*Odontoponera* sp.	15
		Hymenoptera	*Camponotus consobrinus* (Erichson, 1842)	42
		Arthropoda	*Tegenaria* sp.	3
		Araneae	*Badumna insignis* (L.Koch, 1872)	1
		Isopoda	*Philoscia* sp.	6
		Diptera	*Musca domestica* (Linnaeus, 1758)	9
		Coleoptera	*Harpalini* sp.	1
		Blattodea	*Blatella* sp.	4
Paranggupito	Woody	Hymenoptera	*Odontoponera* sp.	3
		Hymenoptera	*Camponotus consobrinus* (Erichson, 1842)	1
		Hemiptera	Hemiptera species	2
		-	Unidentified	2
	Intercropping	Diptera	*Musca domestica* (Linnaeus, 1758)	2
		Hymenoptera	*Camponotus consobrinus* (Erichson, 1842)	76
		Hymenoptera	*Odontoponera* sp.	1
		Coleoptera	*Paederus fuscipes* (Curtis, 1826)	2
		-	Unidentified	1

Table 3. Number of individuals and dominant species in the coastal karst area of Gunung Sewu, Paranggupito Sub-district, Wonogiri District, Indonesia

Village	Vegetation	Number of individuals	Total individuals	Number of species	Total different species
Gunturharjo	Woody	66	299	5	9
	Intercropping	233		5	
Gudangharjo	Woody	86	167	3	8
	Intercropping	81		8	
Paranggupito	Woody	8	90	4	6
	Intercropping	82		5	

The results of the species analysis found in Gunturharjo Village, Gudangharjo Village, and Paranggupito Village showed that there were 16 different species. *Camponotus consobrinus* species can be found in all villages of the research location, both in woody and intercropped vegetation. Then, it can be seen in Figure 4 that the soil macrofauna in woody vegetation land contains 8 different species dominated by *C. consobrinus* species. Figure 5 shows that the soil macrofauna in intercropped vegetation land is more diverse, with 13 species dominated by *C. consobrinus* species.

Table 4 shows that in Gunturharjo Village, the diversity index in woody vegetation was recorded at 0.71, while in intercropping vegetation, it was lower at 0.11. Soil moisture in this village is at 2%, with soil pH remaining neutral with pH 7 and 6.5, respectively. Soil temperature is slightly different, where woody vegetation was recorded at 29.5°C, and in intercropping, it was 29°C. This village also shows a significant difference in light intensity, where woody vegetation only receives 4,810 Lux, while intercropping vegetation receives a much higher intensity of 345,406 Lux. Air humidity is slightly higher in woody vegetation (34.1°C) than intercropping (32.6°C), with air humidity recorded at 29 and 30%, respectively. In the second research location, namely Gudangharjo Village, the diversity index is higher in intercropping vegetation (1.32) than in woody (0.85). The soil moisture in this village is only 1%, with the soil pH remaining neutral (pH 7) for both types of vegetation. The soil temperature in woody vegetation reaches 30.4°C, while in intercropping it is 30°C. Woody vegetation receives 5,550 Lux of light, much lower than intercropping, which reaches 336,905 Lux. The air temperature in woody vegetation is higher (35.1°C) than intercropping (34.5°C), with air humidity ranging from 28 to 30%. At the third research location, namely in Paranggupito Village, the diversity index in woody vegetation was recorded at 1.32, while in intercropping vegetation, it was lower, namely 0.38. The soil moisture in both vegetation types is at 1%, with a neutral soil pH (pH 7). The soil temperature ranges from 29.5°C in woody vegetation and 29.2°C in intercropping. The light intensity also differs significantly, where woody vegetation only receives 6,040 Lux, while intercropping reaches 340,533 Lux. The air temperature in woody vegetation is higher (36.5°C) than intercropping (34.5°C), with air humidity recorded at 29 and 31%, respectively.

Table 5 shows the Pearson correlation value between the species diversity index and various abiotic factors. Soil moisture has a moderate negative correlation of -0.59, which means that the higher the soil moisture, the species diversity tends to decrease. On the other hand, the soil moisture p-value of 0.22 indicates an insignificant correlation between soil moisture and diversity. Many ways can affect this finding, such as the size and the variability of the sample. The pH showed a strong positive correlation to the Shannon-Wiener diversity index with a correlation value of 0.79. This indicates that species diversity tends to increase as the pH approaches neutrality (closer to 7). The p-value of the pH variable is 0.06, which also indicates a low significance of the correlation between pH and diversity.

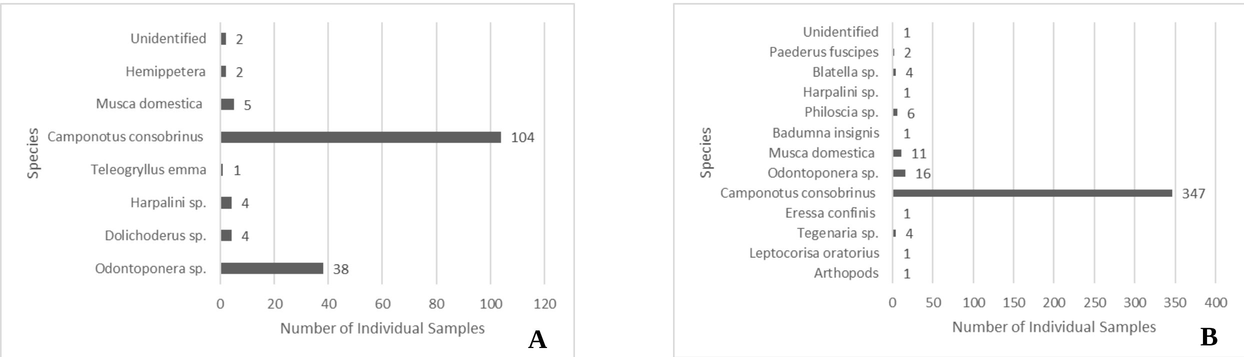

Figure 4. Soil macrofauna dominance in the coastal karst area of Gunung Sewu, Paranggupito Sub-district, Wonogiri District, Indonesia: A. Woody vegetation; B. Intercropping vegetation

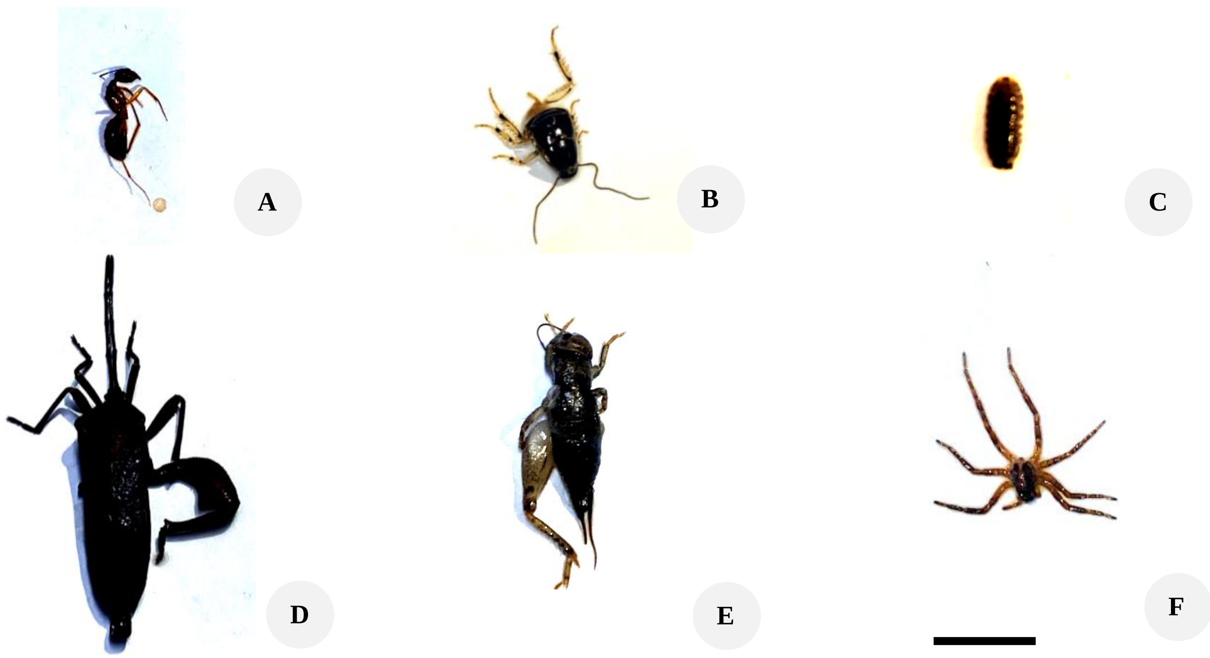

Figure 5. Some soil macrofauna specimens found in the coastal karst area of Gunung Sewu, Paranggupito Sub-district, Wonogiri District, Indonesia: A. *Camponotus consobrinus*; B. *Blatella* sp.; C. Unidentified; D. *Leptocorisa oratoria*; E. *Teleogryllus emma*; F. Arthropod. Bar = 1 cm

Table 4. Shannon-Wiener diversity index and abiotic factors of research locations in the coastal karst area of Gunung Sewu, Paranggupito Sub-district, Wonogiri District, Indonesia

Village	Vegetation	Diversity index	Abiotic factors					
			Soil moisture (%)	pH	Soil temp. (℃)	Lux meter	Air temp. (℃)	Air humidity (%)
Gunturharjo	Woody	0.71	2	7	29.5	4810	34.1	29
	Intercropping	0.11	2	6.5	29	345406	32.6	30
Gudangharjo	Woody	0.85	1	7	30.4	5550	35.1	28
	Intercropping	1.32	1	6,9	30	336905	34.5	30
Paranggupito	Woody	1.32	1	7	29.5	6040	36.5	29
	Intercropping	0.38	1	6,7	29.2	340533	34.5	31

Table 5. Pearson correlation of Shannon-Wiener diversity index and abiotic factors

Correlation factor	P Value	Pearson correlation
Soil moisture (%)	0.22	-0.59
pH	0.06	0.79
Soil temperature (℃)	0.19	0.62
Lux meter (light intensity)	0.42	-0.41
Air temperature (℃)	0.07	0.78
Air humidity (%)	0.44	-0.39

The soil temperature has a moderate positive correlation of 0.62, which indicates that an increase in soil temperature is related to an increase in species diversity. Meanwhile, the p-value shows a high value of 0.19. Conversely, the light intensity or Lux Meter has a weak negative correlation of -0.41, which indicates that an increase in light intensity slightly decreases diversity. The p-value of light intensity is 0.42, which is a fairly strong category between the value of light intensity and diversity. The air temperature factor has a strong positive correlation with a value of 0.78, meaning that the higher the air temperature, the greater the species diversity. While the p-value shows 0.07, that means a high value. Finally, air humidity shows a weak negative correlation of -0.39, which is a weak category between the value of air humidity and diversity, where an increase in air humidity is associated with a slight decrease in species diversity. The p-value of air humidity is 0.44. The calculation of the p-value on all variables shows a high value >0.05, which means that between each variable and the diversity has a low correlation significance.

Discussion

Relationship between macrofauna diversity and abiotic factors in karst areas

This study found that macrofauna diversity in the karst region of Gunung Suwu karst area including Paranggupito Village, Gudangharjo Village, and Gunturharjo Village of Paranggupito Sub-district, Wonogiri District, Central Java, is dominated by 16 species, with *C. consobrinus* being the most prevalent. The study also identified several abiotic factors, including soil moisture, light intensity, air humidity, soil pH, soil temperature, and air temperature, that significantly influence macrofauna diversity. According to Rohyani and Sulistiani (2022), the abundance of soil macrofauna in each area is determined by extrinsic factors, which include biotic and abiotic components, as well as intrinsic factors, namely the tendency of macrofauna to prefer environments with certain conditions. The study also found that the dry season exerts environmental pressure on soil macrofauna, leading them to become more active in their search for food or suitable habitats to survive on the soil surface. This heightened activity increases the likelihood of capture using the pitfall trap method. This finding aligns with the study by Oktapiani et al. (2024), which reported that the dominance of the dry season tends to exhibit higher soil macrofauna diversity, with observed family abundance being nearly four times greater than in the rainy season. Furthermore, deploying pitfall traps during the dry season can minimize environmental disturbances, such as water pooling, rain, and wet litter, which could otherwise reduce the trap's effectiveness (Kelly et al. 2020).

When analyzed based on soil moisture parameters, Gunturharjo Village is the only village with soil moisture of 2% among other villages. However, the results of the diversity index at the location showed small numbers for woody vegetation and intercropping, namely 0.71 and 0.11, respectively. Generally, a humid soil environment has a positive impact on the activity of soil organisms (Sofo et al. 2020). However, based on the Pearson correlation calculation, the results show that soil moisture and species diversity in the study area are negatively correlated. In dry and semi-arid environments, including karst areas, soil moisture parameters are a crucial environmental factor for forming biological communities, including macrofauna communities (Ge et al. 2021). Soil moisture is highly dependent on the unique characteristics of the soil in the karst area. The porosity and drainage properties of the karst area affect the ability of the soil to absorb water so that soil moisture is fluctuating and unstable (Wang et al. 2023).

Like other organisms, macrofauna lives by interacting with abiotic and biotic environmental factors in their habitat. For example, soil pH can be a determinant factor for macrofauna density due to its correlation with nutrient availability in the soil, as shown in Zhou et al. (2022) research that shows a positive correlation between soil macrofauna and soil pH. A similar outcome was observed across all locations within the karst area in this research, showing a strong positive correlation with a value of 0.79. As shown in Table 4, all locations in the woody vegetation category have the same pH level of 7, which is neutral and considered optimal for soil macrofauna life. If the soil contains extreme pH levels, it can affect the growth of soil macrofauna through the disruption of enzyme activity and ionization balance (Zhang et al. 2024). Although the value of pH in the intercropping vegetation category varies and indicates increased acidity, it remains suitable for macrofauna because, according to Nurrohman et al. (2015), most soil macrofauna prefer to live in soil with a pH ranging from 6-7 because of the high availability of nutrients. The unsuitability of soil pH levels can affect the food sources of macrofauna because it can inhibit the growth of plants and microorganisms (Zhang et al. 2024)

The results of the Pearson correlation show a negative correlation, which means that the higher the light intensity at Gunturharjo and Paranggupito Villages, the lower the macrofauna diversity value. The presence of vegetation is one factor affecting light intensity, due to the lack of vegetation, so that no canopy can block sunlight from directly hitting the ground surface. Direct exposure to sunlight can result in death for soil macrofauna (Wibowo and Slamet 2017). The species most commonly found out of all locations with the highest light intensity is *C. consobrinus,* which belongs to the Formicidae (ants) family. Ants are a species resistant to sunlight, so they are often found in parts of the litter that are directly exposed to sunlight. Many factors can affect the results of light intensity measurements, such as measurement time, stand composition, vegetation density, and the angle of incidence of the sun (Ahmad et al. 2024).

Another physical factor that affects the life of soil fauna is soil temperature. Fluctuations in soil temperature affect the availability of nutrient sources for soil insects because they are closely related to the level of decomposition of soil organic material (Rachmasari et al. 2016). Soil macrofauna species generally prefer lower soil temperatures. However, based on the results of the Pearson correlation shows that the higher the soil temperature, the greater the increase in species diversity. The results of the Pearson correlation for air temperature parameters also show the same thing. Temperature plays an important role in the growth and development of soil macrofauna. A positive correlation between soil temperature and air temperature on macrofauna diversity can occur because, in general, the metabolism of macrofauna will increase as the temperature increases, so its growth and development will also increase (Wang et al. 2024).

The humidity parameters at each research location showed inverse results. If the air temperature is high, the percentage of air humidity will decrease. Air humidity will majorly impact soil macrofauna if extreme temperatures occur because when humidity levels increase, the evaporation rate will be reduced, consequently allowing greater retention of soil moisture (Köhli et al. 2021). Generally, soil macrofauna is more suitable for living in highly humid habitats (Wasis et al. 2024). It can be seen in the results of the diversity index in Gudangharjo Village, with a higher type of intercropping vegetation compared to other locations and a fairly high air humidity, which is 30%.

Macrofauna diversity in different vegetation types in karst areas

The intercropping vegetation type is an agricultural system where more than one type of vegetation is planted on land to maximize land use and optimize resource use. As an area that is ecologically known to be vulnerable, karst areas can apply efficient agroforestry technology for water and soil resources. Therefore, intercropping vegetation types can be found in karst areas because of their conservation function. Several previous studies have found an increase in soil macrofauna such as earthworms and ants in intercropping vegetation types because the increasing species of plants will encourage ongoing nutrient recycling and provide a more suitable habitat for soil organisms to grow and develop (Punyalue et al. 2018). It is in accordance with the results of macrofauna identification in the three villages in the intercropping vegetation type, where Formicidae or ants were found in all locations. Ants are one of the macrofauna that can improve the physical structure of the soil and the composition of minerals and organic matter in the soil, and the intercropping vegetation type is beneficial for ants because it will reduce competition in obtaining additional resources from intercropped plants (Usamah et al. 2023).

The type of woody vegetation affects the microhabitat at the location, as the tree canopy can reduce the intensity of direct sunlight exposure to the soil. This affects the life of soil macrofauna. In addition, some soil macrofauna species also prefer forest environments with sufficient foliage and food sources. However, in this study, the species of soil macrofauna that dominates both vegetation types is the same, namely *C. consobrinus* species. That factors can influence include high levels of adaptation.

Identification of dominant macrofauna families in karst areas

Camponotus consobrinus is a species of the Formicidae family that lives in colonies. *Camponotus consobrinus* species, known as sugar ants, is the most dominant species found at the research location. This is because *C. consobrinus* is a pest insect that likes to colonize woody vegetation by building its nest under wood with a large underground area (Kulsum 2018). In addition, its nest can also be found in various places, including plant roots, tree branches, and shrubs, between rocks, in the soil, and under paving stones. These ants have a high tolerance to climate variations, with an ideal arena between 18 to 28°C and a nest part between 21 to 24°C (Fraser et al. 2000). According to Middleton (2014), *C. consobrinus* shows that individuals can handle various light intensities and temperature variations ranging from 7.7-32.3°C in foraging activities. *Camponotus consobrinus* is a nocturnal ant that forages more often at night but can also forage during the day. The dominance of *C. consobrinus* species at the research location may be due to *C. consobrinus* species attacking the nests of other ant species randomly while ignoring other ants nearby (Taylor et al. 2018). These ants are 0.7-1.3 cm in size. The sugar ants have sub-trigonal to elongated-triangular jaws (Khairunnisa 2023). Another species that is abundant is *Odontoponera* sp. *Odontoponera* is a genus of small ants in Southeast Asia in the Formicidae family. There are 2 species of this genus whose distribution is limited to the Southeast Asian region, namely *Odontoponera denticulata* (F.Smith, 1858) and *Odontoponera transversa* (Smith, 1857) (Schmidt et al. 2014). *Odontoponera* sp. are locally abundant, with *O. denticulata* having the widest distribution of this species, from mainland Asia to the Philippines and Sundaland; *O. transversa* is found from the Malay Peninsula south to the islands of Sundaland (Yamane 2009). *Odontoponera* sp. are adaptable and can nest in various environments but prefer to nest in forest areas.

Formicidae family is the dominant family in woody and intercropping vegetation in the research location. This family is a eusocial insect that belongs to the order Hymenoptera, along with bees and wasps. The Formicidae family is an insect that lives in almost every type of ecosystem, except in the polar regions, with various ecosystem roles. Ants are abundant in islands and large land areas and are estimated to reach 15,000 species (Ilhamdi et al. 2024). The results of the research show that the Formicidae family mainly consists of the species *C. consobrinus* and *Odontoponera* sp. The research location is a karst area covered with woody vegetation and an intercropping system with a porous soil structure that supports aeration and water infiltration. Biodiversity can maintain the availability of resources that maintain interactions between plants, microorganisms, and insect species and also contribute to the productivity and health of the karst ecosystem. The existence of soil macrofauna insects in an ecosystem has a very important role in the ecosystem, including as the main predator of several small invertebrates, seed eaters, nectar, plant secretions, aphid secretions, and shredders of dead organic matter (Agus and Septianjaya 2021). Ants help maintain soil aeration and mixing, which increases water infiltration and keeps the soil healthy. They form a symbiosis with other insects and plants and actively spread plant seeds. The role of the Formicidae family is considered quite vital because it will affect other animal species.

Formicidae can be used as a bioindicator of soil fertility. The distribution of the Formicidae family in a habitat is influenced by vegetation structure, human activities, the spread of invasive species, and habitat conditions (Abdillah et al. 2019). Formicidae family is known as a predator in the ecosystem because it searches for food in colonies and has been assigned to go out to find food in a large roaming area (Sijabat et al. 2020). In intercropping vegetation, the Formicidae family has an important role in spreading plant seeds with elaiosomes as an energy source, moving them to the nest, and accelerating the spread and growth of seedlings. However, over time, the karst ecosystem also faces various challenges, both caused by natural factors and anthropogenic activities that have an impact on the distribution of the Formicidae family.

In conclusion, the study found that 16 different species were found in all three villages, and *C. consobrinus* dominated the intercropping vegetation across most locations, outnumbering other species. This study found 16 species, but one of them stated as unidentified due to the limitations of the author and the equipment used, so it needs to be studied further. The diversity index of macrofauna in intercropping was generally lower than in woody vegetation, which offered a more stable microhabitat and protection from direct sunlight. Woody vegetation supported higher macrofauna diversity due to its ability to reduce sunlight and provide organic matter, with *Odontoponera* sp. also abundant in these areas. The diversity of macrofauna at each station was relatively low. In contrast, the relationship between abiotic factors and diversity showed varying correlations, such as soil moisture, lux meter, and air humidity were negatively correlated by -0.59, -0.41, and -0.39, respectively, which means when the values increase, then the diversity tends to decrease and vice versa; In contrast, pH soil, soil temperature, and air temperature were positively correlated by 0.79, 0.62, and 0.78, respectively, showing a moderately strong relationship. Whereas the values increase, the diversity also tends to increase. The discovery of soil macrofauna species in this study shows that macrofauna are able to survive in karst areas, which have an important role in maintaining soil health and fertility, so that their existence must be maintained and preserved.

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Potential and strategy for ecotourism development in the coastal area of Paranggupito Sub-district, Wonogiri District, Indonesia

RATIH NUR AFIFAH[1], LUNETTA KHALIS ALFIYAH[1], MARETTA PATRICIA BERNADETTA[1], MARIO PINTOR DAVID SIMANJUNTAK[1], MARISCA SETYANINGRUM[1], SUNARTO[1], AHMAD DWI SETYAWAN[1,2,♥]

[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia. Tel./fax.: +62-271-663375, ♥email: volatileoils@gmail.com

[2]Biodiversity Research Group, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

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Abstract. *Afifah RN, Alfiyah LK, Bernadetta MP, Simanjuntak MPD, Setyaningrum M, Sunarto, Setyawan AD. 2025. Potential and strategy for ecotourism development in the coastal area of Paranggupito Sub-district, Wonogiri District, Indonesia. Indo Pac J Ocean Life 9: 12-25.* Ecotourism emphasizes environmental conservation while supporting nature preservation and local community welfare. It arose as a response to the harmful effects of conventional tourism, such as ecosystem damage, biodiversity loss, and community disruption, aiming instead for responsible tourism that protects nature. This study aims to determine the management conditions of Karang Payung, Nampu, and Klothok Beaches in Paranggupito Sub-district, Wonogiri District, Central Java, Indonesia and the potential of TAO (Tourist Attraction Objects) that have been operating, as well as beach development strategies. Data collection was carried out by observation and interviews using simple random sampling method to 102 people throughout the beach, which was then analyzed by ADO ODTWA (Analysis of Operational Areas of Objects and Natural Tourism Attractions) method to determine the potential feasibility of the area, then continued with SWOT (Strengths, Weakness, Opportunity, and Threats) analysis as a development recommendation. The results of the ADO ODTWA analysis show that the accessibility aspect of Nampu Beach has a feasibility index on the facilities aspect of 59.50% (not feasible). The accessibility index of Karang Payung Beach is 60.29% (not feasible), and the facility index is 65.71% (not feasible). The results of this analysis indicate the necessity for improvement and development of attractions and accessibility. The results of the SWOT analysis on Nampu Beach and Karang Payung Beach necessitate the formulation of a strategic plan.

Keywords: ADO-ODTWA, nature tourism, SWOT, tourist attraction

INTRODUCTION

Ecotourism is a tourism model that emphasizes environmental sustainability by promoting conservation and improving the welfare of local communities (Nazwin and Hidayat 2022). Ecotourism aims to encourage responsible tourism where tourists do not merely enjoy nature but actively contribute to its preservation (Ritonga and Harahap 2024). This tourism approach is increasingly recognized due to pressing global issues such as climate change, deforestation, and biodiversity loss. Well-planned ecotourism reduces ecosystem pressure, protects endangered species, and ensures long-term environmental benefits (Hariani 2024). Despite its many advantages, implementing ecotourism poses challenges, particularly in balancing environmental conservation and economic benefits. Without proper management, this imbalance can lead to overexploitation of resources and ineffective area management (Wondirad 2020). However, when properly executed, ecotourism can also raise awareness among tourists and stakeholders about the importance of conservation efforts, creating lasting positive impacts (Khanra et al. 2021).

In Indonesia, Wonogiri District possesses significant ecotourism potential, particularly in Paranggupito Sub-district, known for its coastal beauty. Among its attractions are Nampu Beach, Karang Payung Beach, and Klothok Beach, each offering unique coastal typologies (Cahyadi et al. 2017). Nampu Beach has a wide coast, in the form of white sand so that visitors play, walk, swim and do activities on the coast, this beach also offers beautiful sea views. The typology of this coast is the marine deposition coast type (Cahyadi et al. 2017). Marine deposition coast type areas are formed due to the accumulation of marine sediment material towards land carried by ocean waves which then settles along the coast (Giovani et al. 2018). In contrast to Nampu Beach, which has the bottom of the beach in the form of coral. As the name implies, Karang Payung beach is filled with large coral rocks shaped like umbrellas and sand on the coast so that visitors can only enjoy the beauty of the waves and corals. This beach has a wave erosion coast typology type because there is a stack of limestone rubble on the coastal wall/cliff by waves, the stack affects the shape of the beach, becoming irregular and steep (Wibowo et al. 2022). Klothok Beach is located far from Nampu Beach and Karang Payung Beach. The beach is surrounded by steep cliffs/rocks which are one of the characteristics of the Structurally shaped coast typology (Putranto 2020). Coral reefs can be found on the coast and this beach has a strong wave character so that it is equipped with a breakwater.

Beach ecotourism significantly impacts both visitors and local communities. For residents, ecotourism creates economic opportunities, promoting their active involvement in tourism activities, such as hospitality and cultural preservation (Priambono et al. 2021). However, challenges persist, such as inadequate human resource capacity among managers and a lack of awareness about nature conservation within the local community. Educational and training gaps among managers remain critical obstacles to effective ecotourism development (Mu'tashim and Indahsari 2021). Furthermore, continuous interaction with diverse tourists often fails to increase local cultural and environmental awareness, emphasizing the need for clear policies to address these issues. Sustainable tourism management is essential for ensuring the long-term benefits of ecotourism, including environmental protection, economic stability, and community empowerment. It encourages local community participation, fostering social, cultural, and economic benefits through direct and indirect employment opportunities in tourism areas (Silviana and Mubarak 2022). Effective management also safeguards ecosystems and biodiversity, ensuring economic stability while providing a sustainable income source for future generations (Kiswantoro and Susanto 2020).

This study examines the management conditions and tourism potential of Nampu, Karang Payung, and Klothok Beaches in Paranggupito Sub-district. The goal is to identify sustainable development strategies that maintain natural and cultural resources while maximizing socioeconomic benefits for local communities. Sustainable tourism ensures future generations can enjoy these destinations without compromising environmental integrity (Putri and Idajati 2019). The study also aims to offer strategic recommendations for local governments and managers to develop Paranggupito's beaches into globally competitive and environmentally sustainable ecotourism destinations (Silviana and Mubarak 2020).

MATERIALS AND METHODS

Study area

This research was conducted in October 2024, with the research location in the ecotourism areas of Nampu Beach (270 m), Karang Payung Beach (65 m), and Klothok Beach (90 m) in Paranggupito Sub-district, Wonogiri, Central Java, Indonesia (Figure 1). In recent years, Nampu Beach has sometimes been divided into Nampu Beach (Central Java) and Nyawiji Beach (East Java), but we still refer to them as one unit with the original name of Nampu Beach. This research was conducted to provide an overview of the ecotourism development strategy of the coastal areas using qualitative methods, with research samples of tourists and ecotourism managers, besides that, the condition of the infrastructure in the area and the surrounding environment were also considered to be able to determine the level of local wisdom in the area around these beaches.

Procedures

This research used primary data and secondary data. Primary data was collected using direct observation, questionnaires, interviews, and documentation. Observation was carried out directly by observing the ecotourism conditions of each beach and the infrastructure available in the beach area to find out the actual conditions. Questionnaires were conducted using the simple random sampling method, which was distributed randomly to 35 respondents on each beach, resulting in 102 respondents who were visiting tourists aged over 17 years. Interviews were conducted also with the manager of each beach by asking questions to the resource person to get a direct explanation and more accurate information about ecotourism management development strategies. Secondary data were collected from literature studies to complement the primary data to be analyzed.

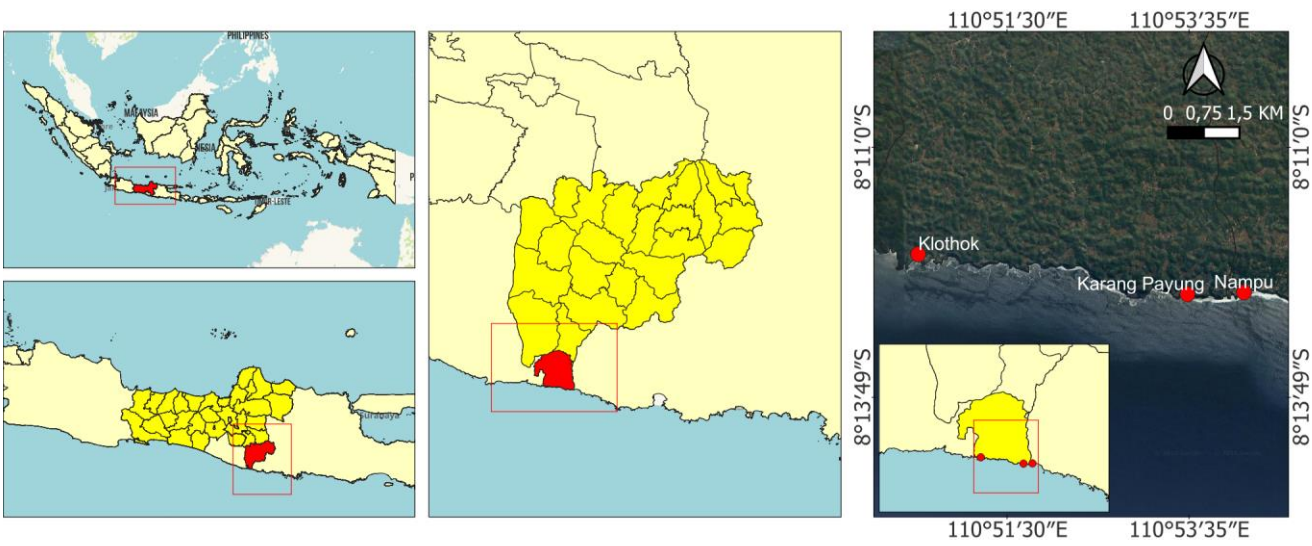

Figure 1. Location of Nampu Beach, Karang Payung Beach, and Klothok Beach in Paranggupito Sub-district, Wonogiri, Central Java, Indonesia

Data analysis

Data collection was carried out by observation and interviews at each beach, which was then analyzed using the ADO ODTWA method (Dirjen PHKA 2003) to determine the potential feasibility of the area, and continued with SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis as a development recommendation. ADO ODTWA, or what is called the Analysis of Operational Areas of Natural Tourism Objects and Attractions, is a guideline that analyzes the feasibility level of criteria in the form of tourist attractions, ease of access, facilities and infrastructure, management and services, accommodation, and environmental conditions, carried out descriptively. We chose four of them, namely: attractions, accessibility, facilities, and perception on management and services. These criteria have a weight value on a scale of 1-6, the following weighting according to the ADO ODTWA guidelines: (i) The weight of the attraction criteria has a value of 6 because the attraction is the reason and cause of tourists visiting; (ii) The weight of the accessibility criteria has a value of 5, access is needed to encourage tourism potential; (iii) The criteria for facility and infrastructure conditions around the area are given a weight of 3; (iv) The perception on management and service criteria are given a weight of 4. Then, the weighting will be processed using the following formula (Dirjen PHKA 2003):

$$S = N \times B$$

Where: S: Score/value of a criterion; N: The sum of the values of the elements in the criterion; B: Weighted value.

The score obtained will be calculated as the level or percentage of eligibility for each variable. Calculating the feasibility index value can be done using the following formula (Purwoko et al. 2023):

$$\frac{Criteria\ score}{Maximum\ total\ score} \times 100\%$$

The maximum score in this study is shown in Table 1. The standard percentage of the feasibility index, namely (i) the feasibility level of more than 66.6%, means that an area has the potential to be designed as a natural tourist destination attraction; (ii) the feasibility level of 33.3-66.6% means that the area does not have the potential to be developed as a natural tourist attraction; and (iii) the feasibility level of less than 33.3% means that the area does not have the potential to be designed as a natural tourist destination attraction.

Table 1. Maximum total score for each variant

Variable	Weight	Max score (max value (5) x respondent (35))	Total aspects in the variable	Maximum total score
Attractions	6	175	2	2,100
Accessibility	5	175	2	1,750
Facilities	3	175	8	4,200
Perception	4	175	5	3,500

To systematically evaluate the internal and external factors influencing a tourist destination, the IFAS (Internal Factors Analysis Summary) and EFAS (External Factors Analysis Summary) matrices are applied (David 2011; Wheelen and Hunger 2012). The EFAS matrix evaluates the impact of external factors on a company by organizing them into opportunities and threats, while the IFAS matrix focuses on assessing internal factors by categorizing them into strengths and weaknesses (Papalapu et al. 2023). Both the weight and the overall IFAS value are included in the weighted IFAS value, which is the foundation of the IE matrix. According to weights, a total EFAS value of 1.0 to 1.99 is regarded as low, 2.0 to 2.99 as average or medium, and 3.0 to 4.0 as high. Similarly, a weak internal position is indicated by an IFAS value with a weight of 1.0 to 1.99, an average or moderate position is indicated by a value between 2.0 and 2.99, and a strong stance is indicated by a value between 3.0 and 4.0 (Suratini et al. 2019).

RESULTS AND DISCUSSION

Nampu Beach

Feasibility analysis of natural tourism objects

Attractions. The attraction criteria include two aspects, namely, the attractiveness of the beach and its comfort and cleanliness. The attraction itself refers to the attraction that makes people want to visit and see firsthand because of its natural beauty, uniqueness, the integrity of natural resources, and the recreational options available (Dzitse et al. 2024). In Table 2 the attraction criteria, Nampu Beach has a score of 1,602, with a feasibility index value of 76.29%, which indicates the potential to be designed as a natural tourist destination attraction. A higher feasibility index value suggests a greater potential for development. This beach offers a stunning natural panorama with clean white sand, clear sea water, and fairly large waves, making it an ideal destination for marine tourism lovers. In addition, the existence of coral cliffs surrounding the beach adds its charm, both for photography and nature exploration. Residents and managers of Nampu Beach themselves allow tourists to camp in the beach area, providing a closer experience to nature. However, tourists must bring their equipment as there are no camping equipment rental facilities around the location.

Accessibility. Conventionally, accessibility can be viewed from various perspectives, such as mobility, access, planning, and transportation systems. Accessibility is defined as the extent to which a system of transportation enables a group or individual to achieve its activities or goals (Jamei et al. 2022). Accessibility criteria include two aspects, namely road access and transportation, as well as the availability of road signs and instructions. In Table 2, the accessibility criteria, Nampu Beach has a score of 1,295, with a feasibility index value of 74%, which is included the potential to be designed as a natural tourist destination attraction. However, access to Nampu Beach still requires further attention, especially in terms of improving road conditions, some of which are still rocky and dirt paths, and improving public transportation facilities for tourists who do not bring private vehicles. In addition, the availability of direction signs to the beach is still limited, so first-time tourists need to rely on digital maps or directions from residents. Improving accessibility by repairing roads, adding adequate public transportation, and installing clear signs will further improve tourist comfort and strengthen the position of Nampu Beach as a leading tourist destination in the Wonogiri region.

Facilities. Tourism facilities are an important element in providing services to tourists while in a tourist attraction and influence the development of tourist attractions. Facilities are facilities and infrastructure that support the operation of tourist attractions to accommodate all the needs of tourists. For instance, a well-maintained parking lot can attract more visitors, thereby boosting the local economy. While these facilities may not directly drive growth, they play a crucial role in the overall development of the tourist attraction, often developing at the same time or after the tourist attraction develops (Asnur and Manggara 2021). The criteria for facilities include several aspects, namely security posts, parking lots, toilets and clean water, food stalls, worship facilities, trash cans, hotels and inns, and electricity and telecommunications networks. At Nampu Beach, one of the recent facility improvements is the addition of worship facilities, which were previously not available directly at the beach area. Before this facility was built, tourists who wanted to worship had to go to a resident's house, which was used as a temporary place of worship. Although the addition of this facility is a positive step in improving tourist comfort, the facilities at Nampu Beach as a whole are still relatively inadequate.

In Table 2 the facilities criteria, Nampu Beach has a score of 2,499, with a feasibility index value of 59.50%, so this criterion is included the accessibility criteria are at a level not yet feasible to develop. This is due to the low potential of facilities and infrastructure based on predetermined parameters and inadequate accessibility. The main factor influencing this low score is the limited facilities and infrastructure, such as the lack of availability of clean and adequate public toilets, the lack of trash bins scattered in the tourist area, and the limited number of inns around the beach that can accommodate tourists who want to stay overnight. In addition, inadequate accessibility, especially in terms of road conditions and limited telecommunications networks, is also an obstacle to improving the quality of tourist facilities in this area.

