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Predicting of HABs by phytoplankton type and abundance in Northern Bone Bay, South Sulawesi, Indonesia

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ABSTRACT

Introduction: Harmful Algal Blooms (HAB) are the rapid growth of algae or cyanobacteria in water that can cause negative impacts on people, animals, or the environment by production of natural toxins. Information about HABs in the bays in Indonesia is limited.

Objective: To predict HABs based on the type and abundance of phytoplankton in the Northern part of Bone Bay, South Sulawesi, Indonesia.

Methods: The study was conducted in four locations, namely Tj Ringgit (TR), Passampa (PS), Siwa (SW), and Barangmamase (BM) between May and July 2024. Various environmental parameters, including nutrients, were measured. Phytoplankton samples were collected by filtering seawater using a 25 µm plankton net and analyzed in the laboratory.

Results: The dominant types of phytoplankton were found to be *Bacteriastrium*, *Chaetoceros*, *Leptocylindrus*, *Rhizosolenia*, *Thalassionema*, and *Ceratium*. All of them are classified as Non-HABs. The identified types of HABs include *Pseudo-nitzschia*, *Dinophysis*, *Prorocentrum*, *Protoperidinium*, and *Oscillatoria*. Orthophosphate and salinity are two environmental parameters that affect the occurrence of HABs. The proportion of HABs abundance was lower than that of non-HABs in all locations. An increase in the abundance of HABs was detected in two locations: SW and BM.

Conclusion: Although the proportion of HABs is lower than that of Non-HABs, the increased abundance of HABs in some locations, such as SW and BM, indicates the potential for future blooms. Monitoring environmental parameters, especially orthophosphate and salinity, is critical to mitigating the impact of the development of HABs, which ultimately affects the ecosystem and human health in Bone Bay. This study emphasizes the importance of sustainable water management to maintain the balance of the ecosystem in the bay.

Key words: phytoplankton; harmful algal blooms (HABs); Bone Bay; orthophosphate; salinity; mitigation.



RESUMEN

Predicción de proliferaciones de algas nocivas por tipo y abundancia de fitoplancton en el norte de Bone Bay, Sulawesi del Sur, Indonesia

Introducción: Las proliferaciones de algas nocivas (PANs) son el crecimiento rápido de algas o Cianobacterias en el agua que pueden causar impactos negativos en las personas, los animales o el medio ambiente mediante la producción de toxinas naturales. La información sobre PANs en las bahías de Indonesia es limitada.

Objetivo: Predecir la aparición de PANs en función del tipo y abundancia de fitoplancton en la bahía de Bone, Sulawesi sur, Indonesia.

Métodos: El estudio se realizó en cuatro localidades: Tj Ringgit (TR), Passampa (PS), Siwa (SW) y Barangmamase (BM), entre mayo y julio de 2024. Se midieron varios parámetros ambientales, incluidos los nutrientes, y se recolectaron muestras de fitoplancton mediante filtración de agua marina. Las muestras se analizaron en el laboratorio.

Resultados: Los tipos dominantes de fitoplancton fueron: *Bacteriastrium*, *Chaetoceros*, *Leptocylindrus*, *Rhizosolenia*, *Thalassionema* y *Ceratium*, todos clasificados como No-PANs. Los taxa identificados de PANs fueron: *Pseudo-nitzschia*, *Dinophysis*, *Prorocentrum*, *Protoperidinium* y *Oscillatoria*. El ortofosfato y la salinidad fueron los principales factores ambientales que afectaron la aparición de PANs. La abundancia de PANs fue menor que la de No-PANs en todas las localidades, aunque en dos sitios, SW y BM, se observó un incremento en la abundancia de PANs.

Conclusión: A pesar de que la proporción de PANs fue menor que la de No-PANs, el aumento de PANs en algunos lugares sugiere un posible desarrollo futuro de estas proliferaciones. El monitoreo de ortofosfato y salinidad resulta esencial para mitigar los impactos de PANs, protegiendo tanto el ecosistema como la salud en la bahía de Bone. Este estudio enfatiza la importancia de la gestión sostenible del agua para mantener el equilibrio del ecosistema en la bahía.

Palabras clave: fitoplancton; proliferaciones de algas nocivas (PAN); Bone Bay; ortofosfato; salinidad; mitigación.

INTRODUCTION

Phytoplankton are microscopic organisms that are found in the surface layers of waters, such as in the open sea (Latasa et al., 2022), lakes (Salmaso & Tolotti, 2021), and bays (Sarkar et al., 2021). Through photosynthesis, phytoplankton absorb sunlight and then convert it into chemical energy to produce glucose as a source of energy and oxygen (Basnayaka et al., 2024). Therefore, they serve as the core of the food chain and oxygen production in the waters. Through the production of energy and oxygen, phytoplankton plays an important role in maintaining the balance of aquatic ecosystems (Wong et al., 2023).