Table 2. Analysis of Nampu Beach attractions, accessibility, facilities, and perception

Variable	Sub variables	Weight	Score	Total score
Attractions	Beach appeal	6	137	822
	Comfort and cleanliness	6	130	780
			Total score	1,602
			Maximum total score	2,100
Accessibility	Road access and transportation	5	131	822
	Availability of road signs and guidance	5	128	780
			Total score	1,295
			Maximum total score	1,750
Facilities	Security post	3	125	375
	Parking lot	3	109	327
	Restrooms and clean water	3	118	354
	Food stalls	3	136	408
	Means of worship	3	102	306
	Garbage bins	3	86	258
	Hotel/lodging	3	114	342
	Electricity and telecommunication networks	3	43	129
			Total score	2,499
			Maximum total score	4,200
Perception	Affordable ticket	4	152	608
	Officer service	4	127	508
	Local community involvement	4	130	520
	Importance of sustainable ecotourism management	4	157	628
	Economic benefits to local communities	4	140	560
			Total score	2,824
			Maximum total score	3,500

Perception. Perception criteria include several aspects, namely ticket affordability, officer services, local community involvement, the importance of sustainable ecotourism management, and economic benefits to local communities. In Nampu Beach, the service aspect of the staff and the involvement of the local community are among the main advantages. Local communities not only play a role as economic actors around the tourist area but are also actively involved in beach management. This provides employment opportunities and increases public awareness of preserving the beach environment. In addition, the existence of an institution that specifically regulates the involvement of local communities in beach management ensures good coordination between the government, tourism managers and residents. Thus, this management system not only has a positive impact on improving the welfare of the community but also creates a sense of ownership and responsibility for the preservation of Nampu Beach.

Based on Table 2, Nampu Beach has a score of 2,824 with a feasibility index value of 80.69%, which indicates that this beach has a high potential to be developed as a sustainable natural tourism destination. This high index value reflects that tourists have a positive perception of ticket accessibility, officer services, and the benefits felt by the local community. Nevertheless, to increase tourist attractiveness, it is necessary to strengthen aspects of ecotourism management, such as implementing the concept of environmentally friendly tourism, improving supporting facilities for tourists, and strengthening conservation education for the community and visitors. With a more sustainable management strategy and active participation from local communities, Nampu Beach can continue to develop as a tourist destination that is not only aesthetically attractive but also provides long-term benefits for the environment and local economy.

Socioeconomic condition

Nampu Beach has socioeconomic conditions that reflect the lives of local people who rely on beach management and daily activities, such as sugar production. Although this beach allows activities such as camping and playing on the beach, due to its coral bottom, it cannot be used to lean or anchor boats. In the past, the Wonogiri government donated a boat, but it is now gone due to damage. This beach does not have tent or chair rentals, unlike Karang Payung Beach, which provides these facilities.

Infrastructure development, such as an additional *mushola* (means of worship) funded by community contributions and government assistance, shows cooperation. The community also manages revenue from the entrance ticket of Rp 5,000 per person, as well as parking for motorcycles at Rp 3,000 and cars at Rp 5,000, with funds going to the village, youth organization, and sub-district treasuries. The beach and parking lot managers receive payment, but the money is also shared for beach security and cleanliness, which is done in cooperation with residents.

Despite the recent decline in visitors due to the megathrust issue, Nampu Beach is usually bustling on weekends and major holidays. However, on weekdays, the beach is quieter. This decline in the number of visitors has a significant impact on the local merchants, most of whom are local residents or from nearby villages. Vendors often clean the beach of trash carried by the waves, such as plastic and bottles, before starting their trading activities.

Customs such as the *Rasulan* ceremony, Javanese tradition after the harvest, are still maintained, with hamlet cleanup ceremonies and offerings as a form of respect to ancestors. However, there are still visitors who lack discipline in disposing of garbage, even though trash bins have been provided. Beach conditions are influenced by the seasons, with tidal phenomena that follow the Javanese calendar. Residents are keenly aware of the need for infrastructure development, especially roads and public facilities, to enhance Nampu Beach's appeal and attract more visits.

The strategy that can be done to connect Strength and Opportunity (SO) based on Table 3 is to carry out community-based development with the help of institutions and the government. Nampu Beach is a beach that many tourists visit, so it has the opportunity to improve the welfare of the community around the beach and has the potential to create new jobs. According to Maulani et al. (2024), the strategy to develop community-based beach ecotourism can be done by involving the community in promoting the beauty of the beach through social media, beautifying the facilities on the beach, making interesting photo spots for tourists, and submitting proposals to the government to advance the infrastructure of tourist attractions on the beach.

The strategy that connects Strength and Threat (ST) based on Table 3 is to work with the surrounding community to add cleaners during the holiday season. The increase in the number of visitors on holidays or weekends is in line with the increase in the amount of garbage on Nampu Beach, so the strategy that can be done to overcome this threat is to increase the number of janitors. In addition to keeping the beach clean, this can also provide employment opportunities for the surrounding community. Strategies that connect Weakness and Opportunity (WO), namely improving infrastructure to support beach cleanliness and holding community empowerment programs and coaching for MSME players. These programs are crucial as they not only empower the community but also play a significant role in the success of the project.

IFAS-EFAS analysis of Nampu Beach

Based on the IFAS analysis as presented in Table 4, it is known that the total scores for strengths and weaknesses are 2.684 and 0.868, so the total score of strengths on Nampu Beach is greater than the total score of weaknesses. The total weight score for strengths and weaknesses is 3.552. This shows that the Nampu Beach area is in an influential position to utilize its strengths to deal with the weaknesses contained in the Nampu Beach tourism area.

The EFAS analysis in Table 5 shows that the total scores for opportunities and threats are 2.043 and 0.782, so the total score of threats is smaller than the total score of opportunities. This indicates that opportunities have a more significant influence on Nampu Beach's tourism development strategy. This is a positive indication and open up much potential for further development. Therefore, these opportunities must be utilized as well as possible in the development of tourism on Nampu Beach. The EFAS and IFAS rating scale uses a range of 1.0-4.0. Values below 2.0 indicate unfavorable conditions, from 2.0-2.99 indicate moderate conditions, and above 3.0 indicate very good conditions. Thus, a high EFAS value indicates many external opportunities, while a high IFAS value indicates internal strengths (Suratini et al. 2019).

Based on the results of the IFAS-EFAS analysis, the next step is to determine the development strategy to be used for Nampu Beach using the IFAS-EFAS quadrant. To determine the X and Y values, we calculate the X factor value by subtracting the total weakness score from the total strength score. This indicates the internal strategic factors that form the horizontal line. Similarly, we calculate the Y factor value by subtracting the total threat score from the total opportunity score. That also indicates the external strategic factors that form the vertical line obtained from the difference between the total opportunity score and the total threat score (Azizah 2017).

X = Strength - Weakness = 2.684 - 0.868 = 1.816

Y = Opportunities - Threats = 2.043 - 0.782 = 1.261

The development strategy that can be used in the development of Nampu Beach is the rapid growth strategy in quadrant 1. This position is obtained from internal strength factors and very high external opportunities. The main objective of this strategy is to fully utilize existing strengths and opportunities to increase tourism growth quickly (Ratnawati 2020). This rapid growth strategy can involve the S-O strategy by adding or expanding tourism facilities and venues at Namu Beach to attract more visitors, improving other supporting facilities such as public services and game accommodation on the beach, and also cooperating with the government, private sector, and the surrounding community in the development of Nampu Beach development.

Table 3. SWOT factors of Nampu Beach

Internal Factors / **External Factors**	**Opportunities** 1. Welfare improvement in the local community 2. Creating new jobs.	**Threats** 1. During the holiday season, the waste generated by visitors also increases.
Strengths	**Strategi S-O**	**Strategi S-T**
1. Social aspects of the community that support the development of ecotourism activities. 2. Road to the beach that is friendly to 2-wheeled and 4-wheeled vehicles.	1. Community-based development with the assistance of institutions and government	1. Cooperate with the surrounding community to add cleaners during the holiday season.
Weakness	**Strategi W-O**	**Strategi W-T**
1. Placement of garbage cans that are not spread out and difficult to find 2. Lack of worship facilities	1. Improved infrastructure to support beach cleanliness 2. Community empowerment program and coaching for MSME players	1. A team was formed to develop tourism and cleanliness by the manager of Nampu Beach.

Table 4. Internal Factors Analysis Summary (IFAS) of Nampu Beach

Strengths	**Weight**	**Score**	**Total score**
Social aspects of the community that support development	0.315	4	1.263
Vehicle-friendly road access	0.315	4.5	1.421
Subtotal	0.631		2.684
Weakness			
Placement of trash cans that are not spread out	0.263	2.5	0.657
Lack of worship facilities	0.105	2	0.210
Subtotal	0.368		0.868
Total	1		3.552

Table 5. External Factors Analysis Summary (EFAS) of Nampu Beach

Opportunities	**Weight**	**Score**	**Total score**
Improved welfare of the surrounding community	0.260	4	1.173
Vehicle-friendly road access	0.217	4.5	0.087
Subtotal	0.478		2.043
Threats			
Generates much trash during the weekend	0.260	1	0.260
Competition with other beaches that have more complete facilities	0.260	2	0.521
Subtotal	0.368		0.782
Total	1		2.826

Karang Payung Beach

Feasibility analysis of natural tourism objects

Attractions. Attractions are the reason for tourists to visit a tourist attraction (Setyasih and Helmy 2021). The attraction criteria are the attractions provided that can be enjoyed by visitors as well as the comfort and cleanliness felt by visitors. Based on Table 6, Karang Payung Beach has a total score of 1,716, so it gets a feasibility index level of 81.71%, which is included in the potential to be designed as a natural tourist destination attraction. This beach's uniqueness lies in its camping facilities, which offer visitors the opportunity to enjoy an overnight stay by the beach, surrounded by stunning natural landscapes. Although camping is one of the facilities provided, the lack of promotion and awareness means that many visitors are not fully aware of this unique offering.

By developing this uniqueness, this beach has a uniqueness compared to Nampu Beach and Klohtok Beach, which only serve natural scenery, entertainment, and water amusements. The addition of camping as a primary attraction provides visitors with an immersive experience that blends adventure and relaxation, appealing to nature enthusiasts, families, and young travelers. This form of tourism also enhances the appeal of the beach as an eco-friendly destination, where visitors can experience the natural environment in a more personal and sustainable way. The uniqueness of a location can be highlighted, such as ecotourism located in Thailand providing bird watching, hiking, rafting, kayaking, and snorkeling activities (Tseng et al. 2019). Similarly, Karang Payung Beach could promote its camping experience alongside other eco-activities, such as guided nature walks, beach clean up programs, and marine life observation, to create a unique ecotourism package. By developing and promoting these activities, Karang Payung Beach has the potential to attract more attention from both domestic and international tourists, thus positioning itself as a leading ecotourism destination within the region.

Accessibility. Accessibility criteria are one of the factors that determine whether a tourist attraction is easy to visit (Rematwa and Estikowati 2022). Based on the results of observations and responses from visitors to Karang Payung Beach, several improvements suggested to improve accessibility include widening the road to the location so that four-wheeled vehicles can access it more easily. In addition, several rocky roads leading to the beach are still in poor condition and require repair so that vehicles can pass smoothly without the risk of damage to the vehicle. In addition, the installation and enlargement of signposts are also necessary because tourists who are new to visiting often have difficulty finding the location of this fairly remote beach. Transportation access for 2-wheeled vehicles was only built in 2021; previously, getting to the location could only be done on foot. This criterion in Table 6 produces a total score of 1,055, which is then multiplied by 100 and divided by 1,750 to obtain a feasibility index level of 60.29%, so the accessibility criteria are at a level not yet feasible to develop.

Table 6. Analysis of Karang Payung Beach attractions, accessibility, facilities, and perception

Variable	Sub variables	Weight	Score	Total score
Attractions	Beach appeal	6	141	846
	Comfort and cleanliness	6	145	870
			Total score	1,716
			Maximum total score	2,100
Accessibility	Road access and transportation	5	101	505
	Availability of road signs and guidance	5	110	550
			Total score	1,055
			Maximum total score	1,750
Facilities	Security post	3	128	384
	Parking lot	3	147	441
	Restrooms and clean water	3	121	363
	Food stalls	3	136	408
	Means of worship	3	115	345
	Garbage bins	3	116	348
	Hotel/lodging	3	94	282
	Electricity and telecommunication networks	3	63	189
			Total score	2,760
			Maximum total score	4,200
Perception	Affordable ticket	4	165	660
	Officer service	4	154	616
	Local community involvement	4	126	504
	Importance of sustainable ecotourism management	4	161	644
	Economic benefits to local communities	4	135	540
			Total score	2,964
			Maximum total score	3,500

This condition shows that although there has been some progress, more needs to be done to improve the accessibility of Karang Payung Beach. To improve the feasibility of this tourist destination, improvements to the main road infrastructure leading to the beach, such as the repair of rocky roads, as well as the development of adequate public transportation, will greatly support the improvement of accessibility quality. In addition, the provision of adequate parking facilities, especially for four-wheeled vehicles, and an improved signage system will make it easier for visitors coming from outside the area and ensure faster and more convenient access to the beach.

Facilities. Facilities are included in the facilities and infrastructure that can support advanced tourism in providing comfort to tourists (Selitara et al. 2024). Karang Payung Beach has developed security infrastructure, namely the addition of cliff road barriers. The assessment of facility criteria in Table 6 obtained a total score of 2,760. With a feasibility index value of 65.71%, it is in the category the area does not have the potential to be developed as a natural tourist attraction. The availability of lodging is very little; it is difficult to find, making visitors travel back and forth every time they visit this beach. The provision of lodging is one of the potential tourism developments (Budiani et al. 2018) and makes it easier for long-distance visitors to travel. Research according to Setyasih and Helmy (2021), located on Maratua Island, which provides resort accommodation, inns, and homestays along the coast and on the island, will always experience overstay during long holidays. Based on the location of Karang Payung Beach, lodging does not need to be built along the beach, and the local community can open homestays or inns close to residential locations.

In response to those who claim that poor infrastructure could deter tourists and undermine ecotourism initiatives, it's important to recognize that while infrastructure investment is crucial, it must be developed in a way that aligns with ecotourism principles. This could include sustainable transport options, minimal environmental impact construction methods, and public-private partnerships to improve accessibility without compromising the area's natural beauty. Promoting local experiences can also attract visitors who prefer authenticity over luxury.

Perception. Perception criteria may refer to management and service. Assessment of service quality refers to tourist satisfaction. According to Selitara et al. (2024) show that visitor satisfaction with services affects the development of a tourist attraction. The feasibility index for the perception criteria of Karang Payung Beach based on Table 6 obtained a value of 84.69%, in feasibility indicates the potential to be designed as a natural tourist destination attraction. This shows that community participation in the management and development of this beach is quite good due to the creation of jobs that can increase community income. If developed optimally, it can attract foreign tourists so that the use of local products will increase and increase, and the government will make improvements to transportation facilities to support (Amalu et al. 2018).

Socioeconomic conditions

Socioeconomic conditions are aspects that can be considered in tourism activities because they can support potential market value. A good social environment will provide comfort for visitors, allowing them to enjoy the beauty of nature better (Harianto et al. 2020). Tourism affects economic activities and creates jobs and local taxes that increase in number due to tourist visits. The management of Karang Payung Beach began in 2020 with makeshift conditions such as road access to the beach that can only be reached by foot, unavailability of shady places to rest, selling stalls, and proper toilets. However, the development was carried out jointly by local residents who are currently the administrators of Karang Payung Beach, with as many as 38 people. Not only that, there is a SAR team from the association for security patrols who stand guard around the beach when the waves are high and tide. Continuous development is carried out with funds coming from individuals and associations as well as the profits from entrance tickets (Table 7).

Table 7. SWOT factors of Karang Payung Beach

Internal Factors / External Factors	Opportunities	Threats
	1. Karang Payung Beach coastal area can be used for camping activities 2. Social media platforms to promote the beauty of the beach.	1. Security and safety factors of visitors with the increasing number of visitors 2, competition with other beaches with better access
Strengths	**Strategi S-O**	**Strategi S-T**
1. Potential for good views and natural beauty preserved 2. Affordable beach entrance fee 3. Plenty of parking space for vehicles	1. Development of camping areas and procurement of equipment 2. Utilizing social media to promote and hold tour package programs	1. Additional facilities to improve visitor safety 2. Procurement of safety information signs 3. Providing micro-insurance for visitors
Weakness	**Strategi W-O**	**Strategi W-T**
1. Access road is rocky and narrow so that it can only be passed by two-wheeled vehicles 2. The local government has not managed the beach 3. There are many corals, so it is not possible to cross the ship	1. Improving road access and providing road signs 2. Create a nature-based camping tour package that is promoted on social media	1. Provide information on access conditions and safety for visitors 2. Establish communication with the government to get assistance in access improvement and management

Several beaches in Wonogiri, including Karang Payung Beach, are bypassed by traditional fishermen looking for lobsters departing from Watu Karung, Pacitan, East Java and Sadeng, Gunung Kidul, Yogyakarta, because the beach here is craggy with high tides making it dangerous for boats to lean on. Karang Payung Beach has not been able to become a source of permanent employment for the community even though visitors on weekdays can reach 50-60 people while on holidays, up to hundreds. This is because the land ownership status of the beach is still in dispute. The government also cannot intervene in overcoming this problem and has not provided any assistance to date. Government assistance in the form of additional lodging or photo spots can ease the burden on the management and add to the potential of the beach so that it can attract more visitors.

IFAS-EFAS analysis of Karang Payung Beach

The IFAS analysis of Karang Payung Beach in Table 8 shows that the total score for strengths is 1.851, and the total score for weaknesses is 0.72; hence, the total score for advantages is higher than the total score for weaknesses. High strengths mean that ecotourism has good capital to be developed because, from an internal perspective, the strengths are more dominant than the weaknesses (Saputro et al. 2024). Strategic steps that can be taken are to maximize the advantages while making efforts to mitigate existing weaknesses. Strengths with higher scores indicate that the beach has strong potential, either in terms of tourist attractions, natural ecosystems, or facilities. Effective strategies include developing superior aspects such as increasing tourism promotion that underscores the uniqueness of the beach and improving accessibility and infrastructure to attract more visitors.

The results of the EFAS analysis in Table 9 show that the total scores of opportunities and threats of Karang Payung Beach are 1.26 and 0.911. The total score of opportunities is higher than the total score of threats, which means that Karang Payung Beach has positive prospects to be developed with greater external opportunities, such as the potential of Karang Payung Beach to be used as a camping area and the potential of social media to promote the beauty of the beach scenery. Promotion on social media can be tailored to market interests that are generally interested in the latest things (Mazaya et al. 2024). A lower threat score indicates that external challenges or obstacles are relatively under control, so this beach can focus more on utilizing existing opportunities to improve its attractiveness and tourism management.

X = Strengths - Weaknesses = 1.851 - 0.72 = 1.131

Y = Opportunities - Threats = 1.26 - 0.911 = 0.349

The development strategy that can be carried out on Karang Payung Beach is to use a rapid growth strategy to accelerate growth by utilizing the great potential of the natural attraction of Karang Payung Beach while still maintaining the principle of sustainability. An example is to conduct a digital campaign on social media to promote and describe the uniqueness and beauty of Karang Payung Beach and use social media, websites, and influencers that focus on tourism and the environment in order to accelerate the growth of tourist visits to Karang Payung Beach. In collaboration with the local government, they will build environmentally friendly facilities such as walking paths, tracking trails, and information centers made from recycled materials to accelerate tourist attraction while maintaining natural sustainability.

Attraction is the main aspect of attracting visitors attention to a tourist area, which can be in the form of highlighting the uniqueness of nature as a characteristic (Harianto et al. 2020). According to Cooper et al. (1998) in Harianto et al. (2020), the following are components of tourist attraction that can attract tourists, namely natural and man-made beauty, culinary, or local wisdom such as traditional events that are usually carried out. The attraction of Klothok Beach lies in its charming natural scenery, where visitors can enjoy the waves crashing against the exotic coral cliffs. This natural beauty, coupled with the gazebo provided for relaxing, makes this beach very friendly for family tourism. However, swimming at this beach is not allowed due to the condition of the large waves, tides, and the presence of rocks along the beach, which can endanger the safety of visitors.

Table 8. Internal Factors Analysis Summary (IFAS) of Karang Payung Beach

Strengths	**Weight**	**Score**	**Total score**
Potential scenery and natural beauty that is good and maintained	0.206	4	0.82
Affordable beach entrance fee	0.137	3	0.413
Plenty of parking lots	0.206	3	0.618
Subtotal	0.551		1.851
Weakness			
Narrow and rocky road access	0.172	1	0.172
The local government has not managed the beach	0.206	2	0.412
Craggy beach bottom	0.068	2	0.136
Subtotal	0.448		0.72
Total	1		2.571

Table 9. External Factors Analysis Summary (EFAS) of Karang Payung Beach

Opportunities	**Weight**	**Score**	**Total score**
Improved welfare of the surrounding community	0.260	4.5	1.173
Vehicle-friendly road access	0.217	4	0.087
Subtotal	0.478		1.26
Threats			
Generates a lot of trash during the weekend	0.260	1.5	0.39
Competition with other beaches that have more complete facilities	0.260	2	0.521
Subtotal	0.368		0.911
Total	1		2.171

Klothok Beach

Feasibility analysis of natural tourism objects

Attractions. Based on Table 10, Klothok Beach has a total score of 1,680, obtaining a feasibility index value of 80%, which is included in the potential to be designed as a natural tourist destination attraction. The stunning natural scenery, combined with the unique characteristics of the beach, can be used as the main attraction to attract more visitors, both local and international tourists. The potential to highlight the beauty and uniqueness of Klothok Beach is huge. If managed properly, this beach can become a tourist destination that not only offers natural beauty but also provides a different and interesting experience for tourists. In comparison, Balikpapan Bay is another example of a tourist attraction that emphasizes its biodiversity as the main attraction. The attractions offered by Balikpapan Bay include the presence of rare animals such as proboscis monkeys and dolphins, as well as the mangrove forest ecosystem, which is an important habitat for various species of cranes, small fish, turtles, and even fireflies. This biodiversity is a very strong attraction, which not only presents natural beauty but also provides education on the importance of environmental conservation. Willard et al. (2022) noted that the natural scenery combined with rich flora and fauna makes Balikpapan Bay a tourist destination with high ecotourism value. Similarly, Klothok Beach can highlight its natural wealth with a similar approach, such as preserving the environment, introducing biodiversity around the beach, and offering tourists a more immersive nature experience.

Accessibility. Accessibility at Klothok Beach based on Table 10 obtained a total score of 875, a feasibility index value of 50%. Based on the results of this assessment, this area is not yet feasible to develop as eco-tourism, mainly due to the limited supporting infrastructure that affects the comfort and convenience of tourists in accessing the location. Tamrat (2016) emphasizes that infrastructure and tourist attraction development have a close relationship because, without good transportation planning and an adequate management system, a destination will be difficult to reach and potentially reduce visitor interest. This is the main challenge for Klothok Beach in increasing its attractiveness as a tourist destination.

In comparison, a study conducted by Setyasih and Helmy (2021) shows that Maratua Island, North Sulawesi, Indonesia has successfully improved its accessibility through the construction of paved roads and is supported by the existence of airports and seaports that allow tourists from various regions to visit more easily. The provision of adequate infrastructure, such as proper roads, not only facilitates the flow of tourists but also has a positive impact on the economic development of the surrounding community, both in terms of trade, transportation services, and accommodation. Currently, the road to Klothok Beach is still in a damaged condition, which is one of the main obstacles in attracting tourists.

Table 10. Analysis of Klothok Beach attractions, accessibility, facilities, and perception

Variable	Sub variables	Weight	Score	Total score
Attractions	Beach appeal	6	142	852
	Comfort and cleanliness	6	138	828
			Total score	1,680
			Maximum total score	2,100
Accessibility	Road access and transportation	5	61	305
	Availability of road signs and guidance	5	114	570
			Total score	875
			Maximum total score	1,750
Facilities	Security post	3	113	339
	Parking lot	3	143	429
	Restrooms and clean water	3	128	384
	Food stalls	3	135	405
	Means of worship	3	125	375
	Garbage bins	3	132	396
	Hotel/lodging	3	88	264
	Electricity and telecommunication networks	3	65	195
			Total score	2,787
			Maximum total score	4,200
Perception	Affordable ticket	4	132	528
	Officer service	4	126	504
	Local community involvement	4	137	548
	Importance of sustainable ecotourism management	4	164	656
	Economic benefits to local communities	4	138	552
			Total score	2,788
			Maximum total score	3,500

Therefore, road improvement by paving is a strategic step that needs to be considered by the local government and local tourism managers to improve accessibility and visitor comfort. In addition, the addition of direction signs, improvement of public transportation facilities to the beach, as well as the development of alternative modes of transportation, such as shuttle buses from the main access point, can be a solution to increase the affordability of the location.

Facilities. Facility criteria include several aspects, namely security posts, parking lots, toilets and clean water, food stalls, worship facilities, garbage bins, hotels and inns, and electricity and telecommunications networks. In the facility criteria based on Table 10, Klothok Beach has a score of 2,787, with a feasibility index value of 66.36%, so this criterion is included in feasibility indicates that an ecotourism area is not yet feasible to develop. Maratua Island has 24-hour health services and the availability of electricity networks by PLTD (Diesel Power Plant) so that tourist comfort is guaranteed (Setyasih and Helmy 2021). The addition of electricity networks and telecommunications networks can be done by asking for assistance from the Wonogiri District Government, supported by the requests of visitors during interviews. To improve the feasibility of Klothok Beach, the addition of electricity and telecommunication networks can be done in coordination with the district government and involving various stakeholders, including tourism managers and local communities. This support can be strengthened by requests from visitors, which show that tourists want better accessibility in terms of internet connectivity and electricity. In addition, the development of facilities such as community-based lodging (homestay), improved access to clean water, and the construction of proper sanitation facilities will further increase the attractiveness of Klothok Beach as a sustainable ecotourism destination. Investment in tourism infrastructure, if done by considering environmental aspects, can also support the principles of sustainable tourism. For example, the application of renewable energy sources such as solar panels or small-scale wind turbines can be an alternative solution to provide electricity without damaging the coastal ecosystem.

Perception. Perception criteria include several aspects, namely ticket affordability, officer services, local community involvement, the importance of sustainable ecotourism management, and economic benefits to local communities. In the perception criteria, Klothok Beach based on Table 10 has a score of 2,788, with a feasibility index value of 79.66%, which is included in feasibility indicates that an ecotourism area is not yet feasible to develop. The development of a tourist attraction will have an impact on the socioeconomic conditions of the local community (Olu et al. 2018). So, the more the community is involved in the development, the more it will produce a superior tourist attraction, able to attract more visitors so that the welfare of the community is guaranteed. The welfare of the local community will affect the services provided to visitors. The more the community is involved in development, the greater the chance of creating a superior tourist destination, attracting more visitors and providing significant economic benefits to the local population. Improving the welfare of local communities has a direct correlation with the quality of services provided to tourists. If residents experience tangible economic benefits from the tourism industry, they will be more encouraged to provide friendly service, maintain cleanliness, and contribute to the management of tourist areas.

Socioeconomic conditions

The management of Klothok Beach is a testament to the power of community-driven initiatives. Led by the local community in collaboration with the Wonogiri District Government, the management team, which includes delegates from the local government and the local community, particularly the Polaris, a community-level institution, is dedicated to managing MCK and ensuring cleanliness. As Yatmaja (2019) highlights, Pokdarwis is a community-level institution where local tourism actors voluntarily contribute to the development of tourism in their area. The entrance ticket price is set at IDR 10,000/person for weekdays and IDR 15,000/person for weekends. A single ticket allows entry to both Klothok Beach and Sembukan Beach, with a visitor capacity of 20 people on weekdays and 500 people on weekends or national holidays (Table 11).

Development still needs to increase the attractiveness of the location to visitors. However, it is constrained by internal conflicts regarding disputed land, so that every development carried out needs the approval of two parties, namely the government as a subsidy for funds and the community who owns the land even though this tourism provides jobs for the people of Paranggupito Sub-district, Wonogiri District. The community has never been disadvantaged in the development of Klothok Beach tourism. Farming is the main livelihood of the local community, but it is seasonal, so it needs to wait for the rainy season; with the existence of Klothok Beach tourism, the community can sell while waiting for planting and harvesting time. Traditional values and historical heritage, referred to as well-preserved local wisdom, can be an attraction (Towoliu and Takaendengan 2015). The community continues to observe traditional customs, namely *Larungan*, which is performed during the *Suro* night (Islamic Hijri New Year calendar). This ceremony involves the symbolic release of cattle heads and feet into the waters off Sembukan beach (nearby Klotok Beach). *Larungan* is a Javanese tradition that involves throwing offerings (e.g. *tumpeng* or other food such as fruits, vegetables, and a head of buffalo or cow) into the sea or to a place considered sacred, representing gratitude, appreciation for life's gifts, and asking for salvation from Allah (Syamsi et al. 2024). Notable nights for this ceremony include the full moon (*malam bulan purnama*), Legi Friday night (*malam Jum'at Legi*), 1 Muharram night/1 Suro night calendar (*malam 1 Suro*) (Basalamah and Hariri 2020).

Klothok Beach development strategy and SWOT analysis

Klothok Beach is one of the beaches that many tourists visit in Wonogiri. However, Klothok Beach still needs to develop its facilities and beach conditions so that it can increase the number of visitors every day. Therefore, the community and the management of Klothok Beach are needed because they have a strategic role in helping to improve the quality of Klothok Beach.

IFAS-EFAS analysis of Klothok Beach

Based on the IFAS analysis as presented in Table 12, it is known that the total scores for strengths and weaknesses at Klothok Beach are 2.55 and 0.8, so the total score of strengths at Klothok Beach is greater than the total score of weaknesses. This means that Klothok Beach has strong internal capital for its development because the strength score is much higher than the weakness. Klothok Beach has promising potential because of its attractive scenery and beautiful and well-maintained beach atmosphere. These advantages allow Klothok Beach to deal more effectively with existing weaknesses. Improvements in road access and bathroom facilities at Klothok Beach will increase visitor comfort and experience, which in turn can increase the attractiveness of the beach as a tourist destination. Visitors tend to have the intention to return if they are satisfied with the facilities, services, and experiences they get (Nugraha and Jerubun 2024).

The results of the EFAS analysis are in Table 13, show that the total scores of opportunities and threats of Klothok Beach are 2.1 and 0.7. The total opportunity score is higher than the total threat score, which indicates that more opportunities can be utilized compared to the threats that must be faced. Development by utilizing revenue opportunities for ecotourism potential, such as improving tourist facilities, better promotion, and developing community-based activities, Klothok Beach can strengthen its position as an attractive tourist destination.

Table 11. SWOT Factors of Klothok Beach

Internal Factors / External Factors	Opportunities	Threats
	1. Income opportunities for the ecotourism potential of Klothok Beach through the sale of food and drinks provided by traders and the surrounding community. 2. The development of ecotourism at Klothok Beach into one of the regional assets will attract the attention of many visitors.	1. Competition with other beaches whose roads are easier to travel and more famous on social media. 2. Land ownership by outsiders
Strengths	**Strategi S-O**	**Strategi S-T**
1. The potential and attractiveness of eco-tourism at Klothok Beach attract visitors 2. The beautiful and well-maintained atmosphere of Klothok Beach, as well as complete and clean facilities, are the reasons why visitors come to this beach.	1. Increased participation of the community, administrators, and local government in the development of Klothok Beach	1. Conducting promotions on social media by following existing trends to reach visitors from various groups. 2. Increasing awareness and strengthening community institutions.
Weakness	**Strategi W-O**	**Strategi W-T**
1. The access road to the beach is still rocky and potentially dangerous for visitors. 2. There is only one bathroom, and it is not strategically located.	1. Propose improvements to the road and access to the beach to the local government with the support of local managers.	1. Design and build facilities such as children's play areas or picnic areas with educational programs for visitors regarding safety when playing at the beach.

Table 12. Internal Factors Analysis Summary (IFAS) of Karang Payung Beach

Strengths	Weight	Score	Total score
The potential and attractiveness of ecotourism at Klothok Beach are interesting	0.3	4.5	1.35
The atmosphere of Klothok Beach is beautiful and well-maintained	0.3	4	1.2
Subtotal	0.6		2.55
Weakness			
Access road is still rocky	0.2	2	0.4
There is only 1 bathroom, and it is not strategically located	0.2	2	0.4
Subtotal	0.4		0.8
Total	1		3.35

Table 13. External Factors Analysis Summary (IFAS) of Klothok Beach

Opportunities	Weight	Score	Total score
Income opportunities for the ecotourism potential of Klothok Beach	0.3	4	1.2
The development of ecotourism at Klothok Beach into one of the regional assets will be interesting	0.3	3	0.9
Subtotal	0.6		2.1
Threats			
Competition with other beaches	0.2	1.5	0.3
Land ownership by outsiders	0.2	2	0.4
Subtotal	0.4		0.7
Total	0.2	1.5	0.3

X = Strengths - Weaknesses = 2.55 - 0.8 = 1.75

Y = Opportunities - Threats = 2.1 - 0.7 = 1.4

The conclusion drawn from the analysis indicates that Nampu Beach, Karang Payung Beach, and Klothok Beach possess tourist attractions that are both aesthetically pleasing and comfortable, and that these attractions have the potential for development. The results of the ADO ODTWA analysis show that the accessibility aspect of Nampu Beach has a feasibility index on the facilities aspect of 59.50% (not feasible). The accessibility index of Karang Payung Beach is 60.29% (not feasible), and the facility index is 65.71% (not feasible). Similarly, the accessibility feasibility index of Klothok Beach is 50% (not feasible). Improving road access and providing adequate transportation for visitors were identified as potential strategies to improve accessibility. In addition, the construction of facilities such as clean toilets and adequate parking areas are also recommended to improve visitor comfort. The SWOT analysis suggests different strategies for each beach. For Nampu Beach, a rapid growth strategy is recommended, focusing on empowering local communities and involving government support in tourism management; improving cleanliness is also crucial to ensure visitor comfort. For Karang Payung Beach, a rapid growth strategy includes improving road access, developing the area as a safe camping site, and gaining local government support. Klothok Beach requires a stable growth strategy that prioritizes better road access and improved restroom facilities, especially during peak holiday periods, to increase visitor satisfaction. By implementing tailored strategies, the development of these beaches can be tailored to their specific strengths, weaknesses, opportunities, and threats, ultimately improving their attractiveness and accessibility as ecotourism destinations.

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Short Communication: Spatial distribution and diversity of intertidal crustaceans in karstic beaches of southern Java, Indonesia

DAIVA ARDHANIA NIRWASITA HARTONO[1], DIAN WIDOWATI[1], EDRIC FARREL SAPUTRA[1], FAUZAN RAFI WICAKSONO[1], PUTRI SEGI PRAMADANINGTYAS[1], CHEE KONG YAP[2], AHMAD DWI SETYAWAN[1,3,♥]

[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia. Tel./fax.: +62-271-663375, ♥email: volatileoils@gmail.com
[2]Department of Biology, Faculty of Science, Universiti Putra Malaysia. 43400 UPM Serdang, Selangor, Malaysia
[3]Biodiversity Research Group, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

Manuscript received: 14 July 2024. Revision accepted: 26 March 2025.

Abstract. *Hartono DAN, Widowati D, Saputra EF, Wicaksono FR, Pramadaningtyas PS, Yap CK, Setyawan AD. 2025. Short Communication: Spatial distribution and diversity of intertidal crustaceans in karstic beaches of southern Java, Indonesia. Indo Pac J Ocean Life 9: 26-35.* Karstic coastal systems in tropical regions are often overlooked in biodiversity assessments despite their ecological complexity and vulnerability. This study investigates the species composition, diversity, and environmental drivers of intertidal crustacean communities across five karstic beaches in Gunungkidul, Indonesia. A total of 18 crustacean species were recorded, with *Coenobita scaevola* emerging as the most dominant and widely distributed taxon. Species richness and the Shannon-Wiener diversity index (H′) varied significantly among sites, with Ngrenehan Beach exhibiting the highest diversity (H′=2.18) and Ngrawah the lowest (H′=1.23). Among the measured abiotic parameters, dissolved oxygen (DO) showed the strongest positive correlation with H′ ($r=0.92$, $p<0.05$), indicating its critical role in structuring crustacean assemblages. Cluster analysis revealed two distinct site groups, reflecting spatial heterogeneity in species composition likely shaped by microhabitat features. The findings underscore the importance of karstic intertidal habitats as localized biodiversity reservoirs and emphasize the need for site-specific conservation strategies and long-term ecological monitoring in tropical coastal regions.

Keywords: Bray-Curtis similarity, *Coenobita scaevola*, crustacean diversity, dissolved oxygen, Gunungkidul, karst beach

INTRODUCTION

Indonesia, as a vast archipelagic nation, possesses one of the richest marine biodiversities in the world. The intertidal zone, located at the interface between terrestrial and marine ecosystems, is a dynamic and ecologically significant habitat that supports diverse assemblages of marine organisms, including crustaceans. These organisms play essential ecological roles in nutrient cycling, sediment turnover, and as prey for higher trophic levels (Snelgrove et al. 2016; Söderhäll 2016). Among the varied coastal geomorphologies in Indonesia, karstic beaches—characterized by limestone cliffs, narrow tidal flats, and rocky substrates—form unique habitats with high environmental heterogeneity yet remain poorly studied in terms of their faunal communities.

Crustaceans, particularly decapods such as crabs and hermit crabs, are prominent and ecologically significant members of intertidal communities. Their distribution and diversity are influenced by a suite of abiotic factors, including temperature, pH, salinity, substrate type, and dissolved oxygen levels (Mokhtari et al. 2015; Semprucci et al. 2019). These variables not only affect species occurrence but also shape ecological interactions and habitat preferences. Moreover, crustaceans have varying degrees of mobility and adaptability to habitat disturbances, making them useful bioindicators for monitoring coastal ecosystem health (Handayani et al. 2016; Marin and Tiunov 2023).

Despite their ecological importance, intertidal crustacean communities in karstic coastal zones of Java, especially in Gunungkidul District, remain understudied. Previous studies in Indonesian waters have mostly focused on mangrove or estuarine systems (Paujiah et al. 2020; Rahmawati et al. 2021), while rocky intertidal habitats in remote and difficult-to-access karst areas have received limited scientific attention. These beaches often exhibit steep geomorphological features and variable exposure to waves, potentially affecting crustacean assemblages in ways that are distinct from those in other coastal settings.

Environmental gradients, particularly abiotic stressors such as low dissolved oxygen or fluctuating pH, can act as filters that structure intertidal communities. For instance, some crustaceans exhibit physiological adaptations to hypoxic conditions or morphological traits suited for burrowing in compact substrates (Bezuidenhout et al. 2021). Karst beaches, with their mix of sandy pockets, coral rubble, and rock platforms, may harbor niche-specialized species whose presence reflects fine-scale environmental variability. Understanding how crustacean communities respond to these gradients is essential for anticipating shifts due to climate change, habitat degradation, or tourism development.

In addition to ecological drivers, human activities increasingly impact intertidal habitats in Gunungkidul. Coastal development, unmanaged tourism, and pollution can alter substrate conditions and water quality, thereby threatening sensitive intertidal species (El-Naggar et al. 2022). However, most management efforts in the region have focused on coral reefs and fisheries conservation, often overlooking intertidal invertebrates. Establishing a baseline of species composition and environmental conditions in these underexplored beaches can inform local conservation strategies and contribute to national biodiversity monitoring goals.

This study investigates the spatial distribution and species diversity of intertidal crustaceans across five karstic beaches in the southern coastal area of Yogyakarta Special Region, Indonesia. We aimed to: (i) document the species richness and community composition of crustaceans in these sites; (ii) evaluate the ecological diversity indices, including Shannon-Wiener diversity, Margalef richness, and evenness; and (iii) examine how environmental variables such as pH, temperature, and dissolved oxygen correlate with crustacean abundance and diversity. By addressing these objectives, we seek to fill a critical knowledge gap in tropical rocky intertidal ecology and provide empirical data relevant to coastal biodiversity conservation.

The findings of this research are expected to contribute to a broader understanding of biotic responses to abiotic stress in tropical intertidal zones and highlight the ecological value of karstic coastal ecosystems. Furthermore, the documentation of crustacean species from relatively undisturbed or minimally studied locations can serve as a valuable reference for long-term monitoring, particularly in the face of anthropogenic pressures and climate variability. Ultimately, this study provides insights into how environmental heterogeneity drives biodiversity patterns in intertidal crustacean assemblages within a unique karst landscape.

MATERIALS AND METHODS

Study area

This study was conducted at five karstic beach locations situated along the southern coast of Gunungkidul District, Yogyakarta Special Region, Indonesia: Pringjono, Torohudan, Ngrawah, Dadap Ayam, and Ngrenehan Beaches (Figure 1). All sites lie within Kanigoro Village, Saptosari Subdistrict, and are part of a unique limestone coastal system characterized by narrow intertidal zones, rocky platforms, and steep cliff backdrops (Nurcahyo et al. 2024). These beaches are generally less accessible than more developed tourist beaches (Fadin et al. 2023), offering relatively undisturbed ecological settings suitable for intertidal biodiversity studies.

Each beach differs in terms of geomorphology and human accessibility. Pringjono Beach is the most isolated, located west of Nguyahan Beach and accessible only by footpaths through rocky terrain and vegetated hills. Torohudan and Ngrawah Beaches lie adjacent to agricultural fields and can only be reached by walking across narrow, unpaved paths. Dadap Ayam Beach, named after the local medicinal tree *Erythrina variegata* (*dadap ayam*), is accessible via steep stone steps through coastal scrub and forest. Ngrenehan Beach is the most developed, serving as a fishing port and tourism site, with well-maintained access and public facilities.

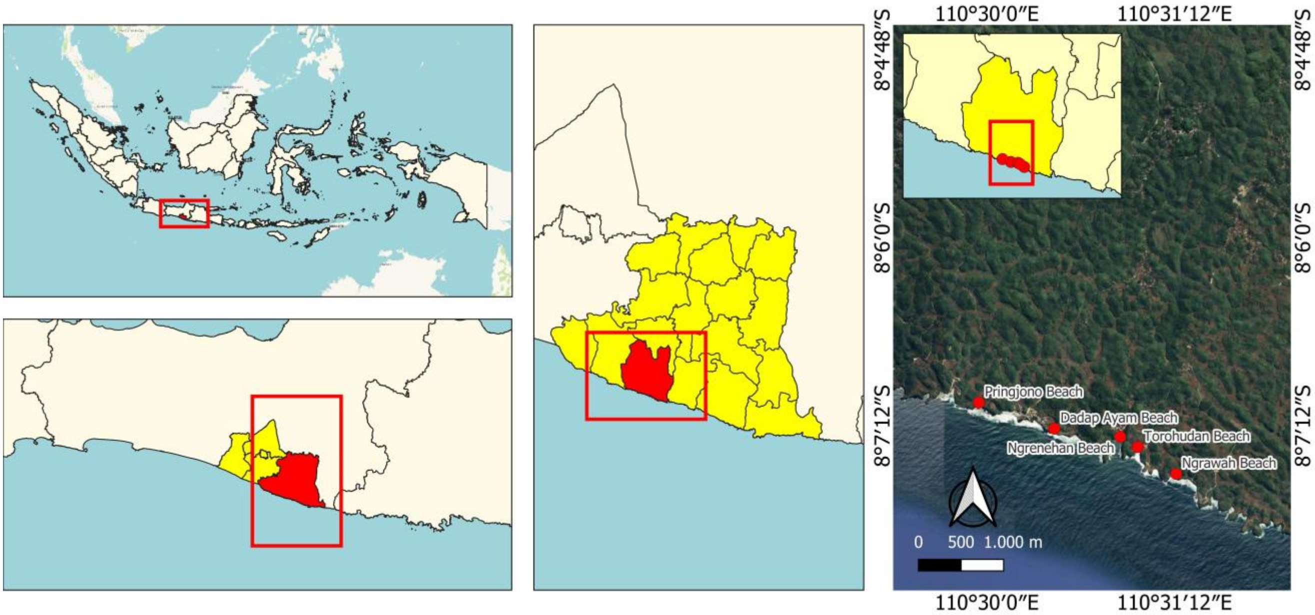

Figure 1. Map showing the location of five karstic beach study sites (Pringjono, Torohudan, Ngrawah, Dadap Ayam, and Ngrenehan) in Saptosari Sub-district, Gunungkidul District, Yogyakarta Special Region, Indonesia

All five beaches are located within a tropical monsoon climate zone, receiving 1,500-2,000 mm of rainfall annually and experiencing average daily temperatures ranging from 26°C to 31°C. The tidal regime is semi-diurnal with moderate amplitude, creating regular cycles of exposure and submersion that define the intertidal zone structure (Furlani et al. 2020). Variations in abiotic conditions such as pH, temperature, salinity, and dissolved oxygen occur spatially across the sites due to differential wave exposure, substrate type, and human impact levels (Hartati et al. 2024).

Sampling design and data collection

Crustacean survey and identification

Field sampling was conducted at each of the five beach locations during low tide in March 2024. A belt transect method was employed to systematically survey crustaceans along a 50-m shoreline segment at each site (Shofi 2021). Within each transect, five square plots of 10×10 m were established to capture habitat variation, including sandy, rocky, and coral-rubble microhabitats.

Crustaceans observed within each plot were collected manually using hand tools, such as small nets, plastic jars, and shovels for burrowing individuals. Only specimens found within the plot boundary during standardized 30-minute search sessions were recorded. To ensure consistency, all sampling was performed during the same tidal phase and time window (08:00-12:00 local time) across all beaches.

Specimens were preserved in 70% ethanol and identified in the laboratory based on morphological characteristics, including carapace shape and texture, coloration, cheliped structure, and body size. Identification referred to field guides and taxonomic keys (Rustikasari et al. 2021), as well as the World Register of Marine Species (WoRMS) online database. When identification to the species level was uncertain, the specimens were assigned to the closest possible genus and marked with "cf." Voucher specimens were not retained due to logistical and ethical limitations, but photographic documentation was archived for all unique morphotypes.

Measurement of abiotic parameters

Abiotic data collection was conducted simultaneously with crustacean sampling to assess local environmental conditions that may influence species distribution. Parameters measured included pH, surface water temperature, and dissolved oxygen (DO) concentration. Measurements were taken at three random points within each transect using portable instruments: a waterproof digital pH meter, a thermometer, and a DO meter (Lutron DO-5510).

Instruments were calibrated prior to each sampling session, and readings were recorded on-site. DO values were cross-validated using the Winkler titration method, particularly in locations where digital readings indicated extremely low oxygen levels. Salinity measurements were excluded due to the minimal variation observed across the study sites.

These abiotic parameters were selected due to their known importance in shaping intertidal community structure. pH influences physiological processes such as carapace formation, while temperature and oxygen availability affect metabolic activity, mobility, and reproductive success in crustaceans (Semprucci et al. 2019; Hartati et al. 2024). Variation in these parameters was later analyzed to explore potential correlations with crustacean diversity patterns.

Biodiversity indices and ecological analysis

Three ecological indices were calculated to evaluate the structure of crustacean communities across the five karstic beaches: the Shannon-Wiener diversity index (H′), Margalef's richness index (Dmg), and Pielou's evenness index (E). These indices provide complementary metrics for assessing species composition, abundance distribution, and community balance within each site (Fachrul 2007; Kusumaningsih and Hendrarto 2015).

The Shannon-Wiener index (H') was calculated using the formula:

$$H' = -\sum(p_i \times \ln p_i)$$

where p_i is the proportion of individuals belonging to the i-th species. Interpretation followed the scale proposed by Fachrul (2007):

$H' < 1$: low diversity
$1 \leq H' \leq 3$: moderate diversity
$H' > 3$: high diversity

Margalef's species richness index (Dmg) was computed as:

$$Dmg = (S - 1) / \ln(N)$$

where S is the number of species and N is the total number of individuals observed at a site. According to Kamaluddin et al. (2019):

$Dmg < 2.5$: low richness
$2.5 \leq Dmg \leq 4$: moderate richness
$Dmg > 4$: high richness

Pielou's evenness index (E) was calculated to assess the equitability of individual distribution among species:

$$E = H' / \ln(S)$$

Classification followed Pielou (1977):
$E < 0.31$: low evenness
$0.31 \leq E \leq 1$: moderate evenness
$E > 1$: high evenness

All indices were calculated using Microsoft Excel and validated with PAST version 4.11. Species counts and ecological indices were then compared across beach sites to detect spatial trends. Additionally, index values were later correlated with abiotic factors to explore possible environmental influences on community structure (Semprucci et al. 2019; Rahmadhani and Martuti 2023).

Data processing and statistical procedures

All raw data, including species counts, ecological indices, and abiotic parameters, were compiled, cleaned, and organized using Microsoft Excel. Descriptive statistics were used to summarize the number of species, individuals, and values of pH, temperature, and dissolved oxygen at each study site. Results were tabulated and visualized to facilitate inter-site comparisons and pattern interpretation.

To explore the relationship between environmental factors and crustacean diversity, Pearson's correlation analysis was conducted. Shannon-Wiener diversity index (H′) values were treated as the dependent variable, while pH, temperature, and dissolved oxygen served as independent predictors. Correlation coefficients (*r*) and significance values (*p*) were calculated using SPSS version 25, with a significance level set at α=0.05.

In addition, hierarchical cluster analysis was applied to examine community similarity among beach sites based on species composition and relative abundance. The Bray-Curtis similarity index was used to generate a dissimilarity matrix, and dendrograms were constructed using the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) in PAST version 4.11 (Semprucci et al. 2019). This analysis allowed the visual grouping of sites with similar crustacean assemblages and facilitated the ecological interpretation of spatial patterns.

All data visualizations—including diversity index plots, abiotic parameter distributions, and dendrograms—were prepared using a combination of PAST, SPSS, and Adobe Illustrator for publication quality. All statistical procedures followed standard assumptions regarding normality and independence; where these assumptions were not met, results were interpreted with caution and noted accordingly.

RESULTS AND DISCUSSION

Species composition and abundance

A total of 18 crustacean species from 14 families were recorded across five karstic beaches in Gunungkidul, Indonesia (Table 1). Species richness and total abundance varied substantially among sites, with Ngrenehan Beach exhibiting the highest diversity (8 species, 98 individuals), and Ngrawah the lowest (4 species, 24 individuals). The most frequently encountered species was *Coenobita scaevola* (long-armed hermit crab), present at all beaches and accounting for 96 individuals or 42.5% of total abundance.

Other abundant taxa included *Xantho cf. poressa* (27 individuals), *Hemigrapsus sanguineus* (21 individuals), and *Coenobita brevimanus* (18 individuals), each with more restricted spatial distributions. Notably, *C. scaevola* showed consistent dominance at Pringjono, Torohudan, Ngrawah, and Dadap Ayam, while *X. cf. poressa* was strongly localized at Ngrenehan (Figure 2).

Several species were rare, being recorded only once across all sites—namely *Platypodia granulosa* (granular reef crab), *Plagusia chabrus* (red rock crab), *Carpilius maculatus* (seven-eleven crab), and *Ozius cf. rugulosus* (tentatively identified as wrinkled rock crab). Their rarity may indicate specialized habitat requirements or low population density within the sampled zones. Figure 2 illustrates the relative abundance of the five most dominant species, namely *C. scaevola*, *X. cf. poressa*, *H. sanguineus*, *Grapsus albolineatus* (lined shore crab), and *C. brevimanus* (giant land hermit crab).

These findings reveal notable inter-site variation in species composition, likely driven by differences in substrate type, tidal exposure, and microhabitat heterogeneity. While Ngrenehan had the highest richness and total individuals, several species occurred exclusively at other beaches, underscoring the importance of localized environmental conditions over a simple spatial gradient (Figure 3).

Diversity indices supported these patterns. The highest Shannon-Wiener index (H′=2.18) was observed at Ngrenehan, and the lowest (H′=1.23) at Ngrawah. Margalef's richness index mirrored this trend, confirming the relatively higher diversity structure at Ngrenehan (Figure 4).

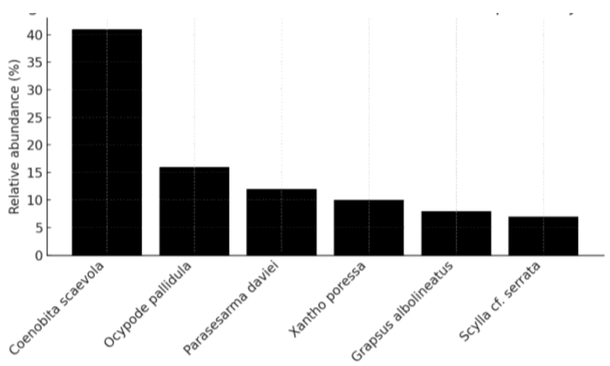

Figure 2. Relative abundance of dominant crustacean species across five karstic beaches in Gunungkidul, Yogyakarta, Indonesia

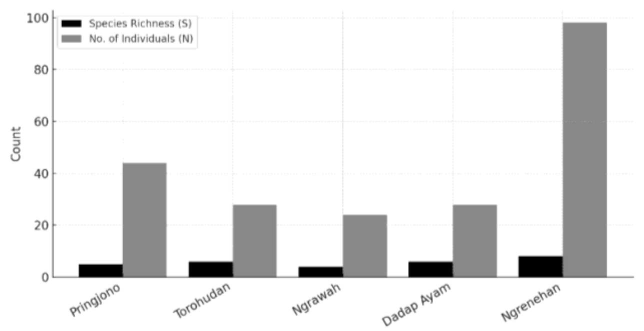

Figure 3. Species richness and number of individuals per beach in Gunungkidul, Yogyakarta, Indonesia

Table 1. Occurrence and abundance of crustacean species across five karstic beaches in Gunungkidul, Indonesia

Scientific name	Common name	Family	I	II	III	IV	V	IUCN status
Etisus dentatus (Herbst, 1785)	Toothed reef crab	Xanthidae	-	3	-	-	1	LC
Carpilius maculatus (Linnaeus, 1758)	Seven-eleven crab	Carpiliidae	-	-	-	1	-	NE
Cardisoma carnifex (Herbst, 1796)	Purple land crab	Gecarcinidae	-	-	-	-	3	LC
Grapsus albolineatus Latreille, 1812	Lined shore crab / Sally lightfoot crab	Grapsidae	-	1	5	-	12	LC
Plagusia chabrus (Linnaeus, 1758)	Red rock crab	Plagusiidae	-	-	-	1	-	LC
Discoplax hirtipes (Dana, 1851)	Hairy land crab	Gecarcinidae	-	-	-	1	-	LC
Hemigrapsus sanguineus (De Haan, 1835)	Asian shore crab	Varunidae	-	-	-	-	21	LC
Hyastenus diacanthus (De Haan, 1839)	Spider decorator crab	Epialtidae	4	-	-	-	-	LC
Ocypode pallidula Hombron & Jacquinot, 1846	Pale ghost crab	Ocypodidae	7	3	-	-	-	LC
Ocypode cordimanus Latreille, 1818	Shore ghost crab	Ocypodidae	-	-	-	2	-	LC
Ozius cf. rugulosus	Wrinkled rock crab (tentative)	Oziidae	-	-	-	-	1	NE
Parasesarma daviei Shahdadi, Schubart & Mendoza, 2021	Davie's mangrove crab	Sesarmidae	8	-	-	-	-	LC
Platypodia granulosa (Rüppell, 1830)	Granular reef crab	Xanthidae	1	-	-	-	-	LC
Schizophrys aspera (H.Milne Edwards, 1831)	Rough spider crab	Majidae	-	2	-	-	-	LC
Scylla cf. serrata	Giant mud crab	Portunidae	-	-	5	-	-	LC
Xantho poressa (Olivi, 1792)	Jaguar round crab	Xanthidae	-	-	-	-	27	LC
Coenobita scaevola (Forskål, 1775)	Long-armed hermit crab	Coenobitidae	24	18	11	16	25	LC
Coenobita brevimanus Dana, 1852	Giant land hermit crab	Coenobitidae	-	1	3	6	8	LC

Note: I: Pringjono Beach, II: Torohudan Beach, III: Ngrawah Beach, IV: Dadap Ayam Beach, V: Ngrenehan Beach. -: Absence of the species at the site. Species marked as *cf.* indicate tentative identification based on morphology and ecological distribution. LC: Least Concern, NE: Not Evaluated

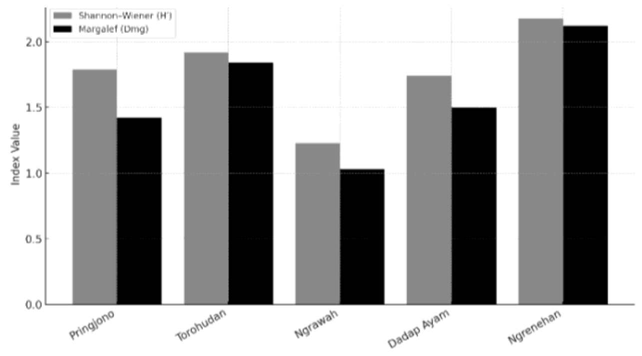

Figure 4. Shannon-Wiener and Margalef's richness indices across beach sites

Morphological variation of key species

Several crustacean species recorded in this study exhibited distinct morphological traits that facilitated both field identification and ecological interpretation (Table 2). The most abundant species, *Coenobita scaevola* (long-armed hermit crab), possessed a small, asymmetrical body adapted for shell-dwelling, with a light brown to pale gray exoskeleton, short eyestalks, and a conspicuously enlarged left chela. It was easily distinguishable from *Coenobita brevimanus* (giant land hermit crab), which exhibited a darker body coloration, shortened walking legs, and a more robust, laterally compressed left chela (Hazlett 1981).

The large-bodied portunid *Scylla cf. serrata* (giant mud crab) was identified based on its broad, polygonal carapace with pronounced frontal lobes and stout, spiny chelae. Although members of *Scylla* are typically associated with mangrove estuaries, the individuals observed in this study were found inhabiting semi-enclosed tidal pools adjacent to rocky platforms, consistent with known ecological plasticity within this genus (Keenan et al. 1998).

Xantho cf. poressa, a xanthid crab restricted to Ngrenehan Beach, featured a reddish-brown, moderately convex carapace with fine granulations and black-tipped chelae. This morphology aligns with xanthid species commonly found on sheltered, rocky intertidal substrates in the Indo-Pacific region (Ng et al. 2008).

Other taxa, such as *Grapsus albolineatus* (lined shore crab) and *Parasesarma daviei* (Davie's mangrove crab), were identified based on general coloration patterns and habitat associations described in existing literature. *G. albolineatus* is recognized by its agility, slender body form, and vivid coloration, often observed darting across rock surfaces. In contrast, *P. daviei* was typically associated with moist rock crevices, and exhibited a squared, maroon carapace with shallow lateral grooves, consistent with previous descriptions of sesarmid morphology (Ng et al. 2008).

Crustacean diversity indices

The diversity of crustacean communities varied across the five study sites, as reflected in the calculated values of the Shannon-Wiener diversity index (H′), Pielou's evenness index (E), and Margalef's species richness index (Dmg). These metrics offer complementary insights into the composition, distribution, and balance of species within each assemblage (Fachrul 2007).

Ngrenehan Beach exhibited the highest diversity (H′=2.18), indicating both relatively high species richness and a balanced distribution of individuals among species (Table 3). In contrast, Ngrawah Beach recorded the lowest diversity (H′=1.23), likely due to a combination of low species number and dominance by one or two taxa.

Pielou's evenness index (E) ranged from 0.56 to 0.97, reflecting variation in species dominance patterns across sites. The highest evenness was observed at Dadap Ayam (E=0.97), suggesting that individuals were evenly distributed among six species, with no single taxon dominating numerically. Conversely, Ngrawah's low evenness (E=0.56) suggests community imbalance, consistent with its lower species richness.

Margalef's richness index (Dmg) also showed inter-site variation, with the highest value at Ngrenehan (2.12), indicating moderate species richness based on classification thresholds. The lowest Dmg was observed at Ngrawah (1.03). After correcting the species count at Dadap Ayam from five to six, its updated richness value (Dmg=1.50) and evenness (E=0.97) reflect a more structured and balanced community than previously assumed.

Figure 4 illustrates the site-specific differences in diversity and richness indices, reinforcing the pattern that structurally complex and oxygen-rich sites tend to support more diverse crustacean assemblages.

Abiotic environmental parameters

Environmental conditions varied among the five study sites, particularly in terms of water temperature and dissolved oxygen (DO)-two key abiotic factors known to influence the structure and function of intertidal communities (Semprucci et al. 2019). As summarized in Table 4, water temperature ranged from 27.4°C at Dadap Ayam to 30.2°C at Pringjono, with Ngrenehan and Torohudan displaying intermediate and relatively stable values (~28.5°C). Ngrawah was slightly warmer (29.1°C), potentially reflecting its more exposed location and limited vegetation cover.

pH levels were relatively uniform across all sites, ranging from 7.4 to 7.8, typical of marine-influenced intertidal environments. Dadap Ayam was the most alkaline (pH 7.8), while Pringjono and Torohudan exhibited slightly lower values (pH 7.4-7.5). These conditions fall within a physiologically favorable range for crustaceans, particularly with regard to exoskeletal calcification and molting processes (Rahmadhani and Martuti 2023).

Dissolved oxygen (DO) levels exhibited the greatest spatial variation, with Dadap Ayam recording the highest average concentration (7.1 mg/L) and Ngrawah the lowest (4.3 mg/L). These differences suggest that microhabitat oxygen availability may play a key role in supporting or limiting species presence, especially in more enclosed or stagnant zones. The low DO at Ngrawah may indicate mild hypoxic conditions, which could contribute to its reduced species richness and evenness. Figure 5 visualizes the spatial gradients of temperature, pH, and DO across the five sites, highlighting the potential ecological implications of abiotic variability in shaping crustacean community patterns.

Table 2. Morphological features of representative crustacean species found at five karstic beaches in Gunungkidul, Indonesia

Species	Body size (mm)	Carapace coloration	Chela morphology	Habitat type	Diagnostic features
Coenobita scaevola (Forskål, 1775)	12-28	Pale brown to gray	Asymmetrical; left larger	Rocky and sandy intertidal	Short eyestalks, shell-dwelling, terrestrial tendency
Coenobita brevimanus Dana, 1852	25-35	Dark brown to black	Flattened, thick chelae	Sheltered rock crevices	Short antennae, stout body, reduced mobility
Scylla cf. serrata	60-110	Dark green to bluish	Large, spiny, robust	Tidal pools, brackish edge	Broad frontal lobe, polygonal carapace
Xantho poressa (Olivi, 1792)	30-50	Reddish-brown	Short, black-tipped	Rocky substrate	Convex carapace, granulated surface
Parasesarma daviei Shahdadi, Schubart & Mendoza, 2021	18-32	Maroon or deep red	Narrow, curved	Moist rock crevices	Square carapace, lateral grooves

Table 3. Diversity indices of crustacean communities at 5 karstic beaches in Gunungkidul, Indonesia

Beach	No. of Species (S)	No. of Individuals (N)	Shannon-Wiener (H′)	Pielou's Evenness (E)	Margalef's Richness (Dmg)
Pringjono	5	44	1.79	0.71	1.42
Torohudan	6	28	1.92	0.72	1.84
Ngrawah	4	24	1.23	0.56	1.03
Dadap Ayam	6	28	1.74	0.97	1.50
Ngrenehan	8	98	2.18	0.70	2.12

Relationship between abiotic factors and crustacean diversity

The relationship between abiotic parameters and crustacean diversity was examined using Pearson's correlation analysis between the Shannon-Wiener diversity index (H′) and three key environmental variables: temperature, pH, and dissolved oxygen (DO). As presented in Table 5, DO exhibited a strong positive correlation with H′ (r=0.92, p<0.05), indicating that higher oxygen availability is closely associated with increased species diversity. This suggests that DO is a critical factor shaping the composition and richness of intertidal crustacean assemblages in karstic environments.

By contrast, temperature showed a weak negative correlation with diversity (r=-0.46), which may reflect a modest inhibitory effect on species richness or evenness, possibly due to thermal stress, reduced oxygen solubility, or disrupted physiological processes. Although the result was not statistically significant, it may hold ecological relevance under scenarios of rising coastal temperatures associated with climate change.

The correlation between pH and H′ was minimal (r=0.10), suggesting that the narrow pH range observed across sites (7.4-7.8) exerted little influence on overall diversity. This aligns with previous findings that moderate pH variation rarely impacts adult crustaceans in stable marine-influenced intertidal systems.

These trends are visualized in Figure 6, which presents scatterplots of H′ against each environmental variable. The clear linear association between DO and diversity underscores the ecological importance of oxygen availability in maintaining species-rich crustacean communities along the karstic shoreline.

Community similarity among beaches

Cluster analysis using Bray-Curtis similarity was performed to evaluate the degree of overlap in crustacean species composition across the five karstic beach sites. The resulting dendrogram (Figure 7) revealed two primary clusters: the first consisting of Pringjono, Dadap Ayam, and Torohudan, and the second comprising Ngrenehan and Ngrawah.

The grouping of Pringjono, Dadap Ayam, and Torohudan indicates a shared species assemblage, likely resulting from similar microhabitat features such as rocky intertidal substrates, moderate wave exposure, and limited anthropogenic disturbance. These sites were consistently inhabited by generalist species, including *Coenobita scaevola*, *Ocypode pallidula*, and *Parasesarma daviei*, which are known for their ecological flexibility and ability to occupy both sandy and rocky microhabitats.

Table 4. Summary of abiotic parameters measured at 5 karstic beaches, Gunungkidul, Indonesia

Beach	Temperature (°C)	pH	Dissolved oxygen (mg/L)
Pringjono	30.2	7.4	5.2
Torohudan	28.6	7.5	6.0
Ngrawah	29.1	7.6	4.3
Dadap Ayam	27.4	7.8	7.1
Ngrenehan	28.5	7.7	6.4

Table 5. Pearson correlation matrix between Shannon-Wiener index (H′) and abiotic parameters

Variable	H′	Temperature (°C)	pH	DO (mg/L)
H′	1.00	-0.46	0.10	0.92
Temperature	-0.46	1.00	-0.20	-0.68
pH	0.10	-0.20	1.00	0.31
DO	0.92	-0.68	0.31	1.00

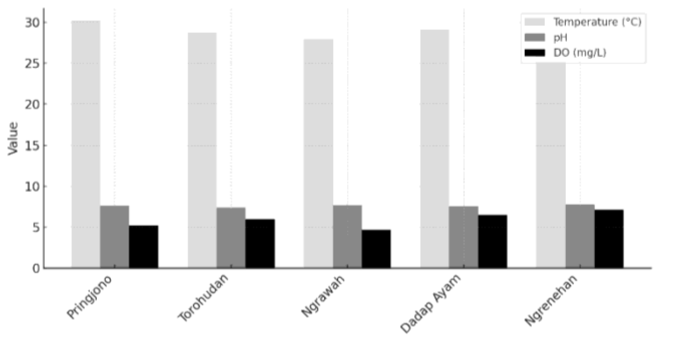

Figure 5. Variation in temperature, pH, and dissolved oxygen (DO) across 5 karstic beaches in Gunungkidul, Indonesia

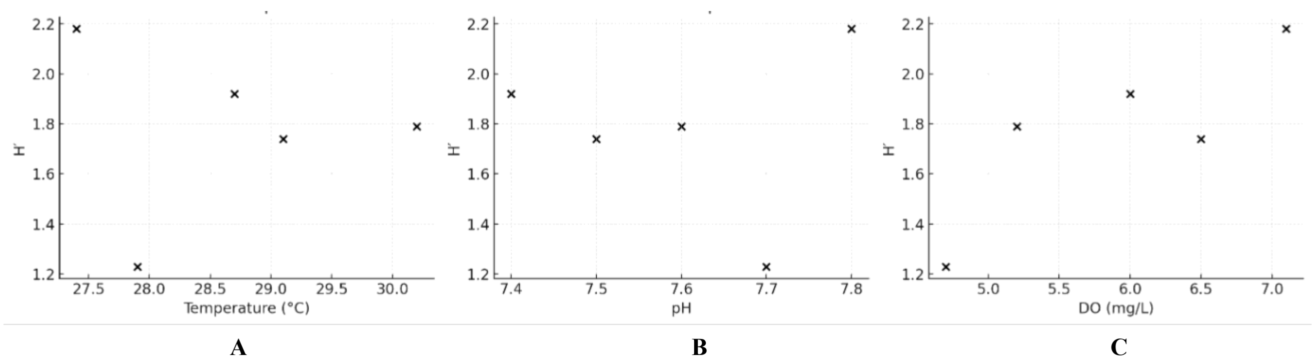

Figure 6. Scatterplots showing the relationship between Shannon-Wiener index (H′) and A. Temperature, B. pH, and C. Dissolved oxygen across five beach sites, Gunungkidul, Indonesia

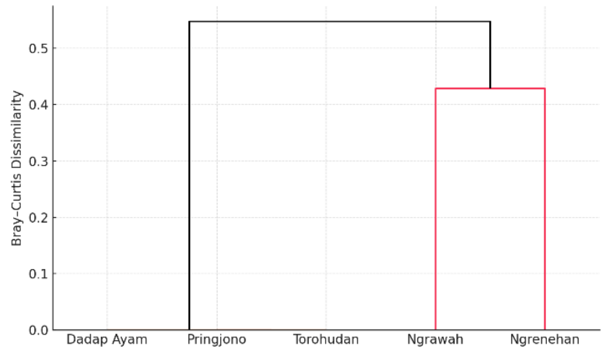

Figure 7. Cluster dendrogram showing similarity in crustacean species composition among five karstic beach sites based on Bray-Curtis similarity index

In contrast, Ngrenehan and Ngrawah formed a distinct cluster, characterized by the localized dominance of *Xantho cf. poressa* and *Scylla cf. serrata*. The limited species overlap with other sites suggests that these beaches harbor more specialized assemblages, shaped by unique environmental conditions. For instance, Ngrenehan's higher DO levels and more stable rock pools, along with Ngrawah's isolated and enclosed habitats, may support species less tolerant of fluctuating or disturbed conditions.

The spatial structuring revealed by the dendrogram highlights the ecological heterogeneity of karstic intertidal systems, even within a confined geographic area. These findings emphasize that each site contributes uniquely to the regional species pool, reinforcing the importance of site-specific conservation approaches that account for localized ecological dynamics and habitat variability.

Discussion

Species diversity and site-level patterns

The study revealed a moderate level of crustacean diversity across the five karstic beach sites, with Ngrenehan exhibiting the highest Shannon-Wiener index (H′=2.18) and Ngrawah the lowest (H′=1.23). This spatial variation highlights the influence of localized habitat conditions in shaping species assemblages. Beaches characterized by greater microhabitat complexity—including shaded crevices, tidal pools, and heterogeneous substrates, as seen at Ngrenehan and Dadap Ayam—tended to support higher species richness and evenness. In contrast, simpler and more physically exposed shores, such as Ngrawah, were associated with reduced diversity. This pattern aligns with previous findings in intertidal zones, where structural heterogeneity is known to enhance niche availability and reduce interspecific competition (Bertness 1999; Geng et al. 2020).

Among the recorded species, *Coenobita scaevola* was the most abundant and widely distributed, occurring at all sites and accounting for over 40% of total individuals. Its ecological success likely reflects its broad environmental tolerance and semi-terrestrial adaptations, which enable it to occupy both sandy and rocky habitats under varying intertidal conditions (Hazlett 1981; Emery et al. 2022). In contrast, taxa such as *Xantho cf. poressa*, *Scylla cf. serrata*, and *Grapsus albolineatus* exhibited more restricted distributions, generally confined to one or two sites. For instance, *X. cf. poressa* was found almost exclusively at Ngrenehan, likely due to its preference for shaded rock pools and moderate hydrodynamic conditions. This habitat specificity is consistent with previous observations of xanthid crabs in Indo-Pacific and Mediterranean rocky shores (Ng et al. 2008).

Notably, species richness (S) and total abundance (N) did not display a linear relationship across sites. Ngrawah, for example, harbored a moderate number of individuals (N=24) but only four species, suggesting the presence of ecological filters or the seasonal absence of less dominant taxa. Conversely, Ngrenehan supported both high richness (S=8) and abundance (N=98), reinforcing its role as a relatively stable habitat. Additionally, the updated data for Dadap Ayam revealed six species with relatively balanced abundances, reflecting a more equitable community structure than initially assumed. These findings emphasize the importance of microhabitat heterogeneity and abiotic moderation—such as oxygen availability and substrate diversity—in sustaining intertidal biodiversity in fragmented karst systems (Semprucci et al. 2019; Ord et al. 2024).

Environmental drivers of crustacean assemblages

Among the environmental variables measured, dissolved oxygen (DO) showed the strongest and most significant positive correlation with the Shannon-Wiener diversity index ($r=0.92$, $p<0.05$), indicating its critical role in structuring crustacean communities in karstic intertidal zones. High DO levels, such as those observed at Dadap Ayam and Ngrenehan, support aerobic metabolism and enhance survival and foraging activity, particularly for taxa sensitive to hypoxic conditions (Horn et al. 2021). In contrast, lower DO levels at Ngrawah likely restricted the number of viable species, contributing to the observed lower diversity.

Temperature exhibited a weak negative correlation with diversity ($r=-0.46$), suggesting that elevated surface temperatures, such as the 30.2°C recorded at Pringjono, may impose thermal stress on certain crustacean taxa. Prolonged exposure to high intertidal temperatures can limit species presence by affecting osmoregulation, molting cycles, or behavioral thermoregulation strategies (Stillman and Somero 2000; Rahmadhani and Martuti 2023). However, the relatively narrow temperature range observed in this study (27.4-30.2°C) may not have been extreme enough to impact the assemblage structure drastically.

The effect of pH was minimal ($r=0.10$), likely due to the narrow and near-neutral range (7.4-7.8) measured across sites. While ocean acidification is known to influence calcification and larval development in marine crustaceans (Kurihara 2008), the relatively stable pH conditions observed in these intertidal pools did not appear to be a major limiting factor for adult crustaceans during the sampling period. This aligns with findings from other tropical rocky shores where pH is less variable and rarely falls below critical thresholds (Geng et al. 2020).

Overall, the findings underscore DO as the most ecologically significant parameter influencing crustacean diversity in these karst beach ecosystems. Elevated DO enhances crustacean larval recruitment and aerobic performance, particularly in species with limited gill surface area (Marochi et al. 2021). Future studies should investigate diurnal DO fluctuations, sediment oxygen demand, and the role of primary producers such as macroalgae in modulating oxygen availability.

Ecological implications of community similarity

Cluster analysis based on Bray-Curtis similarity revealed two distinct groups of beach sites, reflecting differences in crustacean community composition likely shaped by microhabitat conditions. The grouping of Pringjono, Torohudan, and Dadap Ayam into a single cluster suggests these beaches share similar environmental and structural features—such as moderate wave exposure, patchy rocky substrates, and partial shading—that support comparable species assemblages. All three sites harbored core taxa like *Coenobita scaevola*, *Ocypode pallidula*, and *Parasesarma daviei*, which are known for their ecological generalism and remarkable ability to occupy both rocky and sandy microhabitats (Hazlett 1981; Ng et al. 2008).

In contrast, Ngrenehan and Ngrawah formed a separate cluster, characterized by more distinct and site-specific species such as *Xantho poressa* and *Scylla cf. serrata*. The exclusivity of these taxa to the Ngrenehan–Ngrawah cluster may result from specialized habitat features such as tidal pools, crevice-rich platforms, and relative isolation from anthropogenic disturbance. For instance, *X. poressa* is typically associated with shaded rocky substrates and may be sensitive to desiccation, restricting its occurrence to sites with stable microclimates (Simanullang et al. 2024). Similarly, *S. cf. serrata* requires semi-enclosed saline water pockets for foraging and refuge, which were more prevalent at Ngrawah.

This spatial structuring supports the hypothesis that crustacean assemblages in karst coastal systems are highly influenced by microhabitat heterogeneity rather than broad-scale geographic proximity. The results align with studies in other tropical coastal systems, where even small variations in substrate type, moisture retention, and tidal inundation can produce marked community differences (Bertness 1999; Ord et al. 2024).

These findings have implications for conservation planning, emphasizing that each site contributes uniquely to the regional species pool. Conservation strategies should, therefore, consider protecting multiple representative microhabitats rather than assuming ecological redundancy across adjacent coastal locations.

Methodological considerations and limitations

This study provides a baseline understanding of crustacean diversity in karstic beach ecosystems; however, several methodological limitations should be acknowledged. Sampling was conducted over a short temporal window and did not account for seasonal or tidal fluctuations, which may affect species detectability and abundance, particularly for migratory or cryptic taxa. Identification was based solely on external morphology, and while most specimens could be assigned to species or genus level, certain taxa (e.g., *Scylla cf. serrata*, *Ozius cf. rugulosus*) could not be confirmed without molecular or morphometric verification. In addition, abiotic parameters were measured only once per site, limiting the ability to capture diel or weather-related variability. Future research should include repeated sampling across multiple seasons and incorporate genetic tools to improve taxonomic resolution and ecological inference.

Implications for conservation and future research

The findings underscore the ecological importance of karstic beach ecosystems as reservoirs of intertidal crustacean biodiversity, encompassing both generalist species and habitat specialists. Ubiquitous taxa such as *Coenobita scaevola* contribute to habitat connectivity and ecological resilience, while more localized species like *Xantho poressa* and *Scylla cf. serrata* highlight the critical role of specific microhabitat features—such as crevices, shaded pools, and dissolved oxygen-rich substrates—in sustaining unique assemblages. The presence of diverse and spatially structured communities, even in narrow coastal zones, affirms the conservation value of tropical karst landscapes.

Effective management should prioritize the protection of microhabitat diversity across multiple beach sites rather than emphasizing single-site conservation. Strategies may include restricting unsustainable tourism development, controlling coastal pollution, and preserving natural hydrodynamics that promote substrate complexity and oxygenation. Given the patchy nature of karstic shorelines, site-specific approaches tailored to local environmental and biological conditions are essential. In this context, community-based initiatives involving local stakeholders—such as fishers, guides, and eco-tourism operators—can enhance stewardship and align conservation goals with sustainable use (Semprucci et al. 2019; Balata and Williams 2020; Evans et al. 2023).

Future research should incorporate temporal replication to account for seasonal and tidal variability in crustacean assemblages, including larval recruitment and reproductive timing. The integration of molecular tools, such as DNA barcoding, alongside stable isotope analysis and spatial modeling, will enable more accurate assessments of species identity, trophic relationships, and habitat use. These approaches are especially crucial in the face of accelerating anthropogenic pressures and climate change, which threaten the persistence of small-scale biodiversity hotspots in tropical coastal ecosystems.

In conclusion, this study documents the diversity and ecological patterns of intertidal crustaceans across five karstic beach sites in Gunungkidul, Indonesia. A total of 18 species were identified, with community structure varying notably between sites. Ngrenehan Beach showed the highest diversity and richness, while *Coenobita scaevola* emerged as the most widespread and dominant species. Dissolved oxygen was positively correlated with species diversity, underscoring its importance as a key environmental driver. Cluster analysis revealed two distinct site groups, highlighting the role of habitat heterogeneity in shaping assemblages. These findings emphasize the conservation value of karst coastal systems and the need for habitat-specific management strategies. Future research should incorporate seasonal monitoring, broader taxonomic resolution, and integrate local ecological knowledge for more effective biodiversity assessment and protection.

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Plastic waste characteristics and community responses in mangrove-influenced coastal villages of Kampung Laut, Cilacap, Indonesia

ANGELA REGINA ASTUTI[1], DINDA SYAFIRA PUTRI[1], VIDDA ARLYSIA[1], YOUHANA ELI SANTIKA[1], FAUZIANA ERLIS SAFITRI[1], AHMAD DWI SETYAWAN[1,2,♥]

[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia. Tel./fax.: +62-271-663375, ♥email: volatileoils@gmail.com

[2]Biodiversity Research Group, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

Manuscript received: 17 December 2024. Revision accepted: 6 April 2025.

Abstract. *Astuti AR, Putri DS, Arlysia V, Santika YE, Safitri FE, Setyawan AD. 2025. Plastic waste characteristics and community responses in mangrove-influenced coastal villages of Kampung Laut, Cilacap, Indonesia. Indo Pac J Ocean Life 9: 36-45.* Plastic pollution presents a significant threat to coastal and mangrove ecosystems, particularly in low-income and infrastructure-deficient regions of Southeast Asia. This study investigates the composition of plastic waste and the perceptions and behaviors of local communities in three mangrove-influenced villages of Kampung Laut Sub-district, Cilacap, Indonesia. Field surveys conducted in 33 sampling plots revealed that plastic waste was predominantly composed of single-use items, especially polypropylene (PP), low-density polyethylene (LDPE), and polyethylene terephthalate (PET), reflecting both domestic consumption and livelihood-related activities such as fisheries and aquaculture. A structured questionnaire grounded in the Knowledge-Attitude-Practice (KAP) framework was administered to 91 respondents. Statistical analyses, including Principal Component Analysis, Pearson correlation, and Partial Least Squares Structural Equation Modeling (PLS-SEM), were employed to explore the relationships among cognitive and behavioral variables. The results indicated that knowledge significantly influenced attitudes, which were positively associated with pro-environmental behavior; however, knowledge alone did not directly predict action. Sociodemographic constraints—particularly low education and income levels—further limited behavioral change despite moderate awareness. Comparisons with regional and global studies suggest that such gaps are common in coastal communities. These findings underscore the need for integrated waste governance strategies that combine education, infrastructure, and locally adapted regulations, alongside stronger integration between plastic waste management and mangrove conservation efforts.

Keywords: Coastal village, KAP model, mangrove ecosystem, plastic pollution, waste behavior

INTRODUCTION

Plastic pollution has emerged as a critical environmental challenge, particularly in coastal and estuarine ecosystems where land-based activities intersect with marine processes (Eriksen et al. 2014; Jambeck et al. 2015; Suyadi and Manullang 2020). The proliferation of single-use plastics and inadequate waste management infrastructure has led to significant accumulations of plastic debris in rivers, mangroves, and coastal zones (Evode et al. 2021). In Southeast Asia, which hosts some of the most productive mangrove ecosystems, plastic contamination threatens biodiversity, fisheries, and community livelihoods (Thao et al. 2023). As plastic waste degrades, it fragments into microplastics that can enter food chains and pose health risks to both wildlife and humans (Abreo et al. 2020).

Mangrove ecosystems are particularly vulnerable due to their geomorphology and hydrodynamics, which enable them to trap and retain floating debris (Martin et al. 2019). These forests provide vital ecological services such as shoreline protection, carbon sequestration, and nursery grounds for marine life (Hilmi et al. 2021; Jennerjahn et al. 2022; Garmaeepour et al. 2025). However, the accumulation of plastic waste can disrupt these functions by smothering pneumatophores, altering sediment dynamics, and introducing toxic compounds into the food web (Jayapala et al. 2024). The situation is exacerbated in mangrove-adjacent communities with limited access to waste collection services and strong dependence on natural resources (Akram et al. 2023).

Indonesia is among the largest contributors to marine plastic pollution, with over 620,000 tons estimated to enter the ocean annually (Lebreton et al. 2017). This crisis reflects structural issues in waste governance, public awareness, and economic capacity. Recent studies have highlighted the importance of integrating local knowledge and behavior into waste reduction strategies, especially in rural and semi-urban settings (Kurniawan et al. 2020; Shakuto et al. 2024). In this context, understanding how communities perceive and manage plastic waste is essential for developing context-sensitive interventions that are ecologically effective and socially accepted.

One widely adopted framework for assessing public environmental engagement is the Knowledge-Attitude-Practice (KAP) model. This approach has been used to explore public behavior in various domains, including health, sanitation, and environmental protection (Tejada and Cauilan 2019). KAP studies help identify gaps between awareness and action, thereby guiding policy and education initiatives. In the context of plastic waste, KAP assessments have revealed that even where awareness is high, behavior change may lag due to cultural, economic, or infrastructural constraints (Nasir et al. 2023).

Kampung Laut Sub-district in Cilacap, Central Java, presents a unique case for studying plastic pollution in a mangrove-dominated setting. The area is composed of small fishing villages located within the Segara Anakan Lagoon system, a biodiverse estuary characterized by tidal creeks, fishponds, and dense mangroves (Jennerjahn et al. 2022). Due to its geographical isolation, limited waste management services, and high dependence on fisheries, Kampung Laut faces multiple environmental and socio-economic pressures. Informal disposal of plastic waste in rivers, ponds, and mangrove areas has become a visible and chronic issue, affecting both environmental quality and local well-being (Hilmi et al. 2021; Garmaeepour et al. 2025).

Previous research in similar settings has emphasized the need for spatially explicit assessments of plastic distribution and community-level diagnostics of waste behavior (Abreo et al. 2020). However, studies specifically focused on Indonesia's rural mangrove villages remain limited, particularly in terms of integrating quantitative waste data with socio-cognitive models like KAP. This gap hampers efforts to design holistic interventions that align environmental goals with local realities. Understanding the relationship between knowledge, attitudes, and behavior in these communities is key to promoting responsible waste practices and fostering resilience in coastal social-ecological systems.

This study aims to characterize the composition of plastic waste and examine community perceptions and practices related to plastic management in three villages of Kampung Laut Sub-district. Specifically, it (i) quantifies the types and sources of plastic debris across mangrove-influenced habitats, (ii) assesses the levels of knowledge, attitudes, and practices regarding plastic waste among residents, and (iii) explores the interrelationships between KAP components using multivariate statistical models. The findings are intended to inform evidence-based interventions that support sustainable waste governance in vulnerable coastal communities.

MATERIALS AND METHODS

Study area

This study was conducted in Kampung Laut Sub-district, located within the Segara Anakan Lagoon system in Cilacap District, Central Java, Indonesia. The area is characterized by extensive mangrove forests, tidal rivers, and brackish aquaculture ponds. Administratively, Kampung Laut comprises four main villages, of which three—Ujungalang, Klaces, and Ujunggagak—were selected as the study sites due to their high dependency on fisheries and visible accumulation of plastic waste along coastlines and village peripheries.

The region is geographically isolated, accessible mainly by boat, and lacks comprehensive municipal waste services. It is surrounded by mangrove belts that function as natural barriers and nurseries for aquatic species (Jennerjahn et al. 2022). However, these same mangrove areas are also prone to entrap plastic waste due to tidal movement and human dumping behavior, as documented during the field observations.

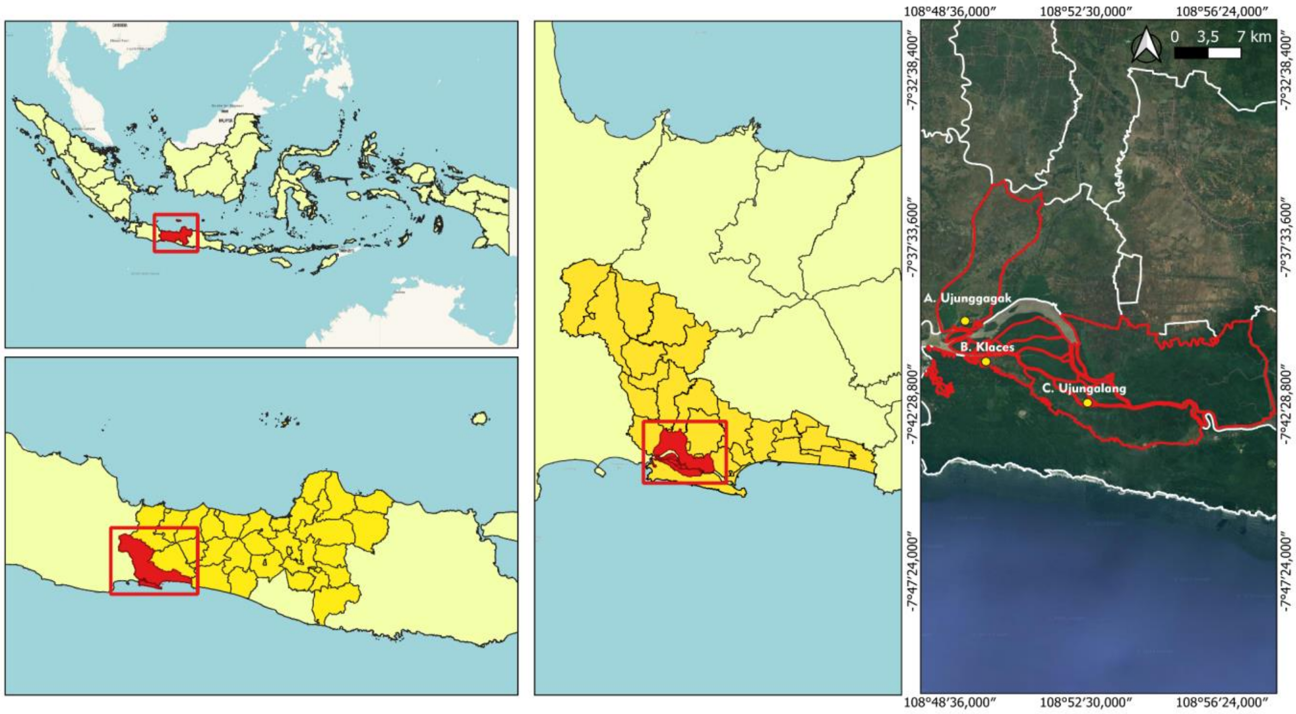

Figure 1. Study site of Plastic waste identification sampling locations and community perceptions in Kampung Laut Sub-district, Cilacap District, Central Java, Indonesia. A. Ujunggagak, B. Klaces, and C. Ujungalang

Small-scale fisheries, brackish pond aquaculture, and informal fish processing dominate the livelihoods of the local population. The area's limited road infrastructure and remote location pose additional challenges to effective waste management and education outreach (Hilmi et al. 2021; Garmaeepour et al. 2025). The selection of the three villages was based on differences in population size, mangrove density, and exposure to plastic accumulation, allowing for comparative analysis across spatial and socio-economic gradients.

Research procedures

Field sampling of plastic waste

Field sampling was conducted in 33 plots distributed equally across Ujungalang, Klaces, and Ujunggagak Villages. Each plot measured 10×10 meters and was selected to represent typical land-use settings within the coastal village environment, including residential yards, riverbanks, fishpond margins, and mangrove fringes. Plastic debris within each plot was manually collected, sorted, and classified in situ.

Plastic items were categorized based on polymer type–such as polypropylene (PP), low-density polyethylene (LDPE), polyethylene terephthalate (PET), and polyvinyl chloride (PVC)—as well as by physical form, including bottles, wrappers, sachets, and ropes. This classification procedure followed standardized field protocols adapted from Thao et al. (2023) and UNEP guidelines. All items were counted individually (pieces) to estimate the abundance of each plastic type.

Photographic documentation was taken at each sampling location to capture contextual information regarding site conditions, land use, and the spatial arrangement of debris. The overall aim of this procedure was to represent actual conditions of unmanaged plastic accumulation in mangrove-affected environments, including both surface and partially buried plastic items. Fieldwork was scheduled during low tide periods to ensure full access to intertidal zones and increase sampling efficiency.

Household survey and questionnaire design

In addition to physical waste sampling, a structured household survey was administered to 91 respondents selected using stratified random sampling across the three villages. Inclusion criteria included permanent residency in the study area, a minimum age of 17, and a willingness to participate voluntarily.

The survey instrument consisted of four sections: (i) sociodemographic characteristics, (ii) knowledge of plastic waste and its impacts, (iii) attitudes toward waste management and the environment, and (iv) self-reported practices related to plastic disposal and reduction. The questionnaire was developed based on prior KAP studies in environmental research (Tejada and Cauilan 2019) and was pre-tested for clarity and local comprehension.

Responses were recorded using Likert scales for attitudinal and behavioral items and multiple-choice or open-ended formats for knowledge-based items. Enumerator training was conducted to ensure consistency in data collection across the three locations. The collected data were then coded, tabulated, and prepared for descriptive and inferential analysis using spreadsheet and statistical tools. No identifying information was collected, and ethical considerations were maintained throughout the survey process.

Data analysis

Descriptive statistical analysis

Descriptive statistics were used to summarize the composition, frequency, and spatial distribution of plastic waste items collected from field plots. Each plastic item was classified by polymer type and physical form, and the percentage contribution of each category was calculated per village. Graphical tools such as bar charts and pie charts were used during the analysis stage to facilitate comparison of dominant plastic waste types across different locations.

The sociodemographic characteristics of the respondents—including age, gender, education, income, and occupation—were tabulated to reveal patterns relevant to plastic waste behavior. KAP questionnaire responses were transformed into ordinal or interval-scale data and assigned numerical values where applicable, enabling subsequent statistical analysis.

Principal Component Analysis (PCA)

To reduce data dimensionality and identify latent variables within the KAP questionnaire, Principal Component Analysis (PCA) was performed using SPSS version 26. Items with low factor loadings (<0.5) or Measures of Sampling Adequacy (MSA) below 0.5 were excluded from further analysis. The retained principal components were used to construct indices representing knowledge, attitude, and behavior dimensions.

Structural Equation Modeling (SEM)

To examine causal relationships among KAP variables, Partial Least Squares Structural Equation Modeling (PLS-SEM) was applied using SmartPLS 4. This variance-based SEM approach is suitable for small to moderate sample sizes and allows the estimation of both direct and indirect effects (Schreiber 2008). Latent constructs (knowledge, attitude, behavior) were modeled from PCA outputs, and path coefficients, factor loadings, and model fit indices were assessed. Model reliability and significance were tested using bootstrapping with 5,000 iterations. The resulting structural model was interpreted to assess how knowledge influences attitudes and how both contribute to behavioral patterns related to plastic waste.

Pearson correlation analysis

In addition to SEM, Pearson correlation analysis was performed to explore bivariate associations among the three KAP domains. Correlation coefficients (r) and significance levels (p-values) were calculated to validate the direction and strength of relationships independently of the SEM model. These correlation results provided complementary insights into the consistency between knowledge, attitude, and practice variables among respondents.

RESULTS AND DISCUSSION

Characteristics of respondents

The survey involved 91 respondents drawn from Ujungalang, Klaces, and Ujunggagak Villages. Their demographic characteristics form a foundational context for interpreting community-level responses to plastic waste issues. Women made up a slightly larger proportion of the sample (57.14%) than men (42.86%), indicating their prominent role in domestic and environmental responsibilities.

In terms of age distribution, the majority of respondents (65.93%) were over 40, while 26.37% were between 25 and 40, and only 7.69% were aged 17 to 24. This skew toward older age groups may reflect entrenched behavioral norms and experiential knowledge related to local environmental changes.

Educational attainment was generally low, with 60.44% of respondents having completed elementary school and 9.89% never attending formal education. Only 17.58% and 12.09% reached junior and senior high school, respectively. Limited educational exposure may constrain understanding of waste management systems and reduce access to sustainability-related information.

Respondents' income levels were concentrated in the lower economic bracket. Nearly half (46.15%) earned between IDR 1,000,000 and 2,000,000 per month, while 21.98% earned below IDR 1,000,000. Only 10.99% reported earnings above IDR 3,000,000. Most respondents (52.75%) were engaged in fisheries-related occupations, such as fishers, fishpond workers, or seafood processors, while the rest worked as traders, laborers, or homemakers. This strong dependence on marine-based livelihoods suggests heightened vulnerability to environmental degradation, including plastic pollution in mangrove zones.

Overall, these patterns indicate structural challenges that may hinder the adoption of formal waste management practices, including financial limitations, informational gaps, and labor priorities centered on subsistence activities. Therefore, intervention strategies should be tailored to the community's socio-economic realities and capacity for behavioral change. Detailed respondent characteristics are presented in Table 1.

Composition and distribution of plastic waste

Plastic debris collected from 33 field plots across Ujunggagak, Klaces, and Ujungalang Villages exhibited substantial variation in both material composition and spatial distribution. The most frequently encountered plastic types were polypropylene (PP), low-density polyethylene (LDPE), and polyethylene terephthalate (PET), which collectively represented the majority of waste items in all surveyed locations. These materials were commonly found in the form of food wrappers, plastic bags, sachets, ropes, and beverage bottles, typically associated with household activities and small-scale fisheries.

As illustrated in Figure 2, PP emerged as the most dominant plastic type across all villages, followed by LDPE and PET, underscoring the prevalence of single-use packaging materials. Quantitatively, Table 3 shows that PP accounted for 59.2% of plastic items in Ujunggagak, 56.0% in Klaces, and 51.7% in Ujungalang. LDPE contributed between 19.4% and 24.9%, while PET ranged from 7.0% to 10.0%. These site-specific proportions are further visualized in Figure 3, which compares the relative percentage composition of key plastic types across the three villages. The observed patterns are closely linked to local consumption behavior and livelihood strategies, particularly those related to aquaculture, fish processing, and coastal household provisioning, which directly affect the type and quantity of plastic waste generated.

In Ujunggagak, plastic debris was most frequently found along riverbanks and residential perimeters, suggesting direct household disposal and tidal deposition. In Klaces, field notes documented rope-like plastics and packaging waste entangled in mangrove roots and trapped along dikes and pond edges–possibly reflecting aquaculture and boat-related activities. In Ujungalang, the high presence of LDPE was likely linked to fish processing and packaging waste. Fragments of PVC pipes and plastic twine were also recorded, indicating diverse and unmanaged plastic sources.

The spatial differences in plastic waste composition among villages reflect varied livelihood strategies, levels of market integration, and proximity to mangrove zones. These findings underscore the need for site-specific waste reduction strategies that consider local plastic use patterns and community infrastructure.

Table 1. Sociodemographic characteristics of respondents in the study area (n=91)

Category	Subcategory	Frequency (n)	(%)
Age	17-25 years	7	7.69
	25-40 years	24	26.37
	>40 years	60	65.93
Gender	Male	39	42.86
	Female	52	57.14
Education	No formal education	9	9.89
	Elementary school	55	60.44
	Junior high school	16	17.58
	Senior high school	11	12.09
Income (IDR)	No income	2	2.20
	<1,000,000	20	21.98
	1,000,000-2,000,000	42	46.15
	2,000,000-3,000,000	19	20.88
	3,000,000-4,000,000	6	6.59
	>4,000,000	2	2.20
Occupation	Fisherman and boat crew	43	47.25
	Aquaculture farmer	18	19.78
	Laborer (non-fisheries)	11	12.09
	Housewife	10	10.99
	Other (trader, services)	9	9.89

Table 3. Composition of plastic waste by village (in pieces and %)

Plastic type	Ujunggagak (pcs)	(%)	Klaces (pcs)	(%)	Ujungalang (pcs)	(%)	All villages (pcs)	(%)
PP	1211	59.2	752	56.0	1016	51.7	2979	56.1
LDPE	491	24.0	261	19.4	489	24.9	1241	23.4
PET	143	7.0	134	10.0	177	9.0	454	8.6
HDPE	103	5.0	117	8.7	151	7.7	371	7.0
PS	88	4.3	67	5.0	118	6.0	273	5.1
PVC	10	0.5	12	0.9	14	0.7	36	0.7
Total	2046	100.0	1343	100.0	1965	100.0	5354	100.0

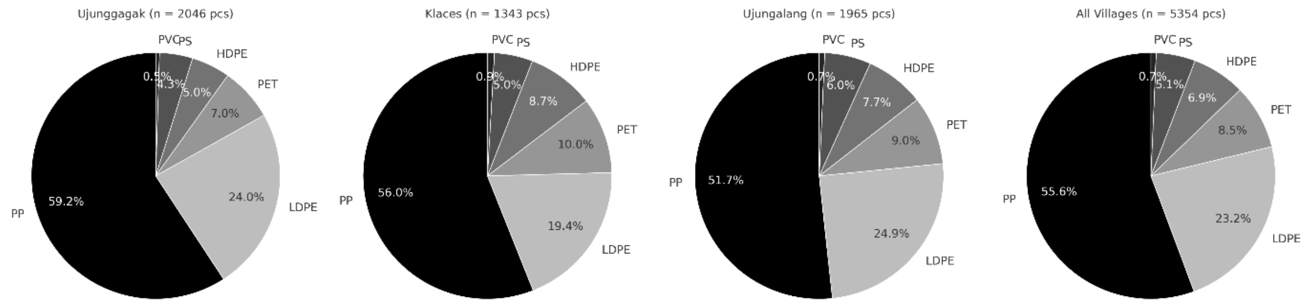

Figure 2. Composition of plastic waste by village and overall in Kampung Laut, Cilacap, Indonesia

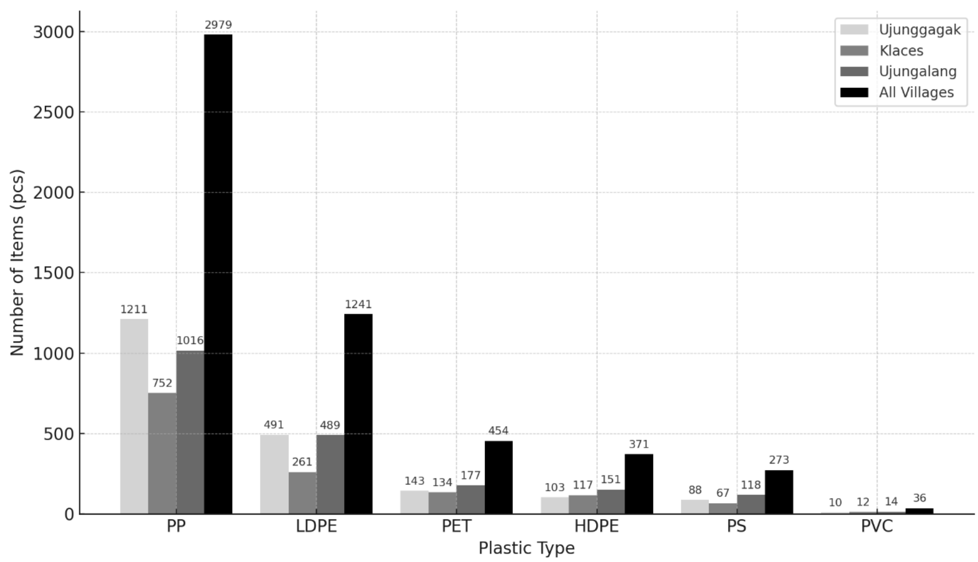

Figure 3. Composition of plastic waste by village and overall (pcs)

Community Knowledge, Attitudes, and Practices (KAP)

Analysis of the KAP questionnaire revealed varying levels of understanding and behavioral responses to plastic waste across the study sites. In practice, the dominant household disposal method was open burning (45.1%), followed by dumping into rivers or the sea (17.3%) and discarding waste behind houses (13.0%). Burying plastic waste and using managed collection services were less frequent, while only 2.6% of respondents reported engaging in recycling or sorting activities (Table 4). These results illustrate an urgent need for effective household-level interventions to reduce plastic leakage into the environment.

Visual representation of these disposal methods confirms the prevalence of unsustainable practices, with open burning standing out across all villages (Figure 4). The reliance on informal or harmful disposal reflects infrastructural gaps and weak enforcement mechanisms.

Despite these behavioral trends, knowledge about the environmental impacts of plastic was generally moderate. A majority of respondents (76.9%) recognized that plastic pollution harms rivers and aquatic life, and more than 60% were aware that plastic materials decompose very slowly. However, key misconceptions remained—only 38.5% could correctly identify recyclable material symbols, and 29.7%

believed that burning plastic posed no serious risk (Figure 5).

Attitudes toward waste management were broadly positive. Around 83.5% of respondents considered plastic pollution a serious local issue, and 79.1% agreed that community participation is essential in solving the problem. Furthermore, 57.1% felt a personal responsibility to reduce plastic consumption, though others perceived that institutional actors such as village leaders or the government should lead waste mitigation efforts (Figure 6).

This attitude—behavior gap was further evidenced by civic engagement patterns: although 72.5% of respondents expressed concern about plastic pollution, fewer than 20% had ever joined cleanup activities or attended environmental outreach programs. These discrepancies reveal structural constraints, including limited waste management infrastructure, low household income, and minimal exposure to environmental education.

The patterns identified through surveys were supported by field observations, which revealed substantial plastic accumulation near homes, waterways, and mangrove zones. Frequently observed forms included scattered packaging, entangled ropes, and burnt residue, all indicating both passive neglect and active disposal in ecologically sensitive areas (Figure 7). These findings underscore the importance of integrated and community-responsive strategies for plastic waste reduction—ones that go beyond awareness to address material and institutional limitations. Field observations supported these self-reported practices, documenting widespread plastic accumulation in mangrove zones, waterways, and domestic surroundings (Figure 8).

Table 4. Reported household plastic waste disposal methods (n=115)

Disposal method	Frequency (n)	Percentage (%)
Open burning	52	45.1
Dumped in river or sea	20	17.3
Thrown behind the house	15	13.0
Buried in the ground	12	10.4
Managed waste collection	10	8.6
Recycled or sorted	3	2.6
Total	115	100.0

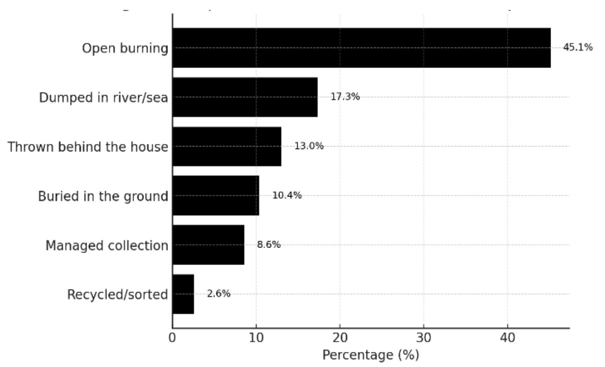

Figure 4. Reported household plastic waste disposal practices

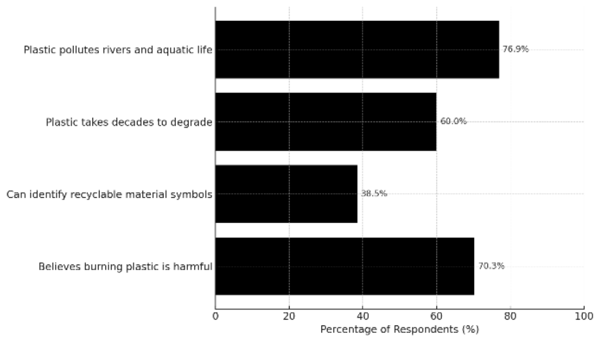

Figure 5. Knowledge of plastic waste impacts among respondents

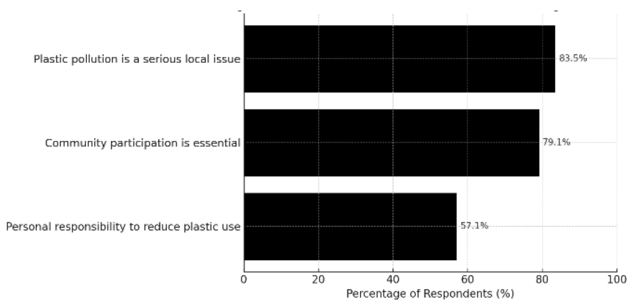

Figure 6. Attitudes toward plastic waste management (%)

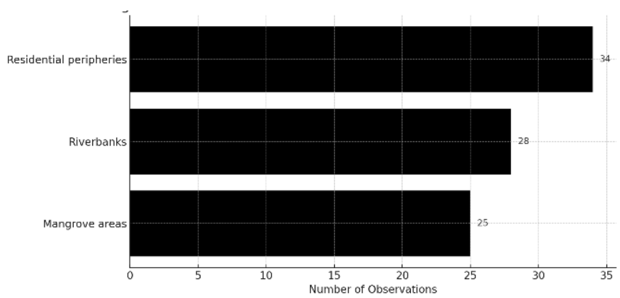

Figure 7. Field observation of plastic waste accumulation near settlements

Figure 8. Field observation. Photos of plastic accumulation in Kampung Laut, Cilacap. A. Dumped along mangrove-lined coastlines, B. Thrown into tidal waterways, C. Discarded and burned in residential yards, highlighting the need for improved waste governance

Structural relationships among KAP variables

Structural Equation Modeling (SEM) was employed to examine the causal relationships among the three main KAP components: knowledge, attitude, and practice. The model fit indicators confirmed that the structural model was statistically valid, with satisfactory factor loadings and path coefficients. The analysis showed that knowledge significantly influenced attitude (path coefficient = 0.62, p<0.01), suggesting that a greater understanding of plastic-related issues leads to more favorable environmental attitudes. Attitude, in turn, exhibited a strong positive effect on behavior (path coefficient = 0.55, p<0.01), indicating that concern for environmental impacts encourages more responsible plastic disposal and reduction practices. Interestingly, the direct effect of knowledge on behavior was weaker and only marginally significant (path coefficient = 0.21, p=0.07), suggesting that awareness alone may not be sufficient to drive behavioral change unless accompanied by supportive attitudes (Figure 9). These findings support the idea that behavioral interventions should focus not only on information delivery but also on motivational and value-based approaches.

These results are consistent with prior environmental KAP studies, which found that attitudes often serve as mediators between knowledge and behavior (Nasir et al. 2023). The implications are clear: improving knowledge is necessary but not enough. Efforts to reduce plastic waste must also foster pro-environmental values and provide enabling conditions that make sustainable behavior feasible in everyday life.

Correlation patterns among KAP components

To complement the structural modeling results, Pearson correlation coefficients were calculated to explore linear relationships between knowledge, attitude, and practice (KAP) regarding plastic waste. These correlations reinforce the causal pathways identified in the Structural Equation Model. A strong and statistically significant correlation was observed between knowledge and attitude (r=0.63, p<0.01), indicating that individuals with better understanding of environmental impacts tend to exhibit more supportive attitudes. A moderate positive correlation was also found between attitude and behavior (r=0.57, p<0.01), suggesting that internalized environmental concern is associated with more responsible plastic management. In contrast, the correlation between knowledge and behavior was weaker and only marginally significant (r=0.29, p=0.06) (Figure 10), mirroring the structural model's implication that knowledge alone is insufficient to drive behavioral change without attitudinal mediation.

These results highlight the importance of integrating cognitive, affective, and contextual factors in designing plastic waste education and intervention programs.

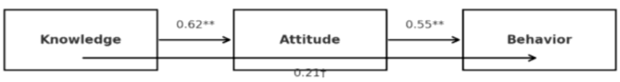

Figure 9. Structural Equation Model (SEM) of the relationships among knowledge, attitude, and behavior

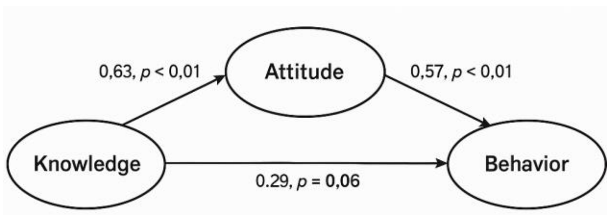

Figure 10. Pearson correlation matrix among knowledge, attitude, and behavior variables

Discussion

Sociodemographic influences on plastic waste behavior

The sociodemographic characteristics of the respondents–particularly education level, income, and occupation–emerged as critical factors shaping community engagement with plastic waste. A large proportion of respondents had only completed elementary school or lacked formal education entirely, which may limit access to environmental information and hinder comprehension of plastic pollution risks. Previous studies have shown that low educational attainment is associated with inadequate waste disposal practices and poor risk perception, especially in rural and coastal contexts (Nasir et al. 2023).

Income constraints further exacerbate the challenge. Many residents in Kampung Laut subsist on modest earnings from small-scale fisheries and informal labor, with limited capacity to invest in alternative packaging, waste bins, or transport to centralized disposal facilities. Similar findings have been reported in Philippine and Vietnamese coastal areas, where economic hardship often leads to short-term disposal strategies such as open burning or dumping (Abreo et al. 2020; Thao et al. 2023). This suggests that even when residents are aware of the negative impacts of plastic, structural limitations prevent the adoption of better practices.

Gender roles also appear to influence plastic waste behavior. The higher proportion of female respondents reflects their central role in managing household waste. Yet despite their involvement, women often face unequal access to formal environmental training or decision-making forums. This reinforces the need for inclusive education programs that engage women as key actors in sustainable waste governance (Shakuto et al. 2024).

Overall, these findings highlight the interplay between knowledge, material resources, and cultural expectations. Addressing plastic waste in mangrove communities, therefore, requires a nuanced approach that accounts for social heterogeneity, builds capacity, and removes structural barriers to behavior change.

Site-specific plastic waste composition and livelihood patterns

The composition and distribution of plastic waste across Ujunggagak, Klaces, and Ujungalang Villages reflect localized livelihood strategies and access to consumer goods. Polypropylene (PP), low-density polyethylene (LDPE), and polyethylene terephthalate (PET) were dominant in all sites, but the proportions varied depending on village activities. For example, the prevalence of LDPE and PVC in Ujungalang likely corresponds with its role as a fishing and trading hub, where plastic sheeting, packaging, and pipe fragments are commonly used in daily operations.

Klaces Village showed a relatively higher proportion of HDPE and multilayer plastics, which are associated with aquaculture infrastructure such as fertilizer sacks, fish feed bags, and rope. This aligns with field observations and supports the interpretation that plastic usage patterns are directly linked to the material demands of local livelihoods. In contrast, Ujunggagak exhibited more domestic-oriented waste, such as snack wrappers and sachets, suggesting greater dependency on household consumption rather than market-driven production.

These village-specific profiles mirror findings from other mangrove or estuarine communities in Southeast Asia. Studies in Thailand and the Philippines have similarly linked plastic debris composition to the nature of subsistence and economic activities in coastal villages (Jambeck et al. 2015; Abreo et al. 2020; Thao et al. 2023). The implication is that a one-size-fits-all waste intervention is unlikely to succeed; rather, waste management must be contextualized to local practices and material flows.

Moreover, the spatial concentration of plastic along mangrove fringes and tidal creeks points to both intentional dumping and tidal trapping. Mangrove forests act as natural filters for floating debris (Martin et al. 2019), but without proper intervention, they become long-term sinks of pollution that undermine their ecological function.

In sum, addressing plastic waste in Kampung Laut requires understanding how environmental degradation is rooted in place-specific interactions between material culture and ecological context. Tailoring solutions to these patterns is essential for improving both environmental quality and community livelihoods.

Knowledge–Attitude–Practice dynamics and behavior gaps

The KAP analysis revealed a structured yet incomplete pathway: while higher knowledge levels were significantly correlated with more favorable attitudes, this did not consistently translate into environmentally responsible behavior. Structural Equation Modeling (SEM) and Pearson correlation analysis both confirmed this pattern, showing a strong link between knowledge and attitude ($r=0.63$, $p<0.01$), and between attitude and behavior ($r=0.57$, $p<0.01$), but only a weak and marginally significant correlation between knowledge and behavior ($r=0.29$, $p=0.06$). This indicates that attitudes function as a key mediating variable between cognitive awareness and concrete action–a finding that echoes trends in other coastal and rural communities (Nasir et al. 2023).

Despite widespread recognition of the dangers posed by plastic pollution—such as threats to aquatic life, food safety, and community health—field data and observations (Figure 8) revealed persistent reliance on unsustainable practices like open burning, river dumping, and unmanaged disposal behind homes. Respondents frequently cited barriers such as limited access to formal waste services, lack of viable alternatives, and competing daily priorities as reasons for non-compliance. Similar structural constraints have been noted in Malaysian and Vietnamese coastal villages, where high environmental awareness does not guarantee behavioral change (Mazelan and Yusuff 2021; Thao et al. 2023).

These findings imply that educational interventions must extend beyond the mere dissemination of facts. Instead, fostering pro-environmental norms, strengthening personal responsibility, and creating enabling environments are crucial. The role of community role models and leadership is particularly salient: Klaces Village, for example, showed more active engagement in clean-ups and informal recycling, coinciding with the presence of a local waste group. Such grassroots initiatives can help bridge the attitude—behavior gap by generating peer influence and shared accountability.

Addressing the KAP dynamics thus requires an integrated, multisectoral strategy that improves knowledge access, nurtures positive environmental attitudes, and removes practical barriers through inclusive infrastructure, targeted incentives, and local regulation.

Comparison with regional and global studies

The patterns identified in Kampung Laut closely mirror broader trends observed in other mangrove-influenced coastal regions across Southeast Asia and beyond. Studies from the Philippines and Vietnam, for example, have reported similar profiles of plastic pollution dominated by low-value, single-use plastics such as polypropylene (PP) and low-density polyethylene (LDPE), largely originating from household consumption, small-scale fisheries, and aquaculture (Abreo et al. 2020; Thao et al. 2023). These polymers are lightweight, inexpensive, and widely used, making them pervasive in rural coastal economies.

At a global level, mangrove ecosystems have consistently been described as effective yet problematic "plastic traps" due to their complex root systems and tidal hydrodynamics (Martin et al. 2019). Research in Sri Lanka confirms that mangroves capture both macroplastics and microplastics, which accumulate in sediments and detrital layers, threatening benthic organisms and increasing the risk of trophic transfer and bioaccumulation (Jayapala et al. 2024). These findings underscore the ecological urgency of preventing plastic entry into mangrove systems rather than relying on their capacity for passive retention.

Community responses to plastic pollution, including the knowledge—behavior gap identified in Kampung Laut, are likewise a global phenomenon. Jambeck et al. (2015) noted that even when awareness is high, behavior change often stalls due to systemic constraints such as inadequate infrastructure, limited economic options, and weak regulatory enforcement. This study's Structural Equation Modeling (SEM) reinforces that while knowledge fosters positive environmental attitudes, actual behavioral transformation is hindered by structural and contextual barriers.

Consequently, the policy implications derived from Kampung Laut align with global best practices: effective plastic waste governance in coastal zones must integrate education, infrastructure development, and community participation. Tailoring these elements to local cultural and socio-economic contexts—through approaches such as incentive-based collection systems, eco-brick initiatives, or social enterprises–can promote sustained behavioral change and reduce plastic leakage into marine and estuarine systems (Kumar et al. 2021).

By situating the Kampung Laut findings within this broader discourse, the study contributes empirical support to the argument that successful plastic management in vulnerable ecosystems depends on context-sensitive, community-driven, and multi-level governance strategies.

Policy implications for mangrove-based communities

The findings from Kampung Laut highlight the urgent need for integrated, community-responsive strategies to manage plastic waste in mangrove-influenced coastal areas. The predominance of low-value, single-use plastics and the persistence of informal disposal methods suggest that interventions must move beyond awareness campaigns to confront the underlying socio-economic and infrastructural constraints that perpetuate pollution.

First, strengthening local waste infrastructure is essential, particularly in geographically isolated villages with limited or no access to municipal waste services. Low-cost, decentralized solutions—such as community-managed drop-off sites, boat-based collection systems, or floating bins tailored for tidal environments—can offer immediate relief. These efforts should be complemented by upstream interventions, including policies that encourage material substitution (e.g., biodegradable packaging) and plastic use reduction in fisheries and trade sectors.

Second, educational initiatives must shift focus from simple knowledge dissemination to fostering behavioral change. School-based programs, peer-led campaigns, and culturally grounded messages—such as those drawn from religious or traditional narratives—can be powerful drivers of normative shifts. Given their central roles in household management and intergenerational transmission of values, empowering women and youth as environmental change agents should be prioritized.

Third, institutional mechanisms must be adaptive and participatory. Locally enacted regulations (*Peraturan Desa*) on waste segregation and disposal can be made more effective through community monitoring and incentive-based compliance schemes. Pilot partnerships with NGOs or private-sector actors—such as waste banks, eco-brick producers, or plastic-for-goods exchanges—can stimulate circular economy models that align ecological goals with livelihood generation.

Importantly, mangrove ecosystems should not be treated merely as passive recipients of pollution, but as active components of coastal waste dynamics. In Kampung Laut, mangrove forests function both as physical traps for plastic debris and as ecological victims of chronic contamination. Accumulated plastics smother pneumatophores, inhibit seedling regeneration, and introduce toxic compounds into the substrate and water column—thereby compromising essential functions such as shoreline stabilization, carbon sequestration, and nursery provisioning for marine life (Martin et al. 2019; Jayapala et al. 2024). This dual role—as both buffer and casualty—demands that plastic waste removal and ongoing protection be explicitly integrated into mangrove conservation and restoration efforts.

Sustainable waste governance in mangrove-based communities thus requires a hybrid approach—one that blends technological innovation, behavioral transformation, and institutional support, grounded in local socio-ecological realities while aligned with broader regional and global frameworks. Such alignment is critical to maintaining the ecological resilience of coastal systems and safeguarding the livelihoods of communities who depend on mangrove services.

In conclusion, this study presents an integrated assessment of plastic waste and community perceptions in the mangrove-influenced villages of Kampung Laut, Cilacap.

The dominant waste types—polypropylene, polyethylene, and PET—mainly stem from household use and fishing activities. Despite relatively high environmental awareness, behavioral change is limited due to low education, limited income, and poor infrastructure. Structural Equation Modeling reveals that attitudes mediate the link between knowledge and behavior, echoing patterns seen in other Southeast Asian coastal areas. These results highlight the urgent need for context-specific interventions that combine improved infrastructure, behavioral education, and localized regulations. Strengthening social capital and utilizing existing community networks are vital to ensure long-term success. Furthermore, integrating plastic management with mangrove conservation efforts is crucial for protecting ecosystem services and building community resilience. The study offers practical guidance for policymakers to design inclusive, ecologically grounded strategies for plastic waste governance in vulnerable coastal regions.

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Review: Bioactive compounds and therapeutic potentials of coral reef organisms

RAHMA NUR SYAMSI[1], SYARIFAH HASNA ROSYIDA[1], TALITHA NASWA ALLYSA[1], WHENY HANIFAH[1], RINOA SALSABILA IZDIHAR[1], DARLINA MD. NAIM[2], AHMAD DWI SETYAWAN[1,3,♥]

[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia. Tel.: +62-271-669376, Fax.: +62-271-663375, ♥email: volatileoils@gmail.com
[2]School of Biological Sciences, Universiti Sains Malaysia. 11800 Penang, Malaysia
[3]Biodiversity Research Group, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

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Abstract. *Syamsi RN, Rosyida SH, Allysa TN, Hanifah W, Izdihar RS, Naim DM, Setyawan AD. 2025. Review: Bioactive compounds and therapeutic potentials of coral reef organisms. Indo Pac J Ocean Life 9: 46-63.* Coral reef ecosystems harbor an extraordinary diversity of marine organisms that are increasingly recognized as rich sources of bioactive compounds. This review examines the biodiversity, chemical composition, and pharmacological activities of coral reef organisms, with a particular focus on soft corals, macroalgae, sponges, and their associated microorganisms. Key classes of compounds—including terpenoids, alkaloids, steroids, and sulfated polysaccharides—have demonstrated potent antibacterial, antiviral, anti-inflammatory, anticancer, and immunomodulatory properties in both in vitro and in vivo studies. Beyond laboratory findings, this study highlights the ethnopharmacological significance of coral-derived organisms in traditional healing systems across Southeast Asian coastal communities. It also explores the continuity and erosion of these practices, and discusses their potential integration into modern complementary medicine frameworks. The final sections address critical challenges in coral-based drug discovery, such as taxonomic underrepresentation, unsustainable harvesting, and regulatory constraints. At the same time, the review identifies emerging opportunities facilitated by omics technologies, synthetic biology, and interdisciplinary collaboration. By synthesizing biomedical and cultural perspectives, this review underscores the immense therapeutic potential of coral reef biodiversity and calls for integrated conservation and research strategies that ensure both ecological integrity and equitable innovation.

Keywords: Complementary medicine, drug discovery, ethnopharmacology, pharmacological activity, traditional medicine

INTRODUCTION

Coral reef ecosystems represent one of the most biologically diverse environments on the planet, harboring a wide array of marine organisms with significant ecological, economic, and biomedical relevance. Among these organisms, corals and their associated biota including sponges, tunicates, algae, echinoderms, and mollusks have emerged as prolific producers of structurally unique bioactive compounds. These compounds exhibit diverse pharmacological activities, such as anticancer, antimicrobial, antiviral, anti-inflammatory, antioxidant, neuroprotective, and antidiabetic effects, thereby attracting increasing attention in the field of drug discovery and natural product research (Mayer et al. 2013; Chen et al. 2016; Blunt et al. 2018).

The harsh and competitive environment of coral reefs has driven the evolution of sophisticated chemical defense mechanisms. These mechanisms result in the production of secondary metabolites with high potency and novel molecular scaffolds that differ significantly from terrestrial analogs. Marine organisms—particularly soft corals, gorgonians, sponges, and reef-associated macroalgae—often generate compounds with greater lipophilicity, halogenation, and stereochemical complexity, enabling interaction with previously “undruggable” molecular targets (Ermolenko et al. 2020). Such characteristics make coral reef-derived metabolites promising candidates for pharmaceutical development, particularly in the context of multidrug resistance, emerging infectious diseases, and chronic inflammatory and metabolic disorders.

Recent years have witnessed a surge in studies exploring the chemical constituents and therapeutic potentials of reef organisms, bolstered by advances in metabolomics, dereplication strategies, and synthetic biology. Innovative technologies such as genome mining, microbial fermentation, and nanocarrier-based delivery systems have opened new avenues for isolating, producing, and formulating marine bioactives (Cooper et al. 2014; Karthikeyan et al. 2022). Moreover, omics-based approaches, including transcriptomics and metagenomics, have revealed the biosynthetic gene clusters responsible for many potent metabolites—some of which originate not from the macroorganisms themselves but from their symbiotic microbial consortia.

Despite these advances, the vast majority of coral reef biodiversity remains chemically uncharacterized, especially in the tropical Indo-Pacific, home to the Coral Triangle. This region, which includes Indonesia, the Philippines, and Papua New Guinea, is recognized as the global epicenter of marine biodiversity, hosting more than 500 species of reef-building corals and a complex web of symbiotic life forms (Putnam et al. 2017; Asaad et al. 2020). Indonesia alone harbors dozens of endemic soft coral genera such as *Sarcophyton*, *Lobophytum*, and *Sinularia*, many of which have already demonstrated pharmacologically significant activities in preliminary assays but remain underexplored in clinical contexts (Figure 1).

The urgency to study these organisms is further heightened by escalating threats to coral reef ecosystems. Anthropogenic pressures such as overfishing, eutrophication, habitat destruction, and unsustainable bioprospecting practices are rapidly degrading reef habitats, while climate change-induced stressors—including ocean acidification and thermal bleaching—pose existential risks. These pressures not only endanger the ecosystems themselves but also jeopardize the discovery of novel marine-based therapeutics (Fudjaja et al. 2020). Additionally, ethical and legal considerations—especially those outlined in the Convention on Biological Diversity and the Nagoya Protocol—emphasize the need for equitable benefit-sharing and the inclusion of local and indigenous knowledge holders in bioprospecting initiatives.

Coral reef organisms also hold an important place in the traditional medicine systems of many coastal communities across Southeast Asia. Ethnomedicinal knowledge, though often overlooked in mainstream pharmacology, provides valuable clues for identifying bioactive species and understanding the cultural significance of marine-derived therapies. In many cases, traditional uses of soft coral or sea cucumber extracts for inflammation, wound healing, or energy restoration have been substantiated by modern pharmacological studies (Pangestuti and Arifin 2017; Fristiohady et al. 2019). As such, integrating ethnopharmacology with modern drug discovery not only enhances efficiency but also fosters biocultural conservation and respect for local health traditions.

Given this background, this review aims to synthesize recent advances in the identification and pharmacological characterization of bioactive compounds derived from coral reef organisms. The review focuses on key chemical classes—including terpenoids, steroids, alkaloids, flavonoids, saponins, and prostaglandin-like compounds—and their respective therapeutic targets and structure-activity relationships. Furthermore, it highlights case studies from tropical Indo-Pacific regions, addresses the cultural and ethnopharmacological relevance of reef organisms, outlines regulatory and ethical considerations in marine bioprospecting, and discusses emerging technologies and strategies for sustainable utilization. By bridging biochemical, ecological, and socio-cultural perspectives, this review underscores the immense promise and urgent need for integrated approaches in coral reef-based drug discovery.

BIODIVERSITY AND CHEMICAL COMPOSITION OF CORAL REEFS

Overview of coral diversity

Coral reefs are composed of a wide variety of organisms, including hard corals, soft corals, sponges, algae, and other invertebrates that together form highly diverse and productive marine ecosystems (Putnam et al. 2017; Bell et al. 2022). Hard corals, also known as hermatypic corals, are responsible for building the calcium carbonate framework that defines reef structure. These include species from genera such as *Acropora*, *Porites*, and *Favia*, which contribute significantly to reef accretion and habitat complexity (Munasik et al. 2020; Putra et al. 2022). In contrast, soft corals—such as *Sinularia*, *Sarcophyton*, and *Lobophytum*—do not contribute to reef-building but play a vital ecological and chemical role through the production of bioactive metabolites (Changyun et al. 2008; dos Santos et al. 2023). These soft-bodied cnidarians often dominate benthic communities in mesophotic and current-exposed zones, where their secondary metabolites serve both defensive and allelopathic functions.

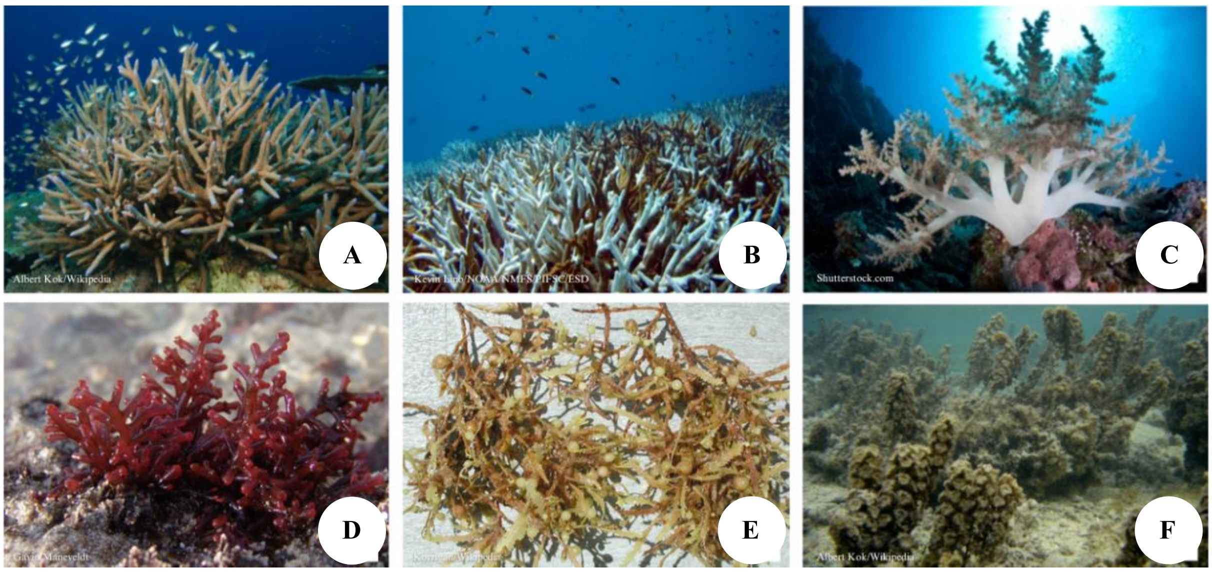

Figure 1. Examples of coral reefs, Organisms, and Habitats: *Acropora cervicornis* (staghorn coral), B. Dead coral substrate, C. *Sinularia* spp. (soft coral), D. Fleshy macroalgae (unidentified species), E. *Sargassum* spp. (brown algae), F. *Turbinaria* spp. (brown algae)

Indonesia hosts more than 569 coral species belonging to 83 genera, making it one of the most biodiverse coral regions in the world (Asaad et al. 2020; Hadi et al. 2020). These species are distributed across various reef types, including fringing reefs, barrier reefs, atolls, and patch reefs, with extensive coverage in regions such as Raja Ampat, Wakatobi, and the Sunda-Banda Seascape (Ministry of Maritime Affairs and Fisheries 2020). This exceptional richness provides a broad platform to explore species-specific chemical compounds and their biomedical relevance. Notably, some genera endemic or highly abundant in Indonesian waters—such as *Cladiella*, *Nephthea*, and *Paralemnalia*—have already shown pharmacologically significant metabolites, yet remain understudied compared to better-known genera.

Soft corals, particularly those in the subclass Octocorallia, are renowned for their structural plasticity and chemical defense mechanisms. Their internal skeletons are composed of spicules made of calcium carbonate and proteinaceous material, and their tissues are often brightly colored due to the presence of pigments and symbiotic zooxanthellae (Rahman et al. 2011; Varijakzhan et al. 2021). These adaptations not only serve ecological functions but also correlate with the presence of diverse secondary metabolites that contribute to pharmacological activity. In particular, coloration intensity and polyp density have been linked to the expression of specific biosynthetic gene clusters, suggesting a functional relationship between environmental cues and metabolite production.

The diversity of coral reef organisms is not only taxonomic but also biochemical, with each genus or species potentially producing distinct sets of compounds. Such diversity offers immense bioprospecting potential, especially when combined with modern molecular and metabolomic tools. Beyond corals themselves, reef ecosystems support chemically rich taxa such as tunicates, bryozoans, and sponges—many of which are symbiotic or epiphytic and contribute to the reef's chemical ecology. These associations frequently involve horizontal gene transfer and microbial consortia capable of producing complex natural products, which can be leveraged through metagenomic and transcriptomic analyses.

Understanding the taxonomic and ecological diversity of coral reef organisms is essential as a foundation for chemical profiling and pharmacological exploration. It enables the identification of target species and compounds, facilitates sustainable harvesting strategies, and supports conservation priorities aligned with biotechnological innovation. Integrating biodiversity mapping with high-throughput screening platforms may significantly enhance the discovery pipeline for novel marine-derived drugs.

Chemical constituents of coral reefs

The coral reef environment harbors a wide spectrum of bioactive secondary metabolites, offering a promising avenue for pharmacological research. These compounds are synthesized by various reef organisms, particularly soft corals, sponges, and symbiotic microbes (Putnam et al. 2017; Cutolo et al. 2024). These compounds are typically involved in chemical defense, reproduction, and interspecies signaling. The majority are low-molecular-weight, lipophilic molecules, often featuring halogenated moieties or unique carbon skeletons not commonly found in terrestrial metabolites (Ermolenko et al. 2020; Hanafy et al. 2022). The presence of such structural novelty increases the likelihood of discovering new mechanisms of action or drug targets not yet addressed by existing therapeutics.

Understanding the chemical composition of coral reefs, particularly the skeletal structure of hard corals, is of paramount importance. The skeletal structure is primarily composed of aragonite ($CaCO_3$), but also contains trace elements such as magnesium, strontium, and occasionally heavy metals, which may influence both structural integrity and bioavailability of associated compounds. In addition, organic matrices embedded within the coral skeleton can contain glycoproteins, lipids, and phenolic residues, some of which may contribute to pharmacological activities when processed as powders or extracts. These matrices have also been proposed as bioceramic templates in tissue engineering and regenerative medicine, particularly in bone graft substitutes and drug delivery scaffolds. Table 1 provides a synthesis of major bioactive compounds reported from various coral reef organisms and highlights their corresponding pharmacological activities, illustrating the chemical richness and biomedical relevance of reef biodiversity.

Soft corals are known to produce an even more diverse range of secondary metabolites than their hard counterparts. Cembranoid-type diterpenoids are among the most studied compounds isolated from genera such as *Sarcophyton*, *Sinularia*, and *Lobophytum* (Fristiohady et al. 2019). These compounds exhibit a wide array of bioactivities, including cytotoxic, antiviral, and anti-inflammatory properties. Steroidal glycosides and prostaglandins have also been isolated from reef gorgonians and soft corals, often with unique side chains that enhance receptor selectivity and pharmacological potency (Chen et al. 2016). Recent Structure-Activity Relationship (SAR) studies suggest that halogenation and epoxidation at specific carbon positions improve cytotoxic selectivity indices and target binding affinity.

Apart from terpenoids and steroids, nitrogen-containing compounds such as alkaloids, nucleosides, and amino acid derivatives are prevalent in reef-associated sponges and tunicates. For example, some sponge-derived alkaloids have shown activity against *Plasmodium* species and multidrug-resistant bacteria (Nusaly et al. 2024). Other nitrogenous compounds, such as brominated tyrosine derivatives, are believed to originate from symbiotic microbes and are often associated with potent cytotoxic or neuromodulatory effects. Some of these compounds have advanced to preclinical testing stages, highlighting their translational potential despite the challenge of sustainable supply.

Marine saponins, while less frequently studied, have also been isolated from echinoderms and coralline algae in reef environments. These amphipathic glycosides exhibit hemolytic, immunomodulatory, and antifungal properties. Flavonoids and polyphenolic compounds, though more commonly associated with plants, have been detected in coral reef macroalgae and contribute to antioxidant activity (Pirian et al. 2017; Avila-Romero et al. 2022). These compounds are often involved in photoprotection and stress responses and may be harnessed for cosmeceutical or nutraceutical applications. Interestingly, some macroalgal flavonoids have shown synergistic effects when combined with marine alkaloids, suggesting combinatorial approaches for drug development.

The chemical ecology of coral reefs is further enriched by microbial symbionts, including bacteria, archaea, and fungi, which often reside in coral mucus or tissues. These microbes contribute to the synthesis of complex polyketides, non-ribosomal peptides, and hybrid molecules that are difficult to obtain from other environments. Metagenomic studies have begun to uncover the biosynthetic gene clusters responsible for these metabolites, offering promising avenues for sustainable biosynthesis and drug development (Cooper et al. 2014). Coupled with genome mining and synthetic biology, these insights have paved the way for heterologous expression of coral reef-derived compounds in model organisms such as *Streptomyces* and *E. coli*.

In summary, coral reefs' chemical constituents encompass a structurally diverse and pharmacologically rich array of molecules. These include major classes such as terpenoids, steroids, alkaloids, flavonoids, saponins, and prostaglandins, each with distinct biological activities and therapeutic relevance. Understanding the origin, structure, and bioactivity of these compounds is essential for guiding bioprospecting efforts and identifying lead candidates for further pharmacological evaluation. Future efforts should prioritize the integration of ecological metadata, omics technologies, and cheminformatics to optimize compound discovery and sustainable utilization.

Major bioactive compound classes

Terpenoids

Terpenoids are among the most frequently reported secondary metabolites in coral reef organisms, particularly soft corals such as *Sarcophyton*, *Sinularia*, and *Lobophytum*. These compounds are synthesized through the mevalonate or Methylerythritol Phosphate (MEP) pathways and typically serve as chemical defenses against predators, fouling organisms, or microbial pathogens (Fristiohady et al. 2019). Cembranoids, a subclass of diterpenoids, are especially abundant in soft corals, often characterized by complex ring structures with epoxide or furan moieties, and exhibit a wide range of biological activities, including anti-inflammatory, cytotoxic, and antimicrobial effects.

Table 1. Summary of bioactive compounds and pharmacological properties of coral reef organisms

Organism/source	Major compounds	Compound class	Pharmacological properties	References
Sarcophyton spp. (Soft coral)	Cembranoids, diterpenes	Terpenoids	Anti-inflammatory, cytotoxic, antibacterial	Cooper et al. 2014; Fristiohady et al. 2019
Sinularia spp. (Soft coral)	Steroids, terpenoids	Steroids, Terpenoids	Antibacterial, antifungal, anti-inflammatory	Mayer et al. 2013
Padina australis (Brown alga)	Phlorotannins, polyphenols	Flavonoids, Polyphenols	Antioxidant, antidiabetic	Pirian et al. 2017
Sargassum polycystum (Brown alga)	Fucoidans, sulphated polysaccharides	Polysaccharides	Antidiabetic, antioxidant, antimicrobial	Pirian et al. 2017; Avila-Romero et al. 2022
Haliclona sp. (Sponge)	Manzamine A, alkaloids	Alkaloids	Antimalarial, anticancer, anti-parasitic	Cooper et al. 2014
Soft coral-associated fungi	Polyketides, terpenes	Microbial metabolites	Cytotoxic, antibacterial	Karthikeyan et al. 2022
Sea cucumber (*Holothuroidea*)	Triterpene glycosides	Saponins	Immunomodulatory, antihypertensive	Cutolo et al. 2024
Symbiotic bacteria (*Pseudoalteromonas*)	Alkaloids, antimicrobial peptides	Microbial metabolites	Antibacterial, antifouling	Song et al. 2018; Karthikeyan et al. 2022
Gorgonians (*Eunicella* spp.)	Sesquiterpenes, diterpenes	Terpenoids	Anti-inflammatory, antimicrobial	Mayer et al. 2013
Zoanthus spp.	Zoanthamines	Alkaloids	Cytotoxic, neuroactive	Cooper et al. 2014
Pseudoalteromonas spp. (Mucus bacteria)	Bromoalterochromides, tambjamines	Microbial metabolites	Antibacterial, anticancer	Karthikeyan et al. 2022
Didemnum spp. (Tunicate)	Cyclic peptides, didemnins	Peptides, Alkaloids	Antiviral, cytotoxic	Cooper et al. 2014; Karthikeyan et al. 2022
Gracilaria spp. (Red alga)	Sulfated polysaccharides, agarans	Polysaccharides	Antioxidant, anticoagulant	Avila-Romero et al. 2022
Caulerpa spp. (Green alga)	Caulerpenyne, carotenoids	Terpenoids, Carotenoids	Antiviral, hepatoprotective	Fristiohady et al. 2019
Sea urchin (*Diadema* spp.)	Echinochrome A, polyhydroxynaphthoquinones	Quinones	Antioxidant, cardioprotective	Cutolo et al. 2024
Starfish (*Acanthaster planci*)	Saponins, steroidal glycosides	Saponins, Steroids	Cytotoxic, antifeedant	Karthikeyan et al. 2022
Bryozoans (*Bugula neritina*)	Bryostatins (macrolides)	Macrolides	Anticancer, memory enhancement	Cooper et al. 2014
Cyanobacteria (*Lyngbya majuscula*)	Lyngbyatoxins, aplysiatoxins	Toxins, Alkaloids	Antitumor, neurotoxic	Karthikeyan et al. 2022

Many terpenoids isolated from corals have highly oxygenated or epoxidized ring structures, contributing to their high reactivity and biological specificity (Cooper et al. 2014). Sarcophytol A, for instance, is a cembranoid diterpenoid known for its antitumor properties, while *sinulariolide* and *lobophytolide* have demonstrated significant anti-inflammatory and neuroprotective activities (Chen et al. 2016). More recent findings have suggested that some diterpenes also modulate ion channels and apoptosis pathways, making them candidates for neurodegenerative disease research. Due to their lipophilic nature and membrane-targeting properties, terpenoids are not only considered promising leads in drug development, but are also actively screened in anticancer, antiviral, and antiparasitic pipelines.

Steroids

Steroidal compounds derived from reef organisms differ structurally from those of terrestrial sources. Marine steroids with their unusual side chains, sulfated moieties, or halogen substitutions engage in unique and fascinating interactions that alter their interaction with biological targets (Ermolenko et al. 2020). These structural differences can enhance receptor specificity or modulate immune response in ways that continue to intrigue researchers. In addition, some marine steroids function as signaling molecules that regulate microbial symbiosis and coral immune homeostasis.

The diversity of marine steroids from coral reef sponges and gorgonians, including classes such as polyhydroxylated sterols, secosteroids, and glycosylated pregnanes, is a source of inspiration for researchers. Many of these steroids exhibit anti-inflammatory, cytotoxic, or antiviral properties (Karthikeyan et al. 2022). Some reef-derived steroids also act as inhibitors of enzymes involved in steroidogenesis or tumor progression. Steroidal metabolites like sarcosteroids and gibberoketosterols have shown inhibitory activity against COX enzymes and estrogen receptors, indicating potential use in hormonal disorders and cancer therapy. This rich diversity and the potential for novel applications in immunomodulation, hormone regulation, and endocrine therapy are motivating factors for further exploration in this field.

Nitrogen-containing compounds

Nitrogenous compounds in coral reef systems include alkaloids, amino acid derivatives, brominated tyrosines, nucleosides, and nitrogenous heterocycles. Reef-associated sponges, tunicates, and microbial symbionts commonly produce these compounds (Nusaly et al. 2024). Alkaloids are particularly valuable for their broad pharmacological spectra, including neurotoxicity, antimicrobial activity, and enzyme inhibition. Their structural diversity includes polycyclic frameworks, spiro systems, and halogenated indoles, making them attractive for CNS drug development.

Marine alkaloids from reef organisms often have halogen substitutions (e.g., bromine or chlorine), which are rare in terrestrial metabolites. For example, *bastadins* from sponges and *lamellarins* from ascidians exhibit anticancer and antiviral effects, respectively. Nitrogen-containing metabolites also include nucleoside analogs such as *cytarabine*, which, although originally isolated from deep-sea sponges, reflect the therapeutic potential of reef microbial analogs. This emphasis on the potential of these compounds can inspire hope for the future of pharmacology. Additionally, bromotyrosines from sponges have shown promising anti-inflammatory and antimalarial effects (Varijakzhan et al. 2021). Ongoing synthetic biology approaches are exploring the heterologous expression of alkaloid biosynthetic pathways to overcome the limitations of natural harvest and low yield.

Other compounds: Flavonoids, Saponins, and Prostaglandins

While terpenoids, steroids, and alkaloids dominate marine chemical studies, other compound classes such as flavonoids, saponins, and prostaglandins are gaining attention for their diverse bioactivities. Flavonoids are commonly found in reef-associated macroalgae, such as *Sargassum* and *Padina*, and function primarily as antioxidants and UV protectants (Avila-Romero et al. 2022). These compounds may have cosmeceutical or nutraceutical applications due to their roles in mitigating oxidative stress and inflammation. Recent studies have demonstrated their ability to modulate MAPK and NF-κB signaling, suggesting broader anti-aging and anti-inflammatory relevance.

Saponins, amphipathic glycosides with detergent-like properties, are occasionally isolated from echinoderms and coralline algae in reef environments. They exhibit hemolytic, cytotoxic, and antifungal effects and may modulate immune responses (Zhao et al. 2024). Due to their membrane-disrupting capabilities, saponins are being explored as vaccine adjuvants and anti-parasitic agents. Moreover, some marine saponins have demonstrated selective toxicity against cancer cells, likely due to their interactions with cholesterol-rich membranes.

Prostaglandin-like compounds, notably from gorgonians and soft corals, mimic mammalian eicosanoids in structure and function. These include prostaglandins A_2 and E_2 analogs, which exhibit smooth muscle relaxation, anti-inflammatory, and antithrombotic properties (Mayer et al. 2013). Their presence in marine organisms reflects the convergent evolution of chemical signaling and underscores their therapeutic relevance. Several coral-derived prostanoids are under investigation for cardiovascular and reproductive health applications.

Collectively, these compound classes reflect the immense chemical richness of coral reef ecosystems and their multifaceted contributions to biomedical research. Understanding their biosynthetic origins, ecological functions, and pharmacological effects is crucial for advancing marine drug discovery sustainably and ethically. To accelerate translational outcomes, interdisciplinary collaboration among chemists, marine biologists, pharmacologists, and conservationists is essential.

PHARMACOLOGICAL ACTIVITIES OF CORAL-DERIVED COMPOUNDS

Antibacterial and antiviral activity

Coral reef organisms are prolific sources of antimicrobial compounds with activity against a broad range of bacterial and viral pathogens. Various secondary metabolites isolated from soft corals, sponges, and their symbiotic microorganisms have shown potent inhibitory effects on Gram-positive and Gram-negative bacteria, as well as on several viral families (Ermolenko et al. 2020; Hanafy et al. 2022). These bioactive compounds are of particular interest in the search for alternatives to conventional antibiotics, especially amid rising antimicrobial resistance and the global threat of neglected tropical diseases.

Soft corals, especially those belonging to the genera *Sarcophyton* and *Sinularia*, are known for producing terpenoids and cembranoids with broad-spectrum antibacterial activity. Sarcophytol A, for instance, has demonstrated inhibitory effects against *Staphylococcus aureus* and *Escherichia coli*, with proposed mechanisms involving membrane disruption and inhibition of protein synthesis (Fristiohady et al. 2019). Similarly, lobophytolide-type diterpenes from *Lobophytum* species have shown activity against Methicillin-Resistant *Staphylococcus aureus* (MRSA) and *Pseudomonas aeruginosa* (Chen et al. 2016). These findings underscore the potential of coral-derived terpenoids as scaffolds for the development of next-generation antibiotics.

Marine sponges are another rich source of antibacterial agents. Alkaloids such as agelasines, manzamines, and related nitrogen-containing compounds, originally isolated from reef-associated sponges, exhibit significant inhibitory activity against *Mycobacterium tuberculosis*, *Helicobacter pylori*, and multidrug-resistant strains of *Salmonella* (Cooper et al. 2014). These metabolites act through multiple mechanisms, including inhibition of DNA synthesis, disruption of membrane integrity, and interference with bacterial enzyme systems. Importantly, some of these alkaloids retain efficacy against strains that exhibit resistance to β-lactams and fluoroquinolones.

In addition to their antibacterial potential, coral reef organisms also produce compounds with notable antiviral properties. Brominated tyrosine derivatives, isolated from both sponges and soft corals, have been reported to suppress replication of Herpes Simplex Virus (HSV), dengue virus, and Human Immunodeficiency Virus (HIV) (Mayer et al. 2013). For example, pseudopterosins, a group of diterpene glycosides from Caribbean gorgonians, inhibit viral entry and reduce inflammation in infected tissues. This dual antiviral and anti-inflammatory action is especially beneficial for the treatment of viral diseases with strong inflammatory responses, such as dengue, hepatitis, and COVID-19.

Coral-associated microbes, especially actinobacteria and fungi, have gained attention as sources of novel antimicrobial agents. These symbionts produce polyketides, macrolides, and depsipeptides with antimicrobial activity equal to or superior to that of their host. Recent metagenomic studies have identified cryptic Biosynthetic Gene Clusters (BGCs) from coral microbiomes that could be harnessed for novel antibiotic discovery (Karthikeyan et al. 2022). These microbial consortia offer a promising avenue for scalable and sustainable compound production.

However, despite extensive in vitro bioactivity reports, only a few coral-derived antimicrobials have progressed to preclinical or clinical development. This gap is primarily due to challenges in compound isolation, low natural abundance, synthesis complexity, and incomplete toxicity profiling. Nonetheless, the antibacterial and antiviral activities of coral-derived compounds continue to offer valuable scaffolds for pharmacological innovation.

Future directions should prioritize in vivo efficacy testing, pharmacokinetic and toxicity assessments, and elucidation of molecular mechanisms of action. Structure-Activity Relationship (SAR) studies and medicinal chemistry optimization are also crucial for improving potency and selectivity. Moreover, exploring synergistic interactions between coral-derived compounds and existing antimicrobial agents could enhance efficacy and help combat resistant infections.

Anti-inflammatory activity

Inflammation plays a pivotal role in the pathogenesis of various acute and chronic diseases, including arthritis, cardiovascular disorders, neurodegeneration, and cancer. Coral reef organisms, particularly soft corals and sponges, have yielded numerous compounds with significant anti-inflammatory properties. Many of these act through the inhibition of key pro-inflammatory mediators, such as nitric oxide (NO), prostaglandins (e.g., PGE_2), cytokines, and nuclear factor-kappa B (NF-κB) signaling pathways (Chen et al. 2016; Fristiohady et al. 2019). These mechanisms are comparable to those targeted by conventional anti-inflammatory drugs but often involve structurally novel compounds with potential for reduced side effects.

Cembranoid diterpenes from *Sarcophyton* species are among the most studied coral-derived anti-inflammatory agents. Compounds such as sarcophytolide B have been shown to downregulate the expression of inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2), key enzymes responsible for the synthesis of NO and PGE_2, respectively (Fristiohady et al. 2019). These effects are believed to be mediated through the suppression of mitogen-activated protein kinase (MAPK) and NF-κB signaling cascades, both central to the inflammatory response.

Similarly, lobophytolides and sinulariolides from *Lobophytum* and *Sinularia* species have demonstrated the ability to reduce pro-inflammatory cytokine secretion, including tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6), in lipopolysaccharide (LPS)-stimulated macrophages (Cooper et al. 2014; Chen et al. 2016). This suggests their potential application in treating immune-mediated conditions such as rheumatoid arthritis and inflammatory bowel disease.

Marine steroids with unique side chains, isolated from gorgonians and reef-associated sponges, also exhibit notable immunomodulatory effects. Compounds such as 24-methylenecholesterol and pregnane derivatives have been reported to inhibit IL-1β and interferon-gamma (IFN-γ) production in vitro (Mayer et al. 2013; Kang et al. 2019). Owing to their partial structural resemblance to corticosteroids, these marine-derived steroids are being explored as alternative modulators with potentially improved pharmacokinetics and safety.

Beyond purified compounds, whole-tissue extracts of soft corals have also shown anti-inflammatory effects in vivo. For instance, methanolic extracts of *Sarcophyton glaucum* significantly reduced paw edema and leukocyte infiltration in carrageenan-induced inflammation models (dos Santos et al. 2023). These findings support traditional coastal uses of coral-based materials for wound healing and the treatment of inflammatory ailments.

Despite these promising results, few coral-derived anti-inflammatory agents have advanced beyond preclinical testing. Limitations include insufficient pharmacodynamic data, incomplete toxicity profiling, and a lack of long-term safety evaluations. Nevertheless, the structural diversity, multi-target capacity, and marine origin of these compounds make them promising candidates for the development of novel anti-inflammatory therapeutics. Future research should prioritize bioavailability enhancement, target specificity, and translational studies to advance these leads into clinical pipelines.

Cytotoxic and anticancer activity

Among the various pharmacological effects of coral reef-derived compounds, their cytotoxicity against cancer cells is one of the most intensively explored. Numerous secondary metabolites isolated from soft corals, sponges, and gorgonians have shown potent antiproliferative effects against a broad spectrum of human tumor cell lines, including leukemia, breast, lung, liver, and colon cancers (Fristiohady et al. 2019; Ermolenko et al. 2020). These compounds represent promising scaffolds for novel chemotherapeutic agents, particularly those targeting drug-resistant malignancies.

Cembranoid diterpenes such as sarcophytolide A and sinulariolide, isolated from *Sarcophyton* and *Sinularia* species, are well-documented for inducing apoptosis in cancer cells. Their mechanisms of action involve mitochondrial membrane depolarization, caspase cascade activation, and downregulation of anti-apoptotic proteins such as Bcl-2 (Cooper et al. 2014; Fristiohady et al. 2019). Notably, these compounds demonstrate preferential toxicity toward malignant cells, with limited impact on healthy cells, highlighting their therapeutic index.

Other bioactive diterpenes such as lobophytolides and isosarcophytoxides, primarily from soft corals, exhibit cytostatic effects on hepatocellular carcinoma (HepG2), human leukemia (HL-60), and breast cancer (MCF-7) cell lines. These compounds often induce cell cycle arrest at the G1 or G2/M phases, indicating possible DNA damage or mitotic inhibition mechanisms (Chen et al. 2016). Such activity supports their potential role as adjuvants in combination therapies with standard chemotherapeutic drugs.

Alkaloids derived from marine sponges, particularly manzamine A, a β-carboline compound, have also demonstrated exceptional anticancer activity. Manzamine A exhibits nanomolar-range cytotoxicity against pancreatic, colorectal, and prostate cancer cells, acting via inhibition of Cyclin-Dependent Kinases (CDKs) and modulation of the Wnt/β-catenin pathway (Cooper et al. 2014; Karthikeyan et al. 2022). Given the limited efficacy of many conventional alkaloids due to resistance mechanisms, the unique structures of marine-derived alkaloids offer alternatives for overcoming therapeutic resistance.

Additionally, prostaglandin analogs isolated from gorgonian corals like *Pseudopterogorgia* exhibit anti-angiogenic and anti-metastatic effects. These compounds suppress Vascular Endothelial Growth Factor (VEGF) signaling and Matrix Metalloproteinase (MMP) activity, thereby inhibiting tumor neovascularization and invasion (Mayer et al. 2013). Such mechanisms are critical for impeding the progression of solid tumors.

Importantly, several coral-derived compounds have demonstrated efficacy against Multidrug-Resistant (MDR) cancer cell lines, including those overexpressing P-glycoprotein (P-gp) or other ATP-Binding Cassette (ABC) transporters. This indicates the potential to bypass common resistance mechanisms, a major limitation of current chemotherapies. Synergistic effects with standard drugs such as doxorubicin and cisplatin have also been reported, though pharmacokinetic and safety data remain limited.

Despite strong in vitro and some in vivo evidence, the clinical development of coral-based cytotoxic agents is still in its infancy. Major obstacles include low compound yields, cytotoxicity to normal cells at higher doses, and challenges in formulation and delivery. However, recent advances in biosynthetic engineering, semi-synthetic derivatization, and nanocarrier-based drug delivery offer realistic pathways for clinical translation.

Antioxidant properties

Oxidative stress, driven by the overproduction of Reactive Oxygen Species (ROS), contributes significantly to the pathophysiology of various chronic diseases, including neurodegenerative disorders, cardiovascular disease, cancer, and age-related conditions. Antioxidants neutralize ROS and protect essential cellular biomolecules—lipids, proteins, and nucleic acids—from oxidative damage. Coral reef organisms, particularly reef-associated macroalgae, soft corals, and microbial symbionts, are rich sources of natural antioxidant compounds with diverse mechanisms of action (Pirian et al. 2017; Avila-Romero et al. 2022). These include radical scavengers, metal ion chelators, enzyme modulators, and enhancers of endogenous antioxidant systems.

Flavonoids and polyphenols isolated from reef macroalgae such as *Sargassum polycystum* and *Padina australis* have demonstrated strong radical-scavenging activity in vitro, particularly through DPPH and ABTS assays (Pirian et al. 2017). Key compounds such as catechins, kaempferol derivatives, and phlorotannins exhibit high redox potential, attributable to their hydroxyl-rich structures, allowing them to effectively prevent lipid peroxidation and oxidative protein damage. Owing to their safety and bioactivity, these molecules are increasingly being explored in functional foods, nutraceuticals, and anti-aging cosmeceuticals.

Soft coral extracts also possess significant antioxidant potential. Methanolic extracts of *Sarcophyton glaucum* and *Sinularia flexibilis* have been shown to reduce intracellular ROS levels and improve fibroblast viability following hydrogen peroxide-induced oxidative stress (dos Santos et al. 2023). These effects are associated with terpenoids, sterols, and phenolic compounds that may activate redox-sensitive pathways, particularly Nrf2/ARE and MAPK, which govern the expression of endogenous antioxidant enzymes.

Beyond crude extracts, several purified marine compounds have demonstrated targeted antioxidant effects. Marine steroids and prostaglandin-like molecules from coral reef organisms have been reported to suppress lipid peroxidation and enhance glutathione (GSH) levels in cellular systems (Mayer et al. 2013). Some also induce the upregulation of Superoxide Dismutase (SOD), catalase, and Glutathione Peroxidase (GPx), thereby strengthening the cellular antioxidant defense system.

These properties are particularly valuable in contexts where oxidative stress is a central disease driver. In neurodegenerative disease models, antioxidant-rich extracts from *Padina* species have shown protective effects against β-amyloid-induced neurotoxicity, relevant to Alzheimer's disease. In metabolic syndrome models, coral-derived antioxidants have demonstrated potential to reduce oxidative lipid peroxidation and improve insulin sensitivity, suggesting roles in diabetes management.

While many antioxidant effects have been validated in vitro, further in vivo studies are essential to assess bioavailability, metabolic stability, and therapeutic windows. Advanced delivery systems—such as lipid-based nanoparticles, emulsions, or hydrogels—could enhance the clinical potential of coral-derived antioxidants. Given their chemical diversity, multifunctionality, and marine origin, these compounds offer unique advantages as candidates for future antioxidant therapies.

Neuroprotective effects

Neurodegenerative disorders, including Alzheimer's, Parkinson's, and Huntington's diseases, are characterized by progressive synaptic dysfunction and neuronal cell death, commonly driven by oxidative stress, chronic neuroinflammation, excitotoxicity, mitochondrial dysfunction, and protein aggregation. Bioactive compounds from coral reef organisms have shown significant potential in modulating these pathological processes (Mayer et al. 2013; dos Santos et al. 2023). The structural diversity of these marine metabolites allows for multimodal actions, including antioxidant defense, anti-inflammatory regulation, and neurochemical modulation, making them attractive candidates for neurotherapeutics.

Terpenoids such as sinulariolide and lobophytolide, isolated from *Sinularia* and *Lobophytum* species, have demonstrated neuroprotective effects in vitro by reducing neuronal apoptosis and suppressing pro-inflammatory cytokine release (Chen et al. 2016). These compounds inhibit the activation of microglia and astrocytes—key mediators of neuroinflammation in response to injury or β-amyloid accumulation—thereby mitigating the production of neurotoxic mediators such as TNF-α and IL-1β. Their ability to modulate the NF-κB, MAPK, and JAK/STAT signaling pathways suggests a dual role in controlling both oxidative stress and neuroinflammatory cascades in the Central Nervous System (CNS).

Flavonoids and polyphenolic compounds derived from reef-associated macroalgae, such as *Padina australis*, have been investigated for their efficacy in counteracting β-amyloid toxicity in neuronal models. These compounds prevent amyloid-β peptide aggregation, preserve mitochondrial membrane potential, and restore neuronal viability, highlighting their potential application in Alzheimer's disease therapy (Gan et al. 2019; Avila-Romero et al. 2022). Molecular docking and in silico analyses have also suggested that these algal flavonoids may interact with tau kinases and acetylcholinesterase, offering broader protective effects on cognitive functions.

Marine steroids and prostaglandin-like molecules from soft corals and reef gorgonians have also emerged as neuroactive scaffolds. Certain marine-derived steroids act as neurosteroids, modulating GABA_A and NMDA receptors and influencing neural excitability, with potential applications in epilepsy, anxiety, and neurodevelopmental disorders (Mayer et al. 2013). These activities reflect a capacity to influence synaptic transmission and neuroplasticity, placing coral steroids within a growing category of natural CNS modulators.

In addition to isolated compounds, several coral and macroalgae extracts have demonstrated nootropic and cognitive-enhancing effects in vivo. For instance, ethanolic extracts of *Sargassum* and *Padina* species have improved memory and spatial learning in scopolamine-induced models of amnesia, accompanied by increased hippocampal acetylcholine levels and reduced oxidative stress markers. These findings suggest the feasibility of developing coral reef-derived nutraceuticals for cognitive health and neurodegenerative disease prevention.

Despite these promising findings, clinical translation remains hampered by challenges such as low oral bioavailability, unknown Blood-Brain Barrier (BBB) permeability, and limited long-term toxicity data. Future research should prioritize pharmacokinetic profiling, in vivo BBB transport studies, and target deconvolution to identify precise receptor or enzyme interactions. Given the multifactorial nature of neurodegenerative diseases, marine-derived compounds with pleiotropic mechanisms—especially those combining antioxidant, anti-inflammatory, and neurotransmitter-modulating properties—may hold superior therapeutic value compared to single-target agents.

Antidiabetic activity

The global burden of diabetes mellitus continues to rise, with type 2 diabetes accounting for over 90% of cases worldwide. Oxidative stress, chronic inflammation, and insulin resistance are recognized as key pathogenic mechanisms. This complex interplay of metabolic dysregulation has fueled interest in natural compounds that can modulate glucose metabolism, enhance insulin signaling, and preserve pancreatic β-cell function. Several coral reef-derived organisms, particularly macroalgae and sponges, have been reported to produce such antidiabetic compounds (Pirian et al. 2017; Avila-Romero et al. 2022). These bioactive substances exert their effects through multi-target mechanisms, including inhibition of carbohydrate-digesting enzymes, antioxidant activity, anti-inflammatory pathways, and insulin-mimetic or insulin-sensitizing actions.

Macroalgae such as *Sargassum polycystum* and *Padina australis*, which are commonly found in reef-associated environments, contain bioactive polysaccharides (e.g., fucoidans), polyphenols, flavonoids, and phlorotannins with α-amylase and α-glucosidase inhibitory activity (Pirian et al. 2017). These enzymes catalyze the hydrolysis of dietary polysaccharides into absorbable monosaccharides. Their inhibition slows postprandial glucose absorption and reduces glycemic spikes, mirroring the pharmacological effect of α-glucosidase inhibitors such as acarbose but with a potentially better gastrointestinal safety profile. Thus, coral reef macroalgae may act as natural functional food ingredients or adjunct therapies for glycemic control.

In vitro and in vivo studies have demonstrated that extracts from *Sargassum* can improve insulin sensitivity, reduce fasting blood glucose levels, and prevent weight gain in diabetic animal models. These effects are attributed to compounds such as fucoidans, sulphated polysaccharides, and phloroglucinol derivatives, which also modulate inflammatory cytokines (e.g., TNF-α, IL-6) and oxidative stress markers such as Malondialdehyde (MDA) (Avila-Romero et al. 2022). Mechanistically, some of these compounds may upregulate GLUT4 expression and activate Insulin Receptor Substrate (IRS) signaling, supporting their utility in metabolic regulation. These findings underscore the immense potential of coral-associated seaweeds to serve as both preventive and therapeutic agents for metabolic disorders.

Beyond algae, sponge-derived compounds such as manzamines, agelasines, and brominated alkaloids have also demonstrated antidiabetic activity. These compounds may exert insulin-sensitizing effects through activation of AMP-activated Protein Kinase (AMPK), a central regulator of glucose and lipid metabolism (Cooper et al. 2014). AMPK activation leads to increased glucose uptake, fatty acid oxidation, and inhibition of hepatic gluconeogenesis—key processes dysregulated in insulin-resistant states. Such mechanism-driven interventions are particularly attractive in the treatment of type 2 diabetes, where conventional therapies often fail to address multiple pathological nodes.

Additional effects observed in coral-derived extracts include inhibition of Advanced Glycation End-products (AGEs) formation, improvement of lipid profiles, and protection of endothelial function. For instance, polyphenol-rich extracts from *Padina* species reduced protein glycation, enhanced Superoxide Dismutase (SOD) activity, and lowered triglyceride levels in streptozotocin-induced diabetic rats, indicating systemic benefits beyond glycemic control. This pleiotropic pharmacology aligns with current trends in diabetes management, which prioritize cardiovascular risk reduction and organ protection.

While preclinical data are promising, clinical translation is still constrained by variability in extract composition, lack of standardized dosing, limited pharmacokinetic data, and incomplete toxicity profiling. Future work should prioritize standardization of bioactive fractions, detailed mechanistic studies in diabetic models, and well-designed pilot clinical trials to validate efficacy and safety in human populations. Nonetheless, coral reef-derived compounds represent a novel and underutilized reservoir for the development of antidiabetic agents with multifaceted and integrative therapeutic potential.

Other pharmacological activities

Beyond antibacterial, anti-inflammatory, cytotoxic, neuroprotective, antioxidant, and antidiabetic effects, coral reef-derived compounds have also been associated with a wide range of additional yet underexplored pharmacological activities. These include anti-parasitic, anticoagulant, antifouling, immunomodulatory, and wound-healing effects—all of which offer novel therapeutic avenues in the treatment of infectious, vascular, autoimmune, and dermatological conditions (Mayer et al. 2013; Fristiohady et al. 2019; Karthikeyan et al. 2022). The remarkable structural and functional diversity of marine secondary metabolites allows them to interact with varied molecular targets, making coral reef organisms a versatile reservoir for innovative drug discovery.

Several studies have reported anti-parasitic activity from coral reef-associated sponges and their alkaloid derivatives, particularly manzamine A. This β-carboline alkaloid, originally isolated from *Haliclona* sponges, has shown potent efficacy against *Plasmodium falciparum* and *Leishmania* species (Cooper et al. 2014). These compounds disrupt mitochondrial membrane potential and nucleic acid synthesis in protozoan parasites, highlighting their promise for combating neglected tropical diseases such as malaria and leishmaniasis. The need for new anti-parasitics due to emerging resistance further amplifies the relevance of such marine-derived leads.

Polysaccharides and sulfated metabolites from macroalgae and coral reef echinoderms have demonstrated anticoagulant properties by targeting key enzymes in the coagulation cascade. These include thrombin and factor Xa, with some compounds also enhancing antithrombin III activity (Qin et al. 2023). Functionally, these molecules mimic the pharmacodynamics of heparin but may offer better biocompatibility, lower immunogenicity, and reduced hemorrhagic risk, making them attractive candidates for safer anticoagulant therapies.

Antifouling compounds from soft corals and gorgonians are also gaining interest—not only for preventing marine biofouling on submerged surfaces but also for their potential to inhibit bacterial biofilm formation on medical implants. For instance, terpenoid derivatives from *Sinularia* and *Pseudopterogorgia* have shown ability to interfere with quorum sensing and microbial adhesion. These properties are especially relevant in addressing device-associated infections and multidrug-resistant biofilm-producing bacteria. The dual applicability of these agents in both environmental and medical contexts underscores their strategic value in sustainable bioprospecting.

Immunomodulatory effects of coral-derived compounds, particularly marine steroids and terpenoids, have been documented in vitro and in vivo. These compounds modulate cytokine profiles—such as reducing IL-6 and TNF-α or enhancing IL-10—and affect the function of immune effector cells including T-cells and macrophages

(Mayer et al. 2013; Kang et al. 2019). Such properties suggest potential for treating autoimmune disorders, inflammatory syndromes, and even as adjuvants in next-generation vaccines.

Wound-healing activity is another promising but relatively underreported area. Topical application of coral and macroalgal extracts in animal models has been associated with accelerated epithelialization, increased collagen deposition, and reduced local inflammation. These effects may be mediated by a synergistic combination of antioxidant, anti-inflammatory, and angiogenic compounds, supporting their potential development as bioactive ingredients in regenerative medicine and dermatological formulations.

Although these activities are currently peripheral in the landscape of marine pharmacology, they represent a rich source of multifunctional bioactivities. Continued exploration, mechanistic studies, and preclinical validation could lead to new therapeutic classes with broad-spectrum applications. Expanding the research focus beyond conventional endpoints may unlock the full biomedical potential of coral reef ecosystems. Table 2 summarizes the principal bioactive compound classes from coral reef sources, including their pharmacological effects and known mechanisms of action, providing a classification-based perspective on coral-derived pharmacology.

ETHNOPHARMACOLOGY AND TRADITIONAL USES

Cultural use of coral reef organisms in traditional medicine

Coastal and island communities in tropical regions have long relied on coral reef ecosystems not only for food and livelihood but also for traditional medicine. Marine organisms—including soft corals, sponges, algae, echinoderms, and mollusks—have been used to treat a variety of ailments, from skin infections to internal inflammations (Fristiohady et al. 2019; Cutolo et al. 2024). Such medicinal knowledge is deeply embedded in local cosmologies and subsistence practices, and is often passed down orally across generations through informal apprenticeship or ritualized knowledge transfer.

In Indonesia, for example, extracts from soft corals are occasionally used in coastal herbal medicine to treat wounds and skin rashes. They are often mixed with coconut oil or applied directly in raw or dried form. Healers in coastal areas of Maluku and East Nusa Tenggara commonly apply these extracts for skin disorders, particularly in fishing communities with high exposure to marine abrasions and infections. Although such uses are often undocumented scientifically, anecdotal reports persist in communities along the eastern archipelago, where marine biodiversity is exceptionally rich. The rationale for these applications is often linked to the belief that organisms exposed to harsh marine environments possess powerful protective substances transferable to humans.

Table 2. Major classes of bioactive compounds from coral reef organisms, their pharmacological activities, and mechanisms of action

Compound class	Example organisms	Representative compounds	Pharmacological activities	Mechanisms of action	References
Terpenoids	*Sarcophyton*, *Sinularia*	Sarcophytol A, Sinulariolide	Anti-inflammatory, cytotoxic, neuroprotective	COX-2 inhibition, apoptosis induction, NF-κB suppression	Chen et al. 2016; Fristiohady et al. 2019
Steroids	Gorgonians, soft corals	24-methylenecholesterol, pregnane types	Anti-inflammatory, immunomodulatory	Cytokine modulation, steroid receptor interaction	Mayer et al. 2013; Ermolenko et al. 2020
Alkaloids	Sponges, tunicates	Manzamine A, bromotyrosines	Antibacterial, anticancer, antiparasitic	DNA synthesis inhibition, mitochondrial disruption	Cooper et al. 2014; Karthikeyan et al. 2022
Flavonoids & Polyphenols	*Padina*, *Sargassum*	Kaempferol, catechins, phlorotannins	Antioxidant, anti-aging, neuroprotective, antidiabetic	ROS scavenging, MAPK/Nrf2 pathway activation	Pirian et al. 2017; Avila-Romero et al. 2022
Saponins	Sea cucumber, starfish	Holothurin A, echinoside A	Immunomodulatory, antifungal, cytotoxic	Membrane disruption, immune cell stimulation	Karthikeyan et al. 2022; Cutolo et al. 2024
Prostaglandins	Soft corals, gorgonians	PGA_2, PGE_2 analogs	Anti-inflammatory, antiangiogenic, vasomodulatory	VEGF/MMP inhibition, smooth muscle modulation	Mayer et al. 2013
Polysaccharides	*Sargassum*, *Gracilaria*	Fucoidans, agarans	Antioxidant, anticoagulant, antidiabetic	α-glucosidase inhibition, anti-inflammatory cytokine regulation	Pirian et al. 2017; Avila-Romero et al. 2022
Microbial metabolites	*Pseudoalteromonas*, fungi	Bromoalterochromides, polyketides	Antibacterial, cytotoxic, antifouling	Ribosomal inhibition, quorum sensing interference	Cooper et al. 2014; Karthikeyan et al. 2022

Sponge extracts are also traditionally known to possess antiseptic and anti-inflammatory properties. In some communities, sponge tissue is boiled, and the water is used to bathe inflamed areas or rashes. This practice is typically performed in the early stages of skin infection, often accompanied by verbal incantations or prayer rituals to enhance efficacy. Similar applications exist for certain marine mollusks, where shell powder is sometimes used as a topical drying agent, believed to accelerate wound healing. In coastal Central Sulawesi, powdered mollusk shell is also used to reduce inflammation in boils and skin lesions.

Macroalgae, such as *Sargassum* and *Gracilaria*, are more widely documented in traditional practices. *Sargassum* spp., in particular, are commonly used in Chinese and Southeast Asian folk medicine to reduce swelling, alleviate thyroid disorders, and detoxify the body (Liu et al. 2012; Anastyuk et al. 2017). Local healers in coastal Java and Sulawesi often prepare decoctions from dried brown algae to treat fever, fatigue, or joint pain. The use of these algae is often seasonal, aligned with coastal harvesting cycles, and their processing may involve sun-drying, boiling, and combination with other herbal ingredients.

In some island societies, echinoderms such as sea cucumbers (*Holothuroidea*) are highly valued not only as tonic foods but also as medicinal preparations. Traditional healers in the Maluku and Papua regions prepare sea cucumber extracts for postnatal care, energy restoration, and wound healing. These preparations are considered part of maternal health care regimens, often reserved for postpartum women or the elderly. These uses are supported by modern pharmacological studies that confirm the presence of bioactive triterpene glycosides and fatty acids (Hanifaturahmah et al. 2024).

The cultural use of coral reef biota often intersects with spiritual beliefs and symbolic associations. For instance, certain soft corals or marine sponges may be considered sacred or taboo, their collection permitted only under specific ritual conditions. These ritual constraints reflect a form of traditional resource management, ensuring that harvesting does not exceed ecological thresholds. This intertwining of ecological knowledge and cosmology underscores the importance of respecting cultural context in ethnopharmacological research.

While many of these traditional practices remain undocumented in formal literature, they offer valuable leads for modern pharmacology and highlight the need for biocultural conservation of reef ecosystems and indigenous knowledge systems. Systematic documentation, participatory validation, and equitable benefit-sharing are essential steps to safeguard and ethically utilize this culturally embedded medicinal knowledge.

Documented ethnomedicinal species and applications

Although scientific studies on the traditional medicinal uses of coral reef organisms are relatively sparse compared to terrestrial plants, several marine species have been documented for their ethnomedicinal relevance. These scattered but significant records provide crucial entry points for marine bioprospecting, particularly when linked to contemporary pharmacological assays. Documenting such uses also supports efforts to protect biocultural heritage and prioritize research on species with dual ecological and therapeutic roles.

Sea cucumbers (*Holothuroidea*) are among the most widely used reef-associated organisms in ethnomedicine, particularly in East and Southeast Asia. In traditional Chinese medicine, species such as *Stichopus japonicus* and *Holothuria scabra* are consumed for their purported ability to improve stamina, wound healing, and kidney function (Cutolo et al. 2024; Hanifaturahmah et al. 2024). Similar uses are reported among coastal Indonesian communities, where *teripang* extracts are applied topically to treat burns and muscle pain. These practices are usually administered post-injury or post-surgery, reflecting empirical knowledge of their regenerative properties. Laboratory findings have confirmed the presence of triterpene glycosides and omega-3 fatty acids with anti-inflammatory and immunomodulatory activities, providing a biochemical basis for these traditional uses.

Soft corals from the genera *Sarcophyton* and *Sinularia* have been occasionally referenced in ethnomedicinal surveys, particularly for their use in topical ointments and poultices. While direct human applications are rare due to potential toxicity, some traditional healers—particularly in ritual contexts—prepare low-concentration infusions for treating skin lesions and joint pain. Their chemical richness—including diterpenoids, cembranoids, and prostaglandin-like compounds makes these taxa promising leads for modern drug development, especially in the fields of inflammation and pain modulation (Fristiohady et al. 2019).

Macroalgae, especially brown algae like *Sargassum polycystum*, are more broadly used and better documented in both traditional and modern contexts. Decoctions from dried *Sargassum* are used to treat goiter, menstrual irregularities, and skin conditions in coastal herbal medicine practices in Java and Sulawesi (Darfiah et al. 2021; Husain et al. 2024; Lee et al. 2024). These uses reflect a long-standing empirical tradition of balancing internal heat and detoxification in humoral-based medical systems. Scientific validation has identified fucoidans and sulphated polysaccharides in *Sargassum* with antioxidant, antiviral, and antitumor properties, reinforcing its integration into both functional foods and pharmaceutical research.

Other reef-related organisms, such as sponges (*Haliclona* spp.) and tunicates (*Didemnum* spp.), are rarely mentioned in ethnomedical texts but have shown cytotoxic and antimicrobial activity in pharmacological assays (Cooper et al. 2014). In coastal regions of Papua and select Pacific Island communities, decoctions or washes from sponge tissues are still used to treat skin infections, with preparation methods emphasizing low-dose extraction and topical administration. While tunicates are less commonly recognized in traditional medicine, emerging interest in their bioactivity suggests untapped potential for ethnopharmacological exploration.

The limited but compelling documentation of these species highlights the importance of interdisciplinary methods—combining ethnographic, ecological, and biochemical approaches—to fully capture their medicinal significance. In summary, although the formal literature on coral reef organisms in traditional medicine remains relatively sparse, existing examples suggest a continuity of use that spans cultural, nutritional, and therapeutic domains. These species not only reflect deep ecological knowledge among coastal communities but also provide a starting point for interdisciplinary research that connects ethnopharmacology with marine biotechnology, drug discovery, and biocultural conservation. Table 3 presents selected examples of coral reef organisms traditionally used in medicine across Southeast Asia, linking local practices with pharmacologically relevant compounds.

Continuity and decline of traditional practices

The transmission of traditional knowledge related to coral reef-based medicine is increasingly threatened by socio-economic change, environmental degradation, and generational discontinuity. In many coastal regions, younger generations are less familiar with the medicinal uses of marine organisms, often viewing such knowledge as outdated or irrelevant in the face of modern healthcare systems (Cutolo et al. 2024). This cultural shift, driven in part by formal education and media exposure, contributes to a loss of confidence in ancestral practices. The erosion of oral traditions poses a critical risk not only to cultural heritage but also to the biocultural diversity that underpins long-term marine pharmacological potential.

One of the primary factors driving this decline is the progressive loss of access to intact and biodiverse coral reef ecosystems. Climate change, destructive fishing practices, pollution, and coastal development have drastically altered reef environments, making many traditionally used species scarce or locally extinct. When resource availability declines, so too does the opportunity for knowledge transfer through observation, collection, and practice. This ecological disconnection disrupts the sensory and experiential learning systems that are foundational to traditional medicine.

In parallel, the increasing dependence on pharmaceutical products and clinical treatment has reduced the perceived value of traditional therapies. While this shift has improved health outcomes in some regions, it also marginalizes ancestral knowledge systems that once provided holistic, community-adapted, and environmentally embedded healthcare solutions. This is particularly problematic in remote island settings where formal healthcare infrastructure remains limited and traditional medicine could still play a complementary or even primary role in public health resilience.

However, there are notable exceptions where traditional marine medicine remains vibrant. In some Pacific Island nations, coral-derived remedies continue to be used alongside modern treatments, often within culturally regulated frameworks. Community-led conservation areas and marine customary tenure systems have also helped preserve both the biological resources and the associated knowledge (Fristiohady et al. 2019). These co-management models demonstrate the feasibility of integrating ecological stewardship with cultural continuity. When cultural institutions and ecological governance mechanisms support traditional practices, they can persist and even be revitalized.

Efforts to document, validate, and revitalize traditional uses of coral reef organisms must therefore be positioned as part of broader, transdisciplinary strategies in marine conservation, ethnopharmacology, and education. By fostering respect for indigenous knowledge and encouraging intergenerational learning, stakeholders can ensure that traditional ethnopharmacology remains a living, evolving part of coastal community identity and resilience. Such approaches are not merely acts of preservation, but investments in future innovation rooted in cultural and ecological integrity.

Integration into contemporary and complementary medicine

The integration of traditional marine-derived remedies into Contemporary and Complementary Medicine (CCM) frameworks is gaining increasing interest among researchers, clinicians, and policy-makers. Many coral reef organisms used in traditional medicine possess bioactive compounds that align with modern pharmacological targets, providing a natural bridge between indigenous knowledge and biomedical innovation (Cooper et al. 2014; Karthikeyan et al. 2022). This convergence reflects a growing recognition that ancestral health systems can contribute meaningfully to diversified, pluralistic healthcare models. Recognizing and respecting this overlap offers both scientific and ethical opportunities to diversify global health resources.

Table 3. Documented ethnomedicinal uses of coral reef organisms in Southeast Asia

Organism	Traditional application	Preparation/form	Region/community	Probable active compound	References
Sarcophyton spp.	Wound treatment, skin rashes	Raw tissue or oil mixture	Maluku, East Nusa Tenggara	Cembranoids, diterpenes	Fristiohady et al. 2019
Sargassum polycystum	Goiter, inflammation, fever	Decoction (dried)	Java, Sulawesi	Fucoidans, sulphated polysaccharides	Darfiah et al. 2021; Husain et al. 2024; Lee et al. 2024
Gracilaria spp.	Blood tonic, menstrual remedy	Boiled or decocted	Northern coastal Java	Sulfated polysaccharides	Nurazizah et al. 2024
Sea cucumber (*Teripang*)	Postpartum care, wound healing	Alcoholic extract, soup	Maluku, Papua	Triterpene glycosides	Hanifaturahmah et al. 2024
Haliclona spp. (sponge)	Skin infections	Boiled and washed	Papua, coastal Kalimantan	Manzamine A, alkaloids	Cooper et al. 2014
Padina australis	Anti-fatigue, diabetes remedy	Tea-like decoction	Eastern Sulawesi	Phlorotannins, flavonoids	Darfiah et al. 2021
Mollusks (mixed species)	Wound drying agent	Crushed shell powder	Central Sulawesi, Java	Calcium salts, trace bioactives	Marwoto et al. 2020; Ngandjui et al. 2024
Pseudoalteromonas (bacteria)	Antiseptic, skin wash	Fermented extract (local)	Unspecified (oral tradition)	Bromoalterochromides	Karthikeyan et al. 2022

One approach to integration involves the rigorous phytochemical characterization and pharmacological validation of traditional remedies. For instance, the traditional use of *Sargassum* decoctions to treat goiter and inflammation has led to the isolation of fucoidans and sulphated polysaccharides with confirmed anti-inflammatory and antithyroid activity (Saraswati et al. 2019; Lomartire and Gonçalves 2022). This discovery not only validates the traditional use of *Sargassum* but also opens up a world of possibilities for the integration of marine compounds into modern pharmacology. Similarly, compounds from sea cucumbers, such as triterpene glycosides, have been developed into commercial health supplements in parts of Asia and the Pacific, demonstrating the economic feasibility of translating traditional marine uses into modern health products.

Incorporating reef-derived natural products into CCM systems requires strict adherence to scientific standards of safety, efficacy, and dosage consistency. Many marine compounds possess narrow therapeutic windows or may interact with conventional drugs, underscoring the need for rigorous pharmacokinetic and toxicological studies. This includes in vivo efficacy trials, metabolic pathway elucidation, and formulation development to improve bioavailability. Nonetheless, when such barriers are addressed, coral-derived agents have potential in areas such as wound healing, cancer support therapy, neurodegeneration, and immune modulation, providing reassurance and confidence in the safety and efficacy of these compounds.

Ethnopharmacological knowledge also contributes to drug discovery by guiding species and compound selection, reducing the need for random screening. For example, observations of traditional wound treatments using soft coral extracts can lead researchers to prioritize cembranoid-rich species for anti-inflammatory assays. Such biocultural targeting not only streamlines research processes but also fosters equitable acknowledgment of local knowledge holders. This targeted approach not only improves research efficiency but also acknowledges and appreciates the intellectual contributions of traditional healers, making them an integral part of the drug discovery process.

Despite these opportunities, integration remains constrained by regulatory, cultural, and logistical barriers. Intellectual property rights and benefit-sharing frameworks are often inadequate or poorly implemented, discouraging communities from sharing knowledge. Moreover, skepticism from both biomedical and traditional sectors can impede mutual understanding. The lack of policy harmonization and scientific literacy within local governance further complicates implementation at the grassroots level. Bridging these divides requires interdisciplinary dialogue, policy reform, and community engagement that places traditional knowledge on equal epistemological footing with modern science.

Several countries have begun to institutionalize marine-based traditional knowledge through herbal pharmacopeias, CCM clinics, and co-designed research protocols. These models offer valuable insights for Indonesia and other coral-rich nations seeking to develop culturally grounded, sustainable health strategies. They also exemplify how respectful integration can be achieved without undermining cultural autonomy. When done responsibly, the integration of coral reef ethnomedicine into modern practice can enrich therapeutic options while strengthening the cultural and ecological foundations of community health.

CHALLENGES AND OPPORTUNITIES IN CORAL-BASED DRUG DISCOVERY

Scientific and technical limitations

Despite the immense pharmacological potential of coral reef-derived compounds, the translation of these natural products into approved therapeutic agents remains limited. Several scientific and technical barriers impede the advancement of coral-based drug discovery from initial bioactivity screening to preclinical and clinical development (Cooper et al. 2014; Karthikeyan et al. 2022). These challenges involve issues of compound supply, structural complexity, reproducibility, and incomplete pharmacological characterization.

One major limitation is the difficulty in obtaining sufficient quantities of bioactive compounds for detailed pharmacological testing. Many coral reef organisms produce secondary metabolites in minute concentrations, often as a defense mechanism under specific environmental conditions. Harvesting large volumes of biomass to isolate these compounds is ecologically unsustainable and technically impractical. Moreover, seasonal variation, habitat-specific stressors, and symbiotic interactions influence the yield and consistency of these metabolites, making reproducibility a significant hurdle. For instance, the diterpenoids found in soft corals such as *Sarcophyton glaucum* are often present in nanomolar concentrations, requiring extensive biomass to yield usable quantities for preclinical trials.

The structural complexity of coral reef-derived compounds also presents obstacles in chemical synthesis and modification. Many compounds from coral reef organisms feature unique scaffolds, multiple stereocenters, and halogenated groups that challenge conventional synthetic chemistry. Although advances in total synthesis and semi-synthesis have enabled production of some compounds in the laboratory, the processes are often low-yielding, expensive, and difficult to scale (Mayer et al. 2013). Compounds like palau'amine and pseudopterosin, while pharmacologically potent, have proven extremely challenging to synthesize due to their polycyclic structures and unstable intermediates. These limitations hinder the development of analogs or derivatives with improved pharmacokinetic profiles.

The lack of standardized bioassay protocols also complicates the evaluation of coral-derived compounds. Bioactivity data are often generated using different cell lines, assay conditions, or extract preparations, leading to inconsistent or non-comparable results across studies. This inconsistency limits the ability to prioritize compounds for further development and impedes meta-analysis or evidence synthesis. Furthermore, the mechanisms of action for many coral reef-derived compounds remain poorly understood, which poses risks for off-target effects or toxicity in clinical applications. For example, several cembranoids exhibit anti-inflammatory properties in vitro, yet their interaction with human signaling pathways remains unclear, limiting their translational potential.

Another major limitation is the absence of robust in vivo validation. While many compounds exhibit promising effects in vitro, relatively few have been tested in animal models, and even fewer have entered clinical trials. This bottleneck reflects both ethical and logistical challenges and the lack of funding for long-term marine pharmacology programs. Without adequate in vivo data, the therapeutic relevance and safety of these compounds remain speculative. Coral reef-derived compounds like eleutherobin, despite strong in vitro anticancer activity, have stalled in development due to lack of in vivo efficacy and toxicity profiling.

In addition, intellectual property issues and bioprospecting regulations can create legal uncertainties in accessing and developing marine genetic resources. The implementation of the Nagoya Protocol has improved benefit-sharing mechanisms, but also introduced administrative complexities that can deter investment in coral-derived drug development. Unclear ownership of marine resources in biodiversity hotspots such as the Coral Triangle has led to delays in research permitting, complicating timelines for compound validation and technology transfer.

Conservation, sustainability, and ethical considerations

The discovery and utilization of coral reef-derived bioactive compounds must be framed within a broader context of environmental ethics and sustainability. Coral reefs are among the most biodiverse yet fragile ecosystems on Earth, and many of the organisms targeted for bioprospecting—such as soft corals, sponges, and macroalgae—play vital ecological roles in maintaining reef structure and function (Putnam et al. 2017; Cutolo et al. 2024). Overexploitation of these organisms for pharmaceutical or commercial purposes may exacerbate reef degradation and undermine long-term research potential. This is particularly critical in regions already experiencing coral bleaching, pollution, and invasive species, where any additional extraction pressure may trigger cascading ecological impacts.

One of the major concerns in coral-based bioprospecting is the ecological impact of biomass collection. Many bioactive compounds are present in low concentrations, necessitating the harvest of large quantities of organisms to obtain sufficient material for study. Without regulated harvesting protocols, this can lead to the local extinction of slow-growing or habitat-specific species. Moreover, physical damage to reef substrates during collection can reduce coral cover, alter species interactions, and compromise reef resilience. Such practices not only jeopardize biodiversity but also reduce the availability of medicinal resources for future generations.

In response, researchers have emphasized the need for non-destructive sampling techniques and alternative supply strategies. These include aquaculture of target species, microbial fermentation of coral-associated symbionts, and synthetic biology approaches that transfer biosynthetic pathways into model organisms (Karthikeyan et al. 2022). Metabolite extraction from cultured coral fragments or sponge explants, for example, provides a renewable source of compounds without depleting wild populations. Such innovations aim to decouple compound access from ecological damage, making marine drug discovery more sustainable and scalable.

Equally important are ethical and legal considerations surrounding access and benefit-sharing. Many coral reef regions are located in the territorial waters of developing countries, where traditional knowledge and local biodiversity are tightly interwoven. The Convention on Biological Diversity (CBD) and its supplementary Nagoya Protocol mandate fair and equitable sharing of benefits arising from the utilization of genetic resources. However, enforcement and compliance mechanisms vary across jurisdictions, and many communities remain undercompensated for their contributions to marine bioprospecting (Putnam et al. 2017). In some cases, lack of legal clarity regarding traditional knowledge ownership has led to biopiracy and mistrust, impeding collaborative research.

Community engagement and co-design of research projects offer promising pathways for ethical marine bioprospecting. Incorporating local knowledge, involving indigenous stakeholders, and ensuring transparent agreements are essential steps toward decolonizing research practices and fostering inclusive conservation. Ethical frameworks that integrate social equity with ecological stewardship are increasingly recognized as best practices in coral reef-derived compounds development. These frameworks should include long-term benefit-sharing schemes, intellectual property protection for traditional healers, and capacity-building initiatives within local research institutions.

Conservation of coral reef biodiversity is not only a moral imperative but also a strategic investment in pharmaceutical innovation. The vast majority of coral reef species remain chemically uncharacterized, and their extinction would represent the irreversible loss of genetic and biochemical resources. Marine Protected Areas (MPAs), sustainable fisheries, and climate adaptation strategies are thus indispensable in maintaining the natural laboratories from which new medicines may emerge. Linking marine conservation goals with drug discovery initiatives can promote synergistic funding opportunities and shared stewardship among scientific and local communities.

In summary, coral-based drug discovery must operate at the intersection of science, ethics, and environmental responsibility. Sustainable collection, fair benefit-sharing, and active reef conservation are prerequisites for ensuring that future generations can continue to explore and benefit from coral ecosystems' medicinal richness. By embedding ecological limits and cultural respect into research protocols, marine pharmacology can evolve into a model of sustainable innovation.

Knowledge gaps and underexplored taxa

Despite decades of marine pharmacological research, significant knowledge gaps persist in the study of coral reef-derived bioactive compounds. Much of the existing literature is focused on a relatively small subset of soft corals, sponges, and macroalgae, while the majority of coral reef-associated organisms remain chemically and pharmacologically unexplored (Mayer et al. 2013; Fristiohady et al. 2019). This taxonomic bias not only limits the discovery of novel bioactive scaffolds but also constrains our understanding of chemical diversity within reef ecosystems.

Among the underexplored taxa are a wide array of sessile invertebrates, symbiotic microorganisms, and cryptic coral species. For example, tunicates, bryozoans, and foraminifera associated with reef systems are known to produce unique secondary metabolites in other ecosystems but have received minimal attention in tropical coral contexts (Karthikeyan et al. 2022). Many of these organisms possess specialized ecological roles and metabolic pathways that may give rise to rare or structurally novel compounds. These organisms may harbor biosynthetic gene clusters capable of producing novel bioactive scaffolds, yet few have been subjected to modern genomic or metabolomic analyses.

Microbial symbionts—particularly bacteria and fungi associated with coral mucus and skeletons—represent another promising but understudied group. These microorganisms often produce bioactive compounds in situ, possibly contributing to the host's chemical defense mechanisms. Some marine-derived antibiotics and anticancer agents originally attributed to macroorganisms have later been traced to associated microbes (Cooper et al. 2014). Recent advancements in metagenomics, metatranscriptomics, and single-cell sequencing are making it increasingly feasible to decode these hidden biosynthetic potentials. The integration of multi-omics approaches could reveal microbial contributions to coral resilience and chemical defense, offering new leads for drug development.

In terms of pharmacological screening, the majority of coral-derived compounds have been tested for antibacterial or cytotoxic effects, with far fewer studies investigating neuroprotective, metabolic, or immunomodulatory properties. This creates a mismatch between therapeutic demand—especially for chronic, non-communicable diseases—and the current direction of coral pharmacology. Emerging global health challenges such as antibiotic resistance, neurodegeneration, and metabolic disorders demand a broader repertoire of pharmacological targets and bioassay systems. Expanding the scope of bioassays and disease models is necessary to uncover the full therapeutic relevance of marine compounds.

There is also a lack of longitudinal and ecological studies that link compound production to environmental conditions, symbiotic relationships, or stress responses. Understanding these ecological drivers could improve the predictability and yield of bioactive compound production. Such insights are particularly relevant in the face of climate change, as reef organisms adapt their metabolic outputs in response to environmental stressors. Monitoring metabolite plasticity over time and space can help identify optimal conditions for compound harvesting or synthesis.

Additionally, many bioactive leads remain chemically uncharacterized or poorly annotated due to limitations in dereplication, compound isolation, or spectral library access. High-throughput dereplication workflows, supported by machine learning and cloud-based compound libraries, are essential to avoid redundant rediscovery and accelerate innovation. Investment in mass spectrometry, NMR-based structural elucidation, and integrated compound databases is essential to accelerate identification and improve data sharing across disciplines.

In conclusion, the field of coral reef drug discovery stands to benefit greatly from expanding its taxonomic, ecological, and pharmacological horizons. By prioritizing underexplored taxa and addressing persistent knowledge gaps, researchers can unlock new dimensions of coral reef biodiversity with transformative implications for medicine and conservation. Targeted exploration combined with interdisciplinary technologies offers a pathway toward more inclusive, efficient, and impactful marine bioprospecting.

Strategic opportunities and emerging technologies

While significant, the challenges of coral-based drug discovery are counterbalanced by a rapidly evolving landscape of technological innovations and strategic approaches that can accelerate and diversify the search for coral reef-derived compounds. Interdisciplinary collaborations, digital tools, and advanced biotechnologies are opening new frontiers in coral pharmacology (Cooper et al. 2014; Karthikeyan et al. 2022). These developments represent a paradigm shift in coral reef-derived compounds research, offering innovative solutions to long-standing limitations such as low compound yield, structural complexity, and ecological constraints.

One promising development is the application of genome mining and synthetic biology to uncover and replicate biosynthetic pathways from coral reef organisms and their symbionts. Many of the compounds of interest are encoded by Biosynthetic Gene Clusters (BGCs) in microbial or invertebrate genomes. By identifying these genes and inserting them into fast-growing host organisms (e.g., *E. coli* or *Streptomyces*), it becomes possible to produce target compounds at scale without harvesting the source organisms (Mayer et al. 2013). This biotechnological approach not only enables sustainable compound production but also facilitates structural modification and pathway engineering for improved pharmacokinetics and therapeutic selectivity.

Metabolomics and cheminformatics tools now allow for high-throughput screening and dereplication of complex coral extracts. Mass spectrometry-based molecular networking, for example, helps to identify novel scaffolds and prioritize bioactive candidates rapidly. These platforms are increasingly integrated with AI-driven predictive models that can simulate bioactivity, toxicity, and target binding, reducing the need for early-stage in vivo assays. Such integration of computational chemistry and machine learning has greatly enhanced the speed, precision, and reproducibility of compound discovery pipelines.

Aquaculture and marine biotechnology also present sustainable production pathways. Soft corals, sponges, and algae can be cultured in controlled environments such as floating ocean farms or land-based tanks. Cultivation not only ensures renewable access to bioresources but also allows manipulation of environmental factors to enhance metabolite production (Leal et al. 2013; Chang and Nichols

2024). Emerging techniques such as bioreactor cultivation, cryopreservation of germplasm, and stress-induced elicitation are further expanding the scalability and consistency of bioactive yields. Moreover, co-cultivation with symbiotic microbes may recreate natural chemical interactions critical to compound biosynthesis.

Marine drug discovery is also benefiting from advances in nanotechnology and drug delivery systems. Encapsulating coral-derived compounds in nanoparticles, liposomes, or emulsions can enhance their stability, solubility, and target specificity, especially for compounds with low bioavailability or high reactivity. Recent studies have demonstrated the efficacy of these delivery platforms in improving the pharmacodynamics of marine compounds, particularly in cancer therapeutics and neurodegenerative disorders. This is particularly relevant for anticancer and neuroprotective agents derived from marine steroids, terpenes, and flavonoids.

Policy and innovation frameworks are beginning to support marine biodiscovery more explicitly. Initiatives such as the UN Decade of Ocean Science (2021-2030) and national marine bioprospecting strategies aim to promote the sustainable use of marine genetic resources while ensuring benefit-sharing with local communities. Regional collaborations, digital bioresource platforms, and blue economy incentives are also contributing to a more supportive ecosystem for marine drug innovation. These global movements align marine research with ethical, environmental, and economic imperatives.

In summary, the future of coral reef drug discovery depends not only on biological curiosity but on our ability to integrate technology, ethics, and ecology strategically. By embracing emerging tools and cross-sector collaboration, we can harness coral biodiversity in ways that are both scientifically productive and socially responsible. The convergence of biotechnological advances, ethical bioprospecting practices, and marine policy innovation offers a promising pathway toward a more inclusive and sustainable era of marine pharmacology.

Toward a sustainable research framework

As coral reef-derived compounds research advances, there is a growing need to establish sustainable frameworks that integrate drug discovery, biodiversity conservation, and socio-cultural equity. Coral reef-based pharmacological exploration, in particular, requires a deliberate shift from extractive practices toward collaborative, regenerative, and ethically grounded research models (Putnam et al. 2017; Fristiohady et al. 2019). Such a paradigm shift ensures that marine drug discovery progresses in tandem with ecological stewardship, social justice, and long-term scientific relevance.

First and foremost, sustainability in coral-based research demands ecological responsibility. Field sampling protocols should prioritize non-destructive or minimally impactful techniques, such as fragment collection, remote sensing-guided harvesting, or reliance on aquaculture specimens. The adoption of ecological monitoring and habitat-sensitive harvesting zones should become a standard practice. Environmental Impact Assessments (EIAs) must be standardized and integrated into all stages of marine bioprospecting, from exploration to compound extraction. Marine Protected Areas (MPAs) and no-take zones should be recognized not as barriers but as ecological reservoirs and biobanks that safeguard the evolutionary potential of reef organisms and the continuity of marine chemical diversity.

Second, the framework must embed equitable benefit-sharing and community participation. Many biodiverse coral reef regions are located within indigenous or traditional territories. The principles of Free, Prior, and Informed Consent (FPIC), as outlined in the Nagoya Protocol, should guide all access to genetic resources and associated knowledge. Co-authorship with local experts, revenue-sharing agreements, and reinvestment in local conservation programs are essential components of ethical bioprospecting (Cutolo et al. 2024). This approach not only acknowledges local rights and expertise but also strengthens social legitimacy and long-term collaboration.

Integration between traditional knowledge systems and modern pharmacology offers a strategic advantage. Ethnomedical insights can guide the prioritization of species and compounds, improving discovery efficiency and cultural relevance. However, mechanisms must be in place to protect intellectual property rights and ensure that traditional healers and knowledge holders are recognized as legitimate contributors. Models of reciprocal knowledge exchange and community-curated ethnobotanical registries can enhance both scientific rigor and cultural preservation. Community-based research models that co-develop hypotheses, methods, and interpretations can generate more holistic and actionable knowledge.

Institutionally, sustainable marine drug discovery calls for long-term investment and capacity building. This includes infrastructure for compound isolation, genome sequencing, bioassay screening, and data sharing in coastal regions where coral diversity is highest. Academic partnerships between institutions in the Global North and South must aim for equitable collaboration, avoiding extractive or asymmetrical dynamics. Investment in local laboratories, marine stations, and open-access training programs will ensure that capacity remains embedded in biodiversity-rich regions. Education and training of local researchers, particularly in bioinformatics, marine pharmacology, and policy, will be vital for sustained impact.

Lastly, a sustainable research framework should promote transparency, open data, and knowledge circulation. Databases that catalog coral reef-derived compounds, their sources, activities, and associated metadata should be made interoperable and accessible to diverse stakeholders. These resources can also aid in the development of early-warning systems to monitor biodiversity loss and chemical diversity decline due to climate change and reef degradation. Global repositories such as MarinLit or GNPS (Global Natural Products Social Molecular Networking) should be expanded to include locally generated data and ensure representation of underexplored regions.

In conclusion, coral-based bioprospecting must evolve beyond opportunistic collection toward a comprehensive, participatory, and conservation-oriented research ecosystem. Such a framework not only secures the ecological foundation for discovery but also elevates the ethical and scientific integrity of marine pharmacology. Moving forward, sustainability must be positioned as a core principle rather than a secondary consideration in marine biomedical innovation.

Collectively, the challenges and opportunities discussed here underscore the urgency of rethinking coral-based drug discovery through an integrated, ethical, and future-oriented lens. The next chapter further explores how these insights can shape strategic policy frameworks and translational applications.

CONCLUSION AND FUTURE PERSPECTIVES

Coral reef ecosystems harbor a vast reservoir of bioactive compounds with remarkable structural diversity and pharmacological potential. Soft corals, sponges, macroalgae, and their associated symbionts have yielded metabolites exhibiting a wide spectrum of biological activities, including antibacterial, anti-inflammatory, cytotoxic, neuroprotective, antioxidant, and immunomodulatory effects. These findings highlight the strategic role of coral reefs in the advancement of drug discovery. However, the translation of these natural products into clinically approved therapies remains constrained by persistent challenges such as limited compound yield, structural complexity, and ecological sensitivity. Moreover, the chemical and pharmacological profiles of many reef organisms remain uncharacterized, underscoring the urgency to expand both taxonomic exploration and therapeutic screening.

To unlock the full potential of coral-based pharmacology, future research must be guided by a convergence of technological innovation, ecological responsibility, and ethical engagement. Emerging tools such as genome mining, metabolomics, synthetic biology, and AI-driven bioinformatics offer promising solutions for overcoming conventional barriers in marine bioprospecting. Equally essential is the integration of traditional ecological knowledge, equitable benefit-sharing, and community-based conservation strategies. A sustainable research framework that safeguards biodiversity while fostering interdisciplinary collaboration and local capacity building will be critical in transforming coral reefs into enduring sources of biomedical innovation. By embracing this holistic paradigm, coral reef ecosystems can be valued not only for their pharmacological promise but also for their ecological and cultural significance in a rapidly changing world.

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Structure and composition of mollusks (Gastropoda and Bivalvia) in the coastal karstic ecosystems of Gunung Kidul, Yogyakarta, Indonesia

ZAHIR ABDURRAHMAN ALGHIFARI[1], FAIZA ALIYA NUR[1], YULIA DINDA SARI[1], ZAKA KHOIRUL ANAM[1], SAFIRA CHAIRUNISA[2], CHEE KONG YAP[3], AHMAD DWI SETYAWAN[1,4,♥]

[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia. Tel.: +62-271-669376, Fax.: +62-271-663375, ♥email: volatileoils@gmail.com

[2]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

[3]Department of Biology, Faculty of Science, Universiti Putra Malaysia. 43400 UPM Serdang, Selangor, Malaysia

[4]Biodiversity Research Group, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia

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Abstract. *Alghifari ZA, Nur FA, Sari YD, Anam ZK, Chairunisa S, Yap CK, Setyawan AD. 2025. Structure and composition of mollusks (Gastropoda and Bivalvia) in the coastal karstic ecosystems of Gunung Kidul, Yogyakarta, Indonesia. Indo Pac J Ocean Life 9: 64-78.* Karstic coastal ecosystems in southern Java remain underexplored in terms of intertidal biodiversity, particularly mollusks. This study examines the structure, composition, and ecological traits of mollusk assemblages across five karst beach sites in Gunung Kidul, Yogyakarta, Indonesia: Pringjono, Torohudan, Ngrawah, Dadap Ayam, and Ngrenehan. A total of 28 valid mollusks species were identified from two classes—Gastropoda (23 species) and Bivalvia (5 species)—representing 17 families. Species richness and density varied across sites, shaped by substrate heterogeneity, tidal exposure, and anthropogenic influence. Gastropods dominated rocky and tide pool microhabitats, while bivalves were more abundant in sediment-rich, sheltered areas. Functional guilds included grazers, filter feeders, and predators, indicating a complex trophic structure. Microhabitat specificity and patchy distribution suggest that environmental filtering and habitat fragmentation play major roles in community assembly. Taxonomic verification was essential, leading to the exclusion of 17 misidentified taxa initially reported. This study highlights the ecological importance and vulnerability of molluscan communities in tropical karst ecosystems. It underscores the need for site-specific conservation strategies, such as protecting rocky and tide pool microhabitats for gastropods and sediment-rich, sheltered areas for bivalves, and improved taxonomic rigor in coastal biodiversity assessments.

Keywords: Bivalvia, Gastropoda, karst beach, mollusca, species richness

INTRODUCTION

Indonesia, as the world's largest archipelagic nation with more than 17,000 islands, harbors an extraordinary wealth of biodiversity (Crib and Ford 2009; Setiawan 2022). Its vast tropical coastline, stretching over 95,000 kilometers, presents a mosaic of ecological habitats that sustain a variety of marine organisms (Peterson and Andres 2021). Among these, coastal karst ecosystems are particularly unique due to their complex geomorphological features and high habitat heterogeneity (Sudarsono and Susantun 2019). The dynamic interface between land and sea in karst regions such as Gunung Kidul fosters biodiversity patterns that are still understudied yet critically important for conservation and resource management (Hayati 2018; Hidayah 2019).

Coastal ecosystems play a central role in maintaining ecological balance and supporting local livelihoods. They serve as nurseries, feeding grounds, and shelters for numerous marine organisms, including mollusks—a taxonomic group comprising gastropods and bivalves—that form a substantial part of benthic communities (Arbi 2012; Alita et al. 2021). Mollusks are of considerable ecological importance, functioning as both prey and predator, and contributing to nutrient cycling and substrate stabilization (Kalay and Lewerissa 2022). Furthermore, due to their sensitivity to environmental changes, mollusks have been widely recognized as effective bioindicators of aquatic health, especially in coastal and estuarine environments (Isnaningsih and Patria 2018; Sitompul 2020).

Mollusks exhibit diverse morphological, physiological, and behavioral adaptations that allow them to occupy a range of habitats, from intertidal rocky shores to sandy beaches and coral rubble (da R. Souza et al. 2020; Maura et al. 2021). Bivalves such as *Meretrix* spp. and *Perna viridis* (Linnaeus, 1758) often inhabit soft substrates where they burrow and filter-feed. At the same time, gastropods, including members of the Cerithiidae, Muricidae, and Cypraeidae families, prefer rocky crevices, coral pools, or vegetation-covered zones (Prasetya et al. 2017). The composition and distribution of these species are shaped by various environmental factors such as temperature, salinity, pH, substrate type, and dissolved oxygen levels, as well as anthropogenic pressures (Adi et al. 2013; Cappenberg et al. 2021).

Karstic coastlines, like those found in Gunung Kidul District in the Special Region of Yogyakarta, are formed from ancient limestone deposits and are characterized by rugged topography, caves, cliffs, and narrow sandy beaches (Kusumayudha et al. 2015; Sudarsono and Susantun 2019).

These physical attributes create a range of microhabitats that influence mollusk diversity and density. The intertidal zones of karst beaches are particularly rich in niche complexity, offering both refuge and food sources for mollusks. However, despite the ecological significance of these areas, systematic studies documenting molluscan communities in Gunung Kidul remain limited.

Previous research in other Indonesian coastal regions has shown that gastropods tend to be more abundant and species-rich compared to bivalves, likely due to their higher motility, broader habitat tolerance, and less reliance on stable sedimentary environments (Baderan et al. 2019; Putra et al. 2021). In comparison, bivalves are more sedentary and often confined to habitats with specific granulometric and chemical conditions. For instance, *P. viridis* thrives in nutrient-rich waters with moderate salinity, while members of Lucinidae and Veneridae tend to prefer organically enriched sandy substrates (Van der Schatte Olivier et al. 2018). These ecological preferences underline the importance of examining mollusks in relation to both biotic and abiotic habitat parameters.

Environmental gradients in coastal karst ecosystems can result in differential species assemblages even across short spatial scales. Variability in substratum—such as coral rubble, sandy flats, and rocky pools—interacts with tidal exposure and human disturbance to affect molluscan community structure (Wahyuni et al. 2017; Umanailo et al. 2021). Furthermore, fluctuating parameters such as temperature and dissolved oxygen, especially during transitional seasons, can limit mollusk physiology, impacting their feeding, reproduction, and survival (Pratiwi and Ernawati 2016; Mulyadi and Lekalette 2020). Given these factors, spatially explicit and taxonomically detailed surveys are essential to understand molluscan biodiversity patterns in karstic coastal zones.

This study was conducted to assess the structure and composition of mollusks in selected karst beaches of Gunung Kidul District, Yogyakarta, Indonesia. By surveying five coastal ecosystems—Pringjono, Torohudan, Ngrawah, Dadap Ayam, and Ngrenehan Beaches—we aimed to document species richness, density, diversity indices, and their relationship with environmental variables. Special attention was paid to verifying species identity to address the misidentification that often occurs in local ecological studies. The results are expected to contribute not only to basic ecological knowledge but also to the design of conservation and management strategies for these unique coastal habitats under increasing anthropogenic stress.

MATERIALS AND METHODS

Study area

This study was conducted in five coastal sites located in the karstic region of Gunung Kidul District, Special Region of Yogyakarta, Indonesia (Figure 1). The selected beaches—Pringjono, Torohudan, Ngrawah, Dadap Ayam, and Ngrenehan—are situated in Kanigoro Village, Saptosari Sub-district, and offer a diverse range of intertidal habitats influenced by both geomorphological variation and marine exposure. These beaches are embedded within a karstic coastal landscape dominated by limestone cliffs, sandy patches, and coral rubble, which together create heterogeneous microhabitats suitable for molluscan colonization (Kusumayudha et al. 2015; Sudarsono and Susantun 2019).

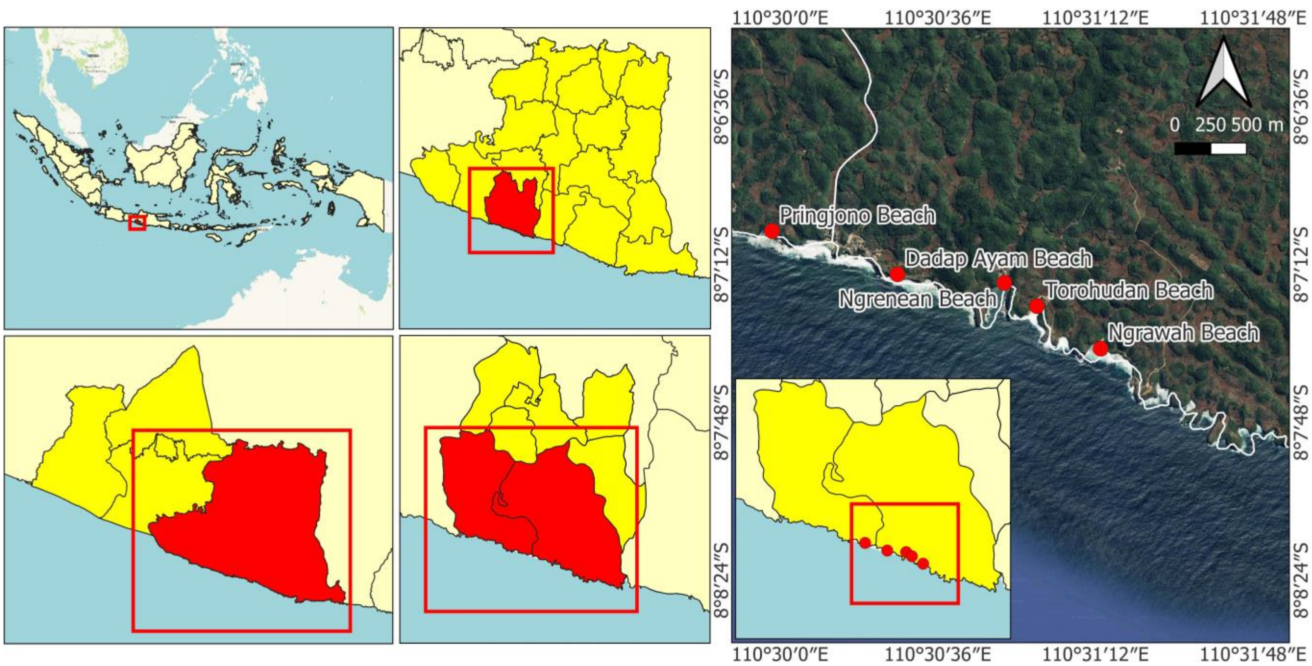

Figure 1. Geographical location of the five coastal study sites in Kanigoro Village, Saptosari Sub-district, Gunung Kidul District, Yogyakarta, Indonesia

Each of the five beaches offers a unique and intriguing intertidal habitat. Pringjono Beach, with its wide sandy shore interspersed with large coral boulders, offers diverse substrates for both gastropods and bivalves. Torohudan Beach, flanked by steep cliffs on either side, has a gently sloping beach face with rough sand and scattered coral outcrops, forming tidal pools during low tide. Ngrawah Beach is a more secluded site with white sandy substrate and coastal vegetation such as pandanus, contributing to organic enrichment of the intertidal zone. Dadap Ayam Beach, enclosed by coral hills, combines sandy flats on the eastern side and rocky formations on the west, frequently covered by macroalgae and sea grasses. Ngrenehan Beach is a shallow bay enclosed by limestone headlands, offering fine white sand and calmer wave conditions, allowing for higher sediment deposition and promising potential for bivalve habitation (Hayati 2018; Hidayah 2019). These five beaches were selected to capture the variability in physical structure and ecological conditions typical of karstic coastal systems. Their differing levels of wave exposure, substrate type, and anthropogenic activity make them ideal for a comparative ecological assessment of mollusk community structure (Figure 1).

Sampling design

A purposive sampling method was employed to assess mollusk diversity and composition across the five selected coastal locations. At each site, five plots of 10 × 10 m were established along the intertidal zone, covering representative habitat features such as sandy flats, rocky outcrops, and coral fragments. The number and size of plots were determined based on previous ecological studies on mollusk communities in similar environments (Setiawan et al. 2019; Putra et al. 2021). Sampling was conducted during low-tide periods to maximize visibility and accessibility of intertidal microhabitats.

The placement of plots aimed to encompass the spatial heterogeneity of each beach while avoiding overlapping areas that might result in double counting. Within each plot, mollusk specimens visible on the surface were collected manually. For organisms burrowed beneath the substrate or lodged within crevices, forceps or tweezers were used carefully to minimize shell damage. In each plot, all mollusks encountered were counted in situ, temporarily stored in labeled containers, and recorded with GPS coordinates.

The purposive sampling design was particularly suited for this study due to the variability in substratum and tide-driven exposure across the karstic coastal system. By targeting ecologically representative microhabitats, this method ensured efficient data collection and minimized sampling bias. In addition to biological data, measurements of abiotic factors were taken directly within or adjacent to each plot to explore environmental correlates of mollusk distribution.

Mollusk collection and preservation

All mollusk specimens encountered within the sampling plots were collected carefully and systematically to avoid damage and ensure reliable identification. Individuals found on the surface of the substrate—including sand, rocks, and coral rubble—were picked up manually. For those partially or fully embedded within sediments or crevices, small forceps were used to extract them without breaking the shell or damaging their soft bodies. The collection process prioritized intact specimens to facilitate accurate morphological identification (Petuch and Berschauer 2020).

Each specimen was placed into labeled plastic containers specific to its collection plot and location. Labels included essential information such as date, site name, plot number, and GPS coordinates. To ensure consistency, all field samples were recorded using standardized data sheets that documented habitat characteristics and visible species abundance.

After field collection, mollusk samples were cleaned using seawater to remove sediment and debris, then preserved in 70% ethanol to maintain tissue integrity. This step was critical for specimens intended for both dry and wet identification processes. Ethanol preservation also allowed for the possibility of future genetic analysis should re-identification be needed.

All preserved specimens were transported to the laboratory at the Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, for further processing. Each specimen was photographed under standardized lighting using a digital microscope or camera, and key morphological features—such as shell shape, coloration, sculpture, aperture, and operculum—were documented and cataloged.

Species identification

Species identification was conducted through morphological analysis of preserved specimens using taxonomic keys, pictorial guides, and reference literature, particularly Tropical Marine Mollusks by Petuch and Berschauer (2020). The identification process emphasized diagnostic characteristics such as shell shape, surface sculpture, coloration patterns, aperture structure, and operculum presence—features commonly used in the taxonomy of both gastropods and bivalves.

To minimize misidentification, each specimen was compared with verified image references from the World Register of Marine Species (WoRMS) and other online databases such as GBIF. When possible, identification was made to the species level; otherwise, ambiguous specimens were classified to genus level, followed by the abbreviation "sp." (e.g., *Cerithium* sp.). This cautious approach was especially important given the taxonomic complexity of tropical mollusks and the potential for local morphological variation or cryptic species.

Problematic identifications—especially those involving rarely recorded or geographically inconsistent taxa—were flagged for re-evaluation and are explicitly marked in the species list. Several previously reported species names were revised based on current nomenclatural standards, and only valid names were retained in the final dataset. This validation process was essential to ensure data accuracy and comparability with other biodiversity assessments.

To maintain consistency, the full scientific name was written in italics at its first mention in the manuscript. In subsequent mentions, abbreviated binomials (e.g., *P. viridis* for *Perna viridis*) were used in accordance with zoological writing conventions. Families were assigned based on current classifications in WoRMS, and each species was also grouped into its respective class—Gastropoda or Bivalvia—for analytical purposes.

Environmental parameter measurement

To assess the abiotic conditions influencing mollusk distribution, several environmental parameters were measured directly at each sampling location. These included water temperature, sand temperature, pH (water and sand), salinity, and Dissolved Oxygen (DO)—all of which are known to affect mollusk physiology, behavior, and habitat suitability (Wahyuni et al. 2017; Cappenberg et al. 2021).

Water temperature and DO were measured using a handheld multiparameter water quality meter. Measurements were taken during low tide at approximately 10-15 cm depth to reflect near-surface intertidal conditions where mollusks are active. Sand temperature was recorded using a digital probe thermometer inserted 5 cm below the substrate surface. These values indicate thermal exposure in different substrate types, which can affect molluscan metabolism and activity levels.

Water pH was measured using a portable pH meter, calibrated on-site using standard buffer solutions. For sand pH, a 1:2 mixture of sand and distilled water was prepared and measured using the same pH probe to approximate the hydrogen ion concentration in interstitial pore water. Salinity was recorded using a refractometer (±0.1 ppt accuracy) and measured from pooled seawater near each sampling plot.

Measurements were repeated at least twice per beach site to ensure reliability, and the average values were used in subsequent ecological analyses. Sites with incomplete data were flagged, and missing measurements were noted. All measurements were conducted between 08:00 and 12:00 local time to maintain temporal consistency across sampling days.

These environmental variables were selected based on their ecological relevance and proven influence on mollusk survival and community dynamics (Pratiwi and Ernawati 2016; Mulyadi and Lekalette 2020). For example, extreme pH or low DO levels may limit the presence of sensitive taxa, while temperature and salinity gradients can drive zonation patterns across intertidal habitats.

Data analysis

The collected data were analyzed to quantify the structure and composition of mollusk communities across the five study sites. The primary metrics used included species density, Shannon-Wiener Diversity Index (H'), Margalef species Richness Index (R), Pielou's Evenness Index (E), and Simpson's Dominance Index (D). These indices are commonly employed in ecological studies to evaluate species distribution patterns, community stability, and dominance relationships (Isnaningsih and Patria 2018; Riantoby et al. 2021).

Species density (individuals per 100 m²) was calculated using the formula:

$$K = \frac{ni}{A}$$

Where:
K : Density of species *i*
ni : Total number of individuals of species *i*
A : Total sampling area in square meters

The Shannon-Wiener diversity index (H') was used to estimate overall community diversity:

$$H' = -\sum(pi \times \ln pi)$$

Where:
pi : Proportion of individuals of the *i*-th species relative to the total number of individuals

Values of $H'<1$ indicate low diversity, $1 \le H' \le 3$ indicate moderate diversity, and $H'>3$ indicate high diversity (Ariani et al. 2019).

Margalef's Richness Index (R) was used to estimate species richness independent of abundance:

$$R = \frac{(S - 1)}{\ln N}$$

Where:
S : Number of species
N : Total number of individuals (Sulistyani et al. 2014)

Richness values below 2.5 are considered low, values between 2.5 and 4 are considered moderate, and values above 4 are considered high (Subhan et al. 2022).

Pielou's Evenness Index (E) measured the relative abundance distribution among species:

$$E = \frac{H'}{\ln S}$$

Evenness values range from 0 to 1, where values close to 1 indicate that individuals are evenly distributed among species, and values close to 0 indicate dominance by a few species (Priyono and Abdullah 2013; Ismaini et al. 2015).

The Simpson Dominance Index (D) was used to assess species dominance:

$$D = \sum(pi^2)$$

Where:
pi : Proportion of individuals of each species

D value near 1 suggests strong dominance by one or a few species, while values closer to 0 suggest a more balanced community structure (Putra et al. 2021; Plaimo et al. 2022).

Descriptive statistics were applied to summarize abiotic data across sites. All calculations were performed using Microsoft Excel and verified manually for consistency. The final results were interpreted with reference to habitat conditions, site-level variability, and previously published mollusk biodiversity benchmarks in tropical coastal systems (Baderan et al. 2019; Paat et al. 2022).

RESULTS AND DISCUSSIONS

Species composition and taxonomic summary

A total of 45 molluscan morphotypes were recorded from five karstic coastal sites in Saptosari Sub-district, Gunung Kidul District, Yogyakarta, Indonesia. Following critical morphological assessment and taxonomic verification through the World Register of Marine Species (WoRMS) and the Global Biodiversity Information Facility (GBIF), 28 species were confirmed as valid, representing two molluscan classes: Gastropoda (23 species) and Bivalvia (5 species), distributed across 20 families. Families with the highest species representation were Muricidae, Cerithiidae, and Conidae (Table 1). Some selected species are shown in Figure 2. Distribution of mollusk species by family illustrates in Figure 3.

Gastropoda exhibited higher richness and ecological plasticity, occurring across a range of intertidal microhabitats such as rocky crevices, coral rubble, algal mats, and sandy flats. Notable taxa included *Macrocypraea dissimilis* (Cypraeidae), *Morula striata* (Muricidae), *Cerithium biminiense* and *Clypeomorus bifasciata* (Cerithiidae), and *Polinices didyma* (Naticidae). Neritid gastropods, notably *Neritina turrita* and *Neritodryas dubia*, were especially abundant in upper intertidal zones influenced by freshwater input. The class Bivalvia was less speciose but contributed significantly to habitat structure. Species such as *Perna viridis* (Mytilidae), *Meretrix meretrix* (Veneridae), and *Saccostrea cucullata* (Ostreidae) were typically found either buried in sandy substrates or affixed to rocky substrates in sheltered coastal zones. Their presence highlights the coexistence of both infaunal and epifaunal bivalves within the study sites (Table 1, Figure 2).

From the 28 valid taxa, 20 were identified to species level, while the remaining 8 were retained at genus level due to diagnostic limitations or low-resolution imagery. These include forms assigned to *Nassarius*, *Columbellidae*, *Myosotella*, and multiple morphotypes within *Conus* that could not be confidently matched to a described species without further anatomical or molecular data. An additional 17 morphotypes were excluded from the analysis due to taxonomic uncertainty, ambiguous nomenclatural status, or mismatch with biogeographic expectations. These morphotypes are documented for completeness but were not included in ecological summaries or diversity indices.

Mollusk density across study sites

The overall density of mollusks varied considerably among the five karstic coastal sites—Pringjono, Torohudan, Ngrawah, Dadap Ayam, and Ngrenehan—reflecting spatial heterogeneity in habitat structure, wave exposure, and substrate type. Molluscan counts were standardized as individuals per 100 m², based on direct field transect observations and stratified sampling across the intertidal zone (Table 2). Ngrenehan Beach recorded the highest total mollusk density at 1.27 individuals/100 m², largely due to the overwhelming dominance of filter-feeding bivalves such as *P. viridis* and *S. cucullata*. These species were typically attached to hard substrates and submerged artificial surfaces in the sheltered bay, highlighting the site's suitability for sessile suspension feeders.

Table 1. Mollusk species found in the coastal karstic ecosystems of Gunung Kidul, Yogyakarta, Indonesia.

Species	Family	Class	Feeding guild
Leucozonia triserialis (Lamarck, 1822)	Fasciolariidae	Gastropoda	Predator
Urosalpinx cinerea (Say, 1822)	Muricidae	Gastropoda	Predator
Macrocypraea zebra subsp. *dissimilis* (F.A.Schilder, 1924)	Cypraeidae	Gastropoda	Grazer
Macrocypraea mammoth Simone & Cavallari, 2020	Cypraeidae	Gastropoda	Grazer
Clypeomorus bifasciata (G.B.Sowerby II, 1855)	Cerithiidae	Gastropoda	Grazer
Varioconus saharicus (Petuch & Berschauer, 2016)	Conidae	Gastropoda	Predator
Varioconus franciscanus (Hwass, 1792)	Conidae	Gastropoda	Predator
Meretrix meretrix (Linnaeus, 1758)	Veneridae	Bivalvia	Filter feeder
Perna viridis (Linnaeus, 1758)	Mytilidae	Bivalvia	Filter feeder
Neritina turrita (Gmelin, 1791)	Neritidae	Gastropoda	Grazer
Vullietoliva foxi (Stingley, 1984)	Olividae	Gastropoda	Predator
Neritodryas dubia (Gmelin, 1791)	Neritidae	Gastropoda	Grazer
Tesselliconus devorsinei (Petuch, Berschauer & Poremski, 2015)	Conidae	Gastropoda	Predator
Cotonopsis lindae (Petuch, 1988)	Columbellidae	Gastropoda	Scavenger
Mya arenaria (Linnaeus, 1758)	Myidae	Bivalvia	Filter feeder
Stramonita alderi (Petuch & Berschauer, 2020)	Muricidae	Gastropoda	Predator
Turbo argyrostomus (Linnaeus, 1758)	Turbinidae	Gastropoda	Grazer
Paphia textile (Gmelin, 1791)	Veneridae	Bivalvia	Filter feeder
Morula striata (Pease, 1868)	Muricidae	Gastropoda	Predator
Pusia luculentum (Reeve, 1845)	Costellariidae	Gastropoda	Predator
Magelliconus jacarusoi (Petuch, 1998)	Conidae	Gastropoda	Predator
Vexilla vexillum (Gmelin, 1791)	Costellariidae	Gastropoda	Predator
Nassarius vibex (Say, 1822)	Nassariidae	Gastropoda	Scavenger
Polinices didyma (Röding, 1798)	Naticidae	Gastropoda	Predator
Cerithium lutosum (Menke, 1828)	Cerithiidae	Gastropoda	Grazer
Cerithium biminiense (Pilsbry & T.L.McGinty, 1949)	Cerithiidae	Gastropoda	Grazer
Siphonaria javanica (Lamarck, 1819)	Siphonariidae	Gastropoda	Grazer
Saccostrea cucullata (Born, 1778)	Ostreidae	Bivalvia	Filter feeder

Figure 2. Photographic documentation of mollusk species observed in the coastal of Saptosari Sub-district, Gunung Kidul District, Yogyakarta, Indonesia: A. *Leucozonia triserialis*, B. *Urosalpinx cinerea*, C. *Macrocypraea dissimilis*, D. *Macrocypraea mammoth*, E. *Clypeomorus bifasciata*, F. *Varioconus saharicus*, G. *Varioconus franciscanus*, H. *Meretrix* sp., I. *Perna viridis*, J. *Neritina turrita*, K. *Vullietoliva foxi*, L. *Neritodryas dubia*, M. *Tesselliconus devorsinei*, N. *Cotonopsis lindae*, O. *Mya* sp., P. *Stramonita alderi*, Q. *Turbo argyrostomus*, R. *Conus berdulinus*, S. *Paphia* sp., T. *Morula striata*, U. *Pusia luculentum*, V. *Magelliconus jacarusoi*, W. *Vexilla vexillum*, X. *Nassarius*, Y. *Polinices* sp., Z. *Cerithium lutosum*, AA. *Cerithium biminiense*, BB. *Siphonaria javanica*, CC. *Saccostrea cucullata*, DD. *Stramonita buchecki*

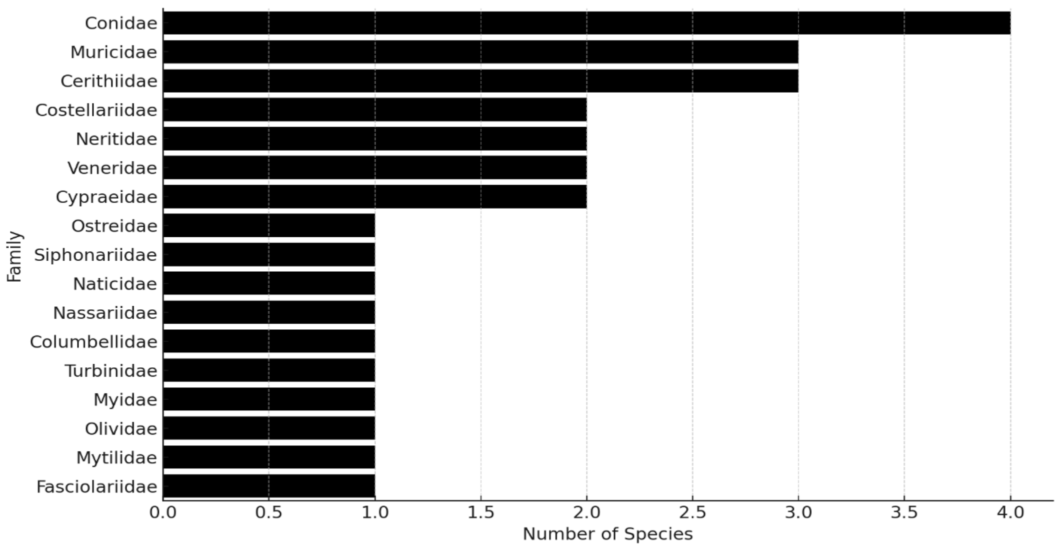

Figure 3. Distribution of mollusk species by family

In contrast, Torohudan and Pringjono exhibited moderate densities (0.81 and 0.53 individuals/100 m², respectively), with mixed contributions from grazers and filter feeders. Dominant species included *N. turrita*, *P. viridis*, *N. dubia*, and *Varioconus saharicus*, which occurred across sandy-rocky transition zones that provided diverse microhabitats.

Ngrawah Beach, despite its lower total density (0.32 individuals/100 m²), supported a distinctive assemblage dominated by *N. turrita* and *Siphonaria javanica*. These gastropods were primarily associated with exposed rocky platforms and tide pools, where biofilm accumulation and algal growth create optimal grazing grounds.

Dadap Ayam, also with 0.32 individuals/100 m², hosted a combination of grazing gastropods (*M. dissimilis*) and infaunal bivalves (*M. meretrix*), suggesting a productive mid-intertidal system with fine sediments, organic detritus, and freshwater seepage.

These findings are further visualized in Figure 4, which highlights variation in total mollusk abundance by site. A broader comparison of species richness, total density, dominant species, and functional guilds for each site is provided in Table 3. These spatial contrasts underscore the ecological complexity of karstic coastal ecosystems in southern Java, where molluscan communities respond sensitively to local geomorphological and hydrological conditions.

Species richness and distribution patterns

Species richness varied noticeably among the five surveyed coastal sites. Ngrawah and Dadap Ayam recorded the highest number of mollusk species, with 23 and 21 species respectively (Table 2). These sites offered a range of intertidal microhabitats, including rocky pools, sandy-muddy flats, and patches of macroalgae, creating diverse ecological niches that support species coexistence. In contrast, Ngrenehan Beach, which exhibited less habitat heterogeneity, hosted only 14 species, the lowest among all sites.

Gastropods were present at all sites and dominated the overall species composition. At Ngrawah, species such as *M. striata*, *C. biminiense*, and *N. turrita* were particularly abundant. These taxa are well adapted to high-energy, wave-exposed environments, often associated with rock surfaces and algal-covered substrates. Generalist species like *S. javanica* and *N. turrita* were observed across all five sites, indicating a broad tolerance for varying substratum types and environmental conditions.

In contrast, bivalves displayed more restricted and site-specific distributions. *P. viridis* and *S. cucullata* were concentrated in relatively sheltered habitats at Pringjono and Torohudan, where calm waters and stable hard substrates favored sessile suspension feeders. Meanwhile, *M. meretrix* and *Paphia textile* were typically located in fine sandy sediments at Dadap Ayam and Ngrenehan, indicating infaunal preferences.

Table 2. Mollusk density (individuals/100 m²) across five karstic beach sites in Gunung Kidul, Yogyakarta, Indonesia

Species name	Pringjono	Torohudan	Ngrawah	Dadap Ayam	Ngrenehan	Total
Leucozonia triserialis	0.03	0.00	0.00	0.00	0.00	0.03
Urosalpinx cinerea	0.01	0.00	0.01	0.00	0.00	0.02
Macrocypraea dissimilis	0.01	0.04	0.00	0.04	0.00	0.09
Macrocypraea mammoth	0.03	0.00	0.00	0.00	0.00	0.03
Clypeomorus bifasciata	0.06	0.00	0.00	0.00	0.00	0.06
Varioconus saharicus	0.06	0.00	0.00	0.00	0.00	0.06
Varioconus franciscanus	0.04	0.00	0.00	0.01	0.00	0.05
Meretrix meretrix	0.01	0.00	0.00	0.06	0.00	0.07
Perna viridis	0.02	0.06	0.00	0.00	0.87	0.95
Neritina turrita	0.01	0.19	0.12	0.10	0.00	0.42
Vullietoliva foxi	0.03	0.00	0.00	0.00	0.00	0.03
Neritodryas dubia	0.17	0.00	0.00	0.00	0.00	0.17
Tesselliconus devorsinei	0.04	0.00	0.00	0.00	0.00	0.04
Cotonopsis lindae	0.00	0.04	0.00	0.00	0.05	0.09
Mya arenaria	0.00	0.06	0.00	0.03	0.00	0.09
Stramonita alderi	0.00	0.03	0.00	0.00	0.00	0.03
Turbo argyrostomus	0.00	0.09	0.00	0.00	0.00	0.09
Paphia textile	0.00	0.00	0.00	0.00	0.01	0.01
Morula striata	0.00	0.05	0.00	0.00	0.00	0.05
Pusia luculentum	0.00	0.01	0.00	0.00	0.00	0.01
Magelliconus jacarusoi	0.00	0.01	0.00	0.00	0.00	0.01
Vexilla vexillum	0.00	0.00	0.01	0.00	0.00	0.01
Nassarius vibex	0.00	0.00	0.01	0.00	0.00	0.01
Polinices didyma	0.00	0.00	0.01	0.00	0.00	0.01
Cerithium lutosum	0.00	0.00	0.01	0.01	0.00	0.02
Cerithium biminiense	0.00	0.00	0.01	0.01	0.00	0.02
Siphonaria javanica	0.00	0.00	0.02	0.00	0.00	0.02
Saccostrea cucullata	0.00	0.00	0.00	0.00	0.33	0.33
Total	0.53	0.81	0.32	0.32	1.27	3.25

Table 3. Summary of mollusk richness and total density per site

Site	Number of species	Total density (individuals/ 100 m²)	Dominant species	Dominant guild
Pringjono	12	0.53	*Neritodryas dubia, Varioconus saharicus*	Grazer and Predator
Torohudan	13	0.81	*Neritina turrita, Perna viridis*	Grazer and Filter Feeder
Ngrawah	9	0.32	*Neritina turrita, Siphonaria javanica*	Grazer
Dadap Ayam	7	0.32	*Macrocypraea dissimilis, Meretrix meretrix*	Grazer and Filter Feeder
Ngrenehan	6	1.27	*Perna viridis, Saccostrea cucullata*	Filter Feeder

Interestingly, 13 species were detected at only one or two sites, suggesting microhabitat specialization or localized population dynamics. *M. dissimilis* and *Trochus niloticus*, for example, were restricted to structurally complex rocky habitats in Ngrawah and Dadap Ayam, while *Columbellidae* sp. was exclusive to tide pools in Torohudan. These patterns likely reflect a combination of natural habitat filtering and anthropogenic disturbances that alter species' persistence and recruitment across sites.

These spatial variations in species composition are visualized in a bar chart illustrating the number of mollusk species shared among one to five coastal sites (Figure 5), underscoring the ecological significance of geomorphological heterogeneity in sustaining molluscan biodiversity within the karstic intertidal environment.

Species richness and distribution patterns

The distribution of mollusk species across the five surveyed karstic beaches in Gunung Kidul District was markedly uneven. Of the 28 verified species (Table 1), only two—*N. turrita* and *M. dissimilis*—were recorded in at least three locations, suggesting relatively broad ecological tolerance and adaptability to a range of intertidal habitats. In contrast, most other species exhibited site-specific occurrences, indicating strong microhabitat preferences or limited dispersal capacity.

Torohudan Beach exhibited the highest species richness, with 15 species identified. This site supported a diverse array of gastropods from the families Muricidae, Conidae, and Cerithiidae, associated with its mixed rocky substrate, presence of tide pools, and moderate hydrodynamic energy. Ngrawah Beach followed closely with 13 species, while Pringjono and Dadap Ayam supported 12 and 10 species, respectively.

Despite recording the highest mollusk density, Ngrenehan Beach had the lowest species richness, with only four confirmed species. The dominance of *P. viridis* and *S. cucullata* on sheltered sandy substrate led to numerical abundance but minimal taxonomic variety. This contrast illustrates the critical distinction between organismal density and ecological diversity in coastal community evaluations.

Several taxa were spatially restricted to a single site, including *Columbellidae* sp., *Turbo argyrostomus*, and *Stramonita buchecki*. These localized occurrences may reflect habitat specificity, recruitment bottlenecks, or site-level anthropogenic pressures. Such patterns emphasize the importance of microhabitat conservation in maintaining localized biodiversity within patchy karstic landscapes.

Species overlap among beaches was generally limited. Only four taxa—*N. turrita*, *C. biminiense*, *Cerithium lutosum*, and *M. dissimilis*—were found at two or more sites. The partial distributional overlap among Ngrawah, Dadap Ayam, and Ngrenehan is visualized in a three-set comparative diagram (Figure 5), while Pringjono and Torohudan were omitted from the visualization due to spatial layout constraints.

These findings underscore the high spatial heterogeneity of molluscan communities in karst coastal ecosystems. Habitat mosaicism, tide-driven zonation, and substrate specificity are likely key drivers of species richness and distribution, reinforcing the need for integrative site-based biodiversity assessments.

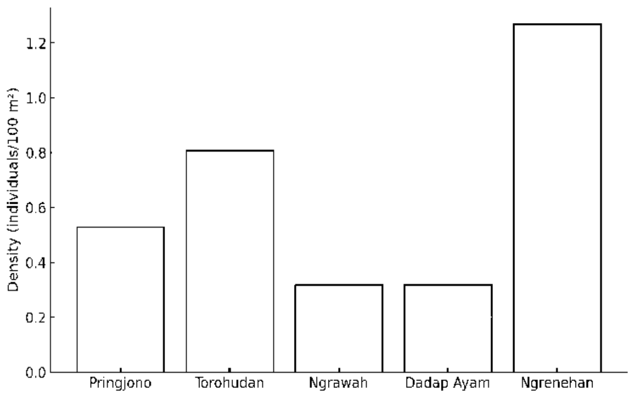

Figure 4. Total mollusk density (individuals/100 m²) per site

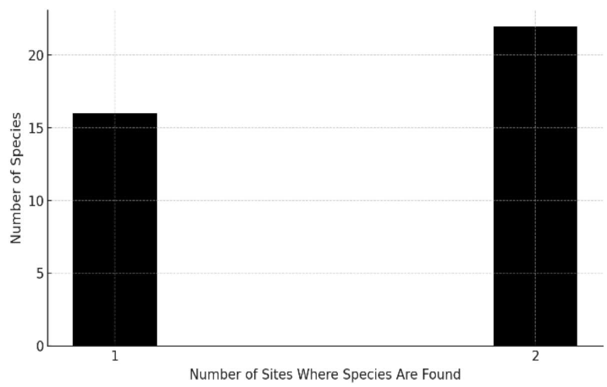

Figure 5. Frequency of mollusk species shared among one to five karstic beach sites in Gunung Kidul, Yogyakarta

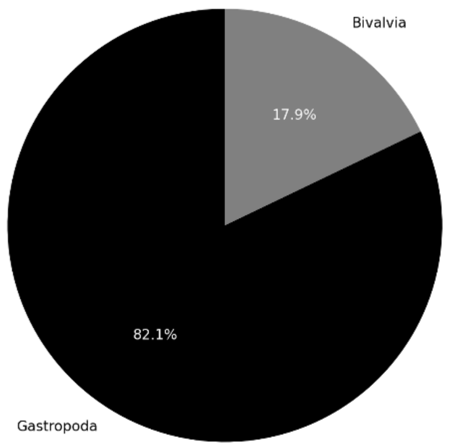

Figure 6. Number of Mollusk species shared across one to five karstic coastal sites in Gunung Kidul, Yogyakarta

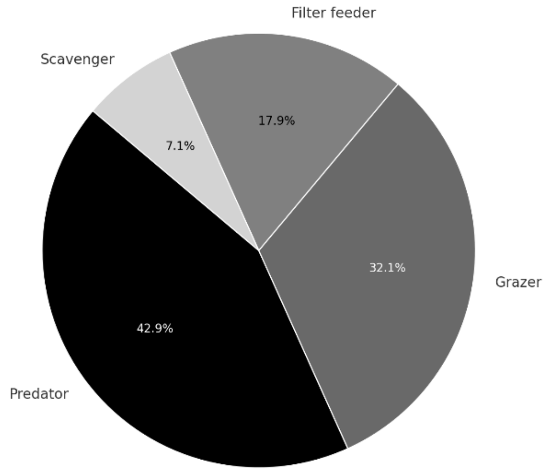

Figure 7. Composition of functional feeding guilds among mollusk species

Table 4. Functional guild composition across sites (percentage of total individuals)

Functional guild	Pringjono	Torohudan	Ngrawah	Dadap Ayam	Ngrenehan	Overall
Grazer	47.2	23.5	65.6	43.8	0.0	36.0
Predator	37.7	26.6	6.3	3.1	0.0	14.7
Filter Feeder	5.7	33.2	0.0	46.9	95.6	36.3
Scavenger	0.0	5.2	12.5	0.0	0.0	3.5
Other/Uncertain	9.4	11.5	15.6	6.3	4.4	9.4

Class-level composition and ecological traits

Of the 28 mollusk species identified in this study (Table 1), the majority—23 species (82.1%)—belonged to the class Gastropoda, while only 5 species (17.9%) were classified as Bivalvia, as also illustrated in Figure 6. This disproportionate representation emphasizes the ecological dominance of gastropods in karstic intertidal habitats, where structurally complex substrates such as rocks, crevices, and algal mats provide favorable conditions for grazing, attachment, and refuge.

Prominent gastropods such as *N. turrita*, *C. biminiense*, and *M. dissimilis* were among the most widespread and abundant taxa, exhibiting broad environmental tolerance and high mobility across tidal zones. These epifaunal grazers primarily feed on periphytic algae and microbial biofilms, contributing to the dynamics of benthic primary consumers. Several predatory or scavenging gastropods—including *Stramonita alderi*, *M. striata*, and unidentified *Columbellidae*—were also recorded, suggesting active trophic interactions and a functioning top-down control mechanism within the intertidal food web.

Bivalves were less diverse and demonstrated more site-specific distributions. Species such as *P. viridis*, *S. cucullata*, and *M. meretrix* were typically restricted to sheltered sites with reduced wave energy and fine sediment substrates, particularly at Ngrenehan and Dadap Ayam. These sessile filter feeders play critical roles in nutrient cycling and water clarification; however, their localized occurrence may render them more vulnerable to environmental stressors such as sedimentation and organic pollution.

Functionally, the mollusk assemblage comprised four major feeding guilds: grazers, predators/scavengers, filter feeders, and a minor group of uncertain or mixed feeders. Grazers—including *N. turrita*, *S. javanica*, and *C.* spp.—dominated the community in several sites and forage on benthic algae and biofilms. Predators and scavengers such as *M. striata*, *S. alderi*, *Columbellidae* sp., and members of Conidae prey on smaller invertebrates or scavenge organic material. Filter feeders—including *P. viridis*, *S. cucullata*, *M. meretrix,* and *M. arenaria*—were concentrated in calmer, sediment-rich beaches. Other taxa, such as *Nassarius vibex* and *P. didyma*, likely function as detritivores, although this requires confirmation through behavioral or gut-content analysis. The relative abundance of these guilds is detailed in Table 4.

This diversity of feeding strategies underscores the ecological multifunctionality of mollusk communities inhabiting karstic coastlines, supporting key ecosystem processes such as biofilm regulation, detritus decomposition, and water purification. The numerical dominance of grazers and filter feeders, in particular, suggests a productive and well-structured benthic trophic network.

Furthermore, the assemblage was dominated by small-bodied and low-mobility taxa (e.g., *Cerithium*, *Pusia*, *Tesselliconus*), as shown in Figure 2, indicating that fine-scale microhabitat availability—rather than dispersal capacity—plays a central role in shaping molluscan community structure. This pattern reinforces the ecological significance of habitat heterogeneity and highlights the conservation value of maintaining microtopographic complexity in karstic intertidal ecosystems.

As shown in Figure 7, predators comprised the most species-rich guild, accounting for 42.9% of the total mollusk species, followed by grazers (32.1%) and filter feeders (17.9%). Scavengers were the least represented, comprising only 7.1% of species. This composition suggests that predator-prey interactions and grazing pressure are likely dominant ecological processes within the studied intertidal system. The relatively lower species richness of filter feeders and scavengers may reflect their habitat specificity or susceptibility to environmental fluctuations such as sedimentation or pollution.

Habitat association and microhabitat preferences

The karstic coastal beaches of Gunung Kidul exhibit pronounced habitat heterogeneity, which plays a pivotal role in structuring molluscan assemblages across the five surveyed sites. Species distributions were strongly tied to substrate type, tidal zone, and microtopographic complexity, emphasizing the importance of fine-scale habitat features in maintaining intertidal biodiversity (Table 1).

Rocky intertidal zones and tide pools emerged as the most species-rich microhabitats, particularly at Torohudan and Ngrawah. These areas supported high abundances of gastropods such as *E. malaccana*, *M. striata*, *C. biminiense*, and *N. turrita* (Table 1). These taxa typically occupied rock surfaces, cracks, and shaded crevices, where periphytic algae and microbial biofilms served as primary food sources. The visual documentation in Figure 3 shows several of these species in their typical habitats. Tide pools offered essential microclimatic buffering—retaining moisture and stabilizing temperature and salinity—which are critical for intertidal survival under prolonged low tide exposure (Harley et al. 2006).

In contrast, sheltered sites like Dadap Ayam and Ngrenehan, characterized by sand or muddy substrates, harbored predominantly infaunal and semi-infaunal bivalves. Species such as *Meretrix* sp., *Mya* sp., and *S. cucullata* were abundant in these environments (Table 1), taking advantage of reduced wave energy, sediment availability, and organic enrichment. Notably, *P. viridis* formed dense aggregations at Ngrenehan, where sediment accumulation and calm hydrodynamic conditions likely facilitated larval settlement and post-metamorphic growth.

Several mollusk species demonstrated clear microhabitat specialization. *T. argyrostomus* was observed exclusively on exposed rocky shores at Torohudan, while *Columbellidae* sp. was restricted to shallow, detritus-rich tide pools. Other small-sized gastropods such as *Pyramidellidae* and *Pusia luculentum* were confined to cryptic niches beneath rocks or embedded in filamentous algal mats (Figure 3), indicating reliance on structural microcomplexity for protection and feeding.

Vertical zonation patterns were also evident. Upper intertidal species such as *S. javanica* and *M. myosotis* occupied splash zones and elevated rocky ledges, tolerating periodic desiccation and variable salinity (Figure 3). The mid-intertidal zone hosted the greatest taxonomic richness and functional diversity, whereas carnivorous gastropods and filter-feeding bivalves were more common in the lower intertidal or shallow subtidal margins.

These habitat associations underscore the critical role of microhabitat diversity in sustaining molluscan community structure. Rather than being evenly distributed, species were concentrated in distinct habitat types defined by substrate, hydrodynamics, and tidal exposure. This mosaic of ecological conditions represents a hallmark of tropical karst coastlines and highlights the need to conserve multiple intertidal habitat forms to protect benthic biodiversity effectively.

Discussion

Diversity and taxonomic composition of mollusks

The molluscan assemblages documented from the karstic coastal habitats of Gunung Kidul exhibit moderate species richness, comprising 28 confirmed species distributed across 22 genera and 17 families. Gastropods dominated the community, accounting for 78.6% of the taxa, while bivalves represented the remaining 21.4%. This taxonomic distribution reflects typical patterns in tropical intertidal ecosystems, where gastropods tend to predominate due to their broad ecological plasticity, including adaptability to diverse microhabitats and varied feeding modes (Davenport et al. 2011; Hadiyanto et al. 2023).

The most speciose families were Conidae, Muricidae, and Cerithiidae, each contributing multiple taxa of ecological relevance. Predatory gastropods from the families Conidae and Muricidae, including *S. alderi* and *Purpuriconus stanfieldi*, play a crucial role in regulating prey populations and maintaining trophic balance within the intertidal food web (Cernohorsky 1984; Taylor 1984). In contrast, cerithiid grazers such as *C. biminiense* and *C. bifasciata* are important in biofilm consumption and periphyton control, contributing to nutrient cycling and the maintenance of substrate quality in rocky shore environments.

The presence of filter-feeding bivalves such as *P. viridis*, *S. cucullata*, and *Meretrix* sp. in sheltered and sedimentary beaches further adds to the functional diversity of the assemblage. Although fewer in number, these species contribute significantly to benthic-pelagic coupling, filtering organic particulates and stabilizing substrate through byssal attachment or burrowing (Dame 1996; Bracken and Nielsen 2004).

Taxonomic clarification was a necessary step in this study, as initial identifications—based largely on visual assessment—contained numerous misapplied names, including several fictional or invalid taxa such as *Bullata lilacina* and *Macrocypraea mammoth*. These taxa were excluded following rigorous cross-referencing with recognized databases (e.g., MolluscaBase 2023; WoRMS 2024). This underscores the importance of taxonomic accuracy in biodiversity assessments, especially when common names or image-based identifications are prone to error (Rosenberg 2014).

The distribution pattern observed—with the majority of species occurring at only one or two sites—suggests a patchy and site-dependent composition, likely driven by small-scale environmental heterogeneity. This pattern is common in karstic and rocky intertidal systems where microhabitats such as tide pools, rock crevices, and sediment pockets vary drastically even across short distances (Underwood and Chapman 1996; Gray 2002).

Compared to other molluscan surveys in tropical Southeast Asia, the species richness documented here is modest but ecologically significant. For instance, studies in Malaysian mangrove-rocky systems report 35-50 mollusk species (Tan and Clements 2008), while Philippine volcanic coasts yield 30-40 intertidal taxa (Reyes et al. 2020). The slightly lower diversity in Gunung Kidul may reflect a combination of geomorphological constraints, seasonal sampling limitations, and human-induced habitat degradation (e.g., trampling, waste, or collection pressure). The molluscan diversity recorded reflects a functionally and taxonomically varied assemblage, with both widespread generalists and localized specialists. Such a structure provides a foundation for ecosystem resilience, but also highlights the vulnerability of narrowly distributed species to disturbance and habitat fragmentation.

Ecological drivers of species richness and distribution

The uneven distribution of mollusk species among the five surveyed beaches—Pringjono, Torohudan, Ngrawah, Dadap Ayam, and Ngrenehan—suggests that local ecological conditions strongly influence species richness and composition. Key factors shaping these patterns include substrate type, wave exposure, tidal amplitude, and organic matter availability, all of which vary markedly across the karst coastline of Gunung Kidul.

Sites with complex rocky substrates, such as Torohudan and Ngrawah, supported the highest molluscan diversity. These areas provide a mosaic of tide pools, crevices, and algal mats, which offer refuge from desiccation and predation, as well as abundant food resources for herbivores and scavengers. Such structural complexity has long been recognized as a driver of species richness in intertidal habitats (Gratwicke and Speight 2005; McArthur et al. 2010). For example, *N. turrita* and *C. biminiense* were consistently associated with tide pools and algal-covered rock surfaces, indicating habitat specialization and microhabitat fidelity.

In contrast, Ngrenehan Beach, which is more sheltered and dominated by sandy and silty substrates, exhibited the lowest species richness but the highest total mollusk density, largely due to the dominance of bivalves such as *P. viridis* and *S. cucullata*. These filter feeders thrive in nutrient-enriched environments with lower hydrodynamic stress, emphasizing how substrate type and water movement shape community composition (Gosling 2003; Babarro and Reiriz 2010).

Tidal amplitude and exposure duration also play crucial roles in determining which species can persist in each zone. Understanding these zonation patterns is of paramount importance in our quest to comprehend the intricate dynamics of intertidal ecosystems. High-shore mollusks such as *S. javanica* and *Myosotella myosotis* tolerate desiccation and variable salinity, while mid- and low-shore species are more dependent on constant moisture or submersion. Such zonation patterns are consistent with intertidal ecological theory (Levinton 2001; Little and Kitching 1996), and they explain why some species were restricted to narrow vertical ranges despite being present across multiple sites.

Another ecological driver is anthropogenic influence, particularly trampling and resource extraction. Interviews with local residents indicate that certain beaches, especially Pringjono and Dadap Ayam, are frequented by tourists or shell collectors, potentially disturbing microhabitats and reducing sensitive taxa. The potential impact of these human activities on the delicate balance of intertidal ecosystems is a cause for concern. Although this study did not directly measure human pressure, prior studies have shown that even low-level disturbance can alter intertidal mollusk community structure (Addessi 1994; Brosnan and Crumrine 1994).

Ecological heterogeneity—both natural and anthropogenic—is a key determinant of mollusk distribution and diversity in this karst coastal system. The contrasting patterns observed across sites suggest that conservation and management efforts must be tailored to the specific ecological dynamics of each beach, rather than applying a uniform strategy across the region.

Microhabitat heterogeneity and functional guilds

One of the defining features of the Gunung Kidul coastal ecosystem is its pronounced microhabitat heterogeneity, particularly within the intertidal zones of its karstic beaches. This spatial complexity plays a pivotal role in shaping molluscan community structure by supporting a broad spectrum of functional guilds that collectively contribute to ecological functioning, resilience, and trophic integration.

The diversity of molluscan microhabitats—ranging from exposed rocky platforms, tide pools, and crevices, to sandy flats and buried sediments—facilitates the coexistence of taxa with divergent ecological strategies. Herbivorous gastropods such as *N. turrita* and *C. biminiense* thrive in algae-rich microhabitats, where they regulate periphytic growth and drive nutrient cycling (Lubchenco 1978; Denny and Gaines 2007). These grazers form a crucial component at the base of intertidal food webs and are often considered indicators of primary productivity.

Filter-feeding bivalves like *P. viridis*, *S. cucullata*, and *M. meretrix* occupy functionally distinct roles, relying on water column productivity and suspended particulates. Their distribution in sheltered bays such as Ngrenehan and Dadap Ayam reflects both their sensitivity to hydrodynamic stress and their role in benthic-pelagic coupling—essential for water filtration and nutrient redistribution in coastal systems (Newell 2004).

Carnivorous gastropods such as *S. alderi*, *M. striata*, and members of Columbellidae represent key mesopredators that help control the abundance of sessile and mobile prey taxa. Their site-specific distribution indicates microhabitat dependence, particularly for shaded or crevice-bound environments where prey density is higher (Paine 1974; Fairweather and Underwood 1983). Taxa like *S. javanica* and *M. myosotis* are adapted to supralittoral conditions, tolerating periodic desiccation, heat, and salinity fluctuations. Though often overlooked in biodiversity inventories, these species contribute to post-disturbance recolonization and biofilm regulation in high-shore zones (Little and Kitching 1996).

Analysis of species-level feeding guild composition (Figure 7) reinforces the ecological multifunctionality of this assemblage. Predatory mollusks comprised the most species-rich guild, followed by grazers and filter feeders, indicating that energy flow in these systems is predominantly channeled through herbivory and carnivory rather than detritivory. This aligns with the dominance of mobile epifaunal taxa adapted to hard substrates and variable tidal exposure.

The presence of multiple feeding strategies and life-history adaptations suggests that the molluscan community is both functionally diverse and ecologically compartmentalized. This supports the growing consensus that biodiversity assessments should emphasize functional diversity in addition to taxonomic richness (Petchey and Gaston 2002; Mouillot et al. 2013), as these dimensions better capture the ecosystem-level contributions of species.

The occurrence of habitat specialists such as *T. argyrostomus* and *P. luculentum* underlines the vulnerability of functional diversity to habitat degradation. The loss of microhabitat features—whether through coastal erosion, tourism infrastructure, or unmanaged harvesting—may trigger disproportionate declines in specialized species, compromising ecosystem function and resilience. The functional roles of mollusks in Gunung Kidul's karstic intertidal zones are intricately tied to geomorphological heterogeneity. Conservation strategies must prioritize the protection of microhabitat mosaics to safeguard not only species richness but also the ecosystem services provided by these ecologically diverse and functionally integral taxa.

Comparison with other tropical karst and coastal ecosystems

Molluscan assemblages documented in the karst beaches of Gunung Kidul share several ecological and taxonomic features with those found in other tropical limestone and rocky shore systems. Yet, they also exhibit localized patterns shaped by regional geomorphology, climate, and anthropogenic influences.

Similar karstic coastal zones in Southeast Asia—such as Pangasinan and Palawan (Philippines) and Langkawi (Malaysia)—also support molluscan communities dominated by Gastropoda, particularly members of Muricidae, Neritidae, and Cerithiidae, reflecting the affinity of these taxa for hard substrates and complex intertidal structures (Tan and Clements 2008; Reyes et al. 2020). However, the specific composition and distribution of species often vary. For example, while *N. turrita* and *Cerithium* spp. are widely distributed across the Indo-Pacific (Kano et al. 2001), species such as *M. striata* and *S. alderi* may exhibit more localized or discontinuous occurrences, potentially influenced by larval dispersal capacity and coastal hydrodynamics (Kay and Palumbi 1987).

The species richness in Gunung Kidul (28 confirmed taxa) is modest compared to reports from coral rubble or reef-associated intertidal zones, which may host 40-80 mollusk species due to higher habitat complexity and connectivity (Rahmawati et al. 2021; MolluscaBase 2023). However, for non-reefal, karst-dominated beaches, this diversity is relatively representative and ecologically meaningful, particularly given the limited vertical and horizontal intertidal extent of many Gunung Kidul beaches.

Notably, bivalve representation in the study area is lower than in mangrove-mudflat systems (e.g., Myanmar delta or Thai estuarine coasts), where soft sediments and high organic content support dense populations of filter feeders and detritivores (Matthews and Fairweather 2003). In contrast, the patchy occurrence of bivalves in Gunung Kidul is restricted to more sheltered and sediment-rich sites such as Ngrenehan and Dadap Ayam. This difference underscores the importance of substrate type and wave exposure as primary drivers of benthic community composition in karst ecosystems (Gray 2002).

In terms of functional groups, the molluscan assemblages of Gunung Kidul also resemble those of other tropical rocky intertidal zones, with a predominance of grazers, followed by filter feeders and carnivores. However, the study area shows relatively low representation of large-bodied mollusks (e.g., *Tectus*, *Trochus*, or large *Strombus* species), which are often recorded in less disturbed or better-connected reef-coastlines (Prasetya et al. 2017). This could reflect human harvesting pressure, ecological degradation, or natural limitations of karstic topography in sustaining larger macrofauna.

Compared to Indonesian coastal studies in areas like Bali, South Sulawesi, or Lombok, which emphasize coral reef-associated mollusks, the Gunung Kidul region provides an important counterpoint by documenting molluscan diversity in non-reefal, karst-dominated intertidal systems, which remain underrepresented in regional biodiversity inventories (Zusron et al. 2019; Ginantra et al. 2020), while sharing broad ecological themes with other tropical coasts, the mollusk fauna of Gunung Kidul is shaped by karst geomorphology, wave exposure gradients, and human activity, warranting localized conservation strategies and more detailed comparative biogeographic analysis.

Conservation implications and management priorities

Molluscan assemblages in the karstic beaches of Gunung Kidul provide important ecological services, including nutrient cycling, biofiltration, and regulation of algal and detrital matter. Yet, their sustainability is increasingly threatened by anthropogenic pressures and environmental change. This study's findings underscore several key conservation concerns and offer pathways for informed management.

First, the presence of microhabitat specialists and site-restricted species—many of which were found only in one location—highlights the vulnerability of these organisms to habitat disturbance. Even minor physical alterations to tide pools, rock crevices, or sediment patches (e.g., due to trampling, unmanaged tourism, or infrastructure development) could disproportionately impact these species and disrupt local food webs (Addessi 1994; Brosnan and Crumrine 1994). Therefore, conservation efforts must prioritize microhabitat preservation as much as species protection.

Second, the exclusion of 17 taxa during the re-identification process due to taxonomic inconsistencies or fictive naming reveals a significant challenge in biodiversity documentation: the reliance on informal or erroneous species labels. This issue, common in rapid surveys or non-expert-led identifications, risks overestimating diversity and undermining ecological interpretations (Rosenberg 2014). Training local stakeholders and ecotourism guides in basic taxonomic literacy—paired with accessible field guides and digital tools—could improve data quality and conservation awareness.

Third, several beaches—particularly Ngrenehan and Dadap Ayam—support high mollusk density but low species richness, suggesting functional dominance by a few opportunistic taxa. Such skewed assemblages may reflect ecological imbalance or stress and warrant further investigation. On the other hand, sites like Torohudan and Ngrawah, with higher species richness and functional diversity, could be proposed as priority conservation zones or ecological reference sites.

Fourth, most karst beach systems in Gunung Kidul currently do not have formal protection status despite their unique geomorphological and biological features. Establishing community-managed Marine Protected Areas (MPAs) or ecotourism zoning schemes—backed by scientific data and participatory planning—could enhance stewardship and long-term habitat resilience (Walters et al. 1998; Christie et al. 2005).

Lastly, the results advocate for an integrated management approach that considers both biodiversity and local livelihoods. Many mollusk species in this study are harvested or traded locally for food, decoration, or cultural purposes. Developing sustainable harvest protocols, seasonal closures, or no-take zones can reconcile conservation goals with economic needs, particularly if combined with environmental education and incentive-based schemes.

In conclusion, the mollusk communities of Gunung Kidul's karst beaches serve as ecological indicators and conservation priorities. Their protection requires a mix of scientific monitoring, habitat-specific strategies, and community engagement, ensuring that biodiversity and ecosystem services are maintained for future generations. In this study also provides the first detailed account of mollusk diversity, distribution, and ecological associations across five karstic beach ecosystems in Gunung Kidul, Yogyakarta, Indonesia. A total of 28 valid species were identified, with Gastropoda overwhelmingly dominant over Bivalvia, reflecting the structural complexity and tidal exposure of the rocky intertidal habitats. Species richness and density varied markedly among sites, shaped by microhabitat heterogeneity, substrate type, and hydrodynamic conditions. Functional guilds—including grazers, filter feeders, and carnivores—were differentially distributed, indicating a compartmentalized and ecologically diverse molluscan community. The exclusion of 17 misidentified or unverified taxa underscores the importance of accurate taxonomy in ecological studies, especially in under-surveyed karst regions. This highlights the methodological importance of the study. Conservation efforts should prioritize tide pools and rocky shore microhabitats, which harbor the highest diversity and many specialist species. Moreover, local management plans must consider both biological significance and socio-economic context to ensure sustainable use of molluscan resources. Overall, the mollusk fauna of Gunung Kidul represents an ecologically important, yet vulnerable, component of coastal karst ecosystems, deserving of greater research attention and conservation investment. This baseline assessment offers critical insights for future biodiversity monitoring, community-based conservation, and integrated coastal management in Java and beyond.

The observed molluscan assemblages demonstrate the intricate link between habitat heterogeneity and biodiversity maintenance in karstic coastal systems. Conservation strategies should therefore prioritize the protection of microhabitats and spatial mosaics to sustain ecological functions and adaptive potential in the face of environmental change.

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