As organisms that can absorb carbon dioxide (CO₂) from the atmosphere, phytoplankton play a role in the global carbon cycle (Boyd et al., 2024). The absorbed carbon is stored in its body (Naselli-Flores & Padisák, 2023). When this organism dies, the carbon sinks to the seafloor (Wang et al., 2024). That process

is known as a “carbon biological pump”, which helps reduce CO₂ levels in the atmosphere (Siegel et al., 2023). Through the food chain, carbon stored in the body of phytoplankton can be transferred to other organisms, spreading its benefits throughout marine ecosystems and reducing the impact of climate change (Kabir et al., 2023).

The presence of phytoplankton becomes dangerous when the community overgrows, producing a toxic phytoplankton bloom in the waters. Harmful Algal Blooms (HABs) are a term that is often used to describe the event (Li et al., 2023). HABs can grow if environmental conditions favor their growth (Ou et al., 2024). It can inhibit the growth of other phytoplankton (Chatterjee & More, 2023) and the death of fish (Feng et al., 2024). As HABs grow and develop, they also secrete toxic substances that are released into the waters. These toxins then affect other type of phytoplankton, which can stunt growth and cause them to die (Lan et al., 2024). HABs can also cause fish death

(Parra-Saldivar et al., 2023). When HABs are consumed by fish or attached to their gills, the fish's physiological function will be disrupted, causing stress and ultimately causing death (Hallegraeff et al., 2023).

When fish die from HABs, they decompose in the waters. This decomposition process is carried out by bacteria that need oxygen to decompose organic matter from phytoplankton and dead fish. In the event of a significant death, bacteria consume very high amounts of oxygen, reducing dissolved oxygen levels. This condition is known as hypoxia, which can create dead zones where oxygen levels are too low to support the life of other aquatic creatures, such as fish and shrimp, ultimately leading to ecosystem damage (Zahir et al., 2024).

Some phytoplankton type often associated with HABs are *Karenia* (Kuroda et al., 2024). This type is known to cause poisoning of fish and marine mammals. Other type, such as *Dinophysis*, can produce toxins that affect human health by consuming contaminated seafood (Vieira et al., 2024). *Alexandrium* is also an organism that causes seafood to contain toxins, especially in areas that often experience HABs (Bui et al., 2024). Given the severe impact it causes, monitoring and research on HABs is very important to maintain the health of aquatic ecosystems and human safety.

In its development, the increase in the number and abundance of HABs in waters, including bays, shows a significant increase (Anderson et al., 2021). The results showed that nutrient-rich bays, such as those in the Chesapeake Bay, often experience HABs such as *Karlodinium* and *Microcystis* blooms. Both have been studied for their harmful impacts on aquatic ecosystems and the shellfish industry (Wolny et al., 2020). Similarly, in the Gulf of Mexico, the explosion of the toxic population of *Karenia* type (commonly known as red tides) has been of particular concern, as it produces brevetoxins that are harmful to marine life and humans (Tominack et al., 2020).

The growth of phytoplankton type, including HABs (Blooms) in the bay, is due to anthropogenic processes on land. The activity

increases the concentration of nutrients that promote the growth of different phytoplankton type, including HABs (Blooms) (Rajapaksha et al., 2024). As a result, it affects the health of the ecosystem and the fisheries and tourism industries (Álvarez et al., 2024). For this reason, effective monitoring and management of factors that trigger HABs is essential to protect public health and the sustainability of aquatic resources (Carias et al., 2024).

Based on various occurrences of HABs in several bays worldwide, we have conducted studies to predict the emergence of HABs based on the type and abundance of phytoplankton in the Northern part of Bone Bay, South Sulawesi, Indonesia. This is a preliminary study because information about HABs in the region, including in other bays in Indonesia, is limited. This is related to the fertility conditions of the waters in the Bay. The analysis of available literature shows limited data related to phytoplankton type, including data on environmental parameters that affect it. However, the potential for HABs to develop in this bay is very likely, considering that Bone Bay is classified as fertile due to the input of inorganic and organic materials from anthropogenic activities, such as ponds, agriculture, households, ports, and high fishing activities.

MATERIAL AND METHODS

Time and Location of the study: The research was conducted from May to July 2020. The data was collected in Northern Bone Bay, South Sulawesi, Indonesia. Four research locations (Fig. 1) are located in the coastal waters of Palopo City: Tj Ringgit (TR), Passampa (PS) from Luwu Regency, Siwa (SW), and Barangmamase (BM).

Research materials and design: The primary material used in this study is seawater samples collected from four locations. Specific environmental parameters are measured directly in the field, while others are analyzed in the laboratory. This research is non-experimental. The parameters observed without intervention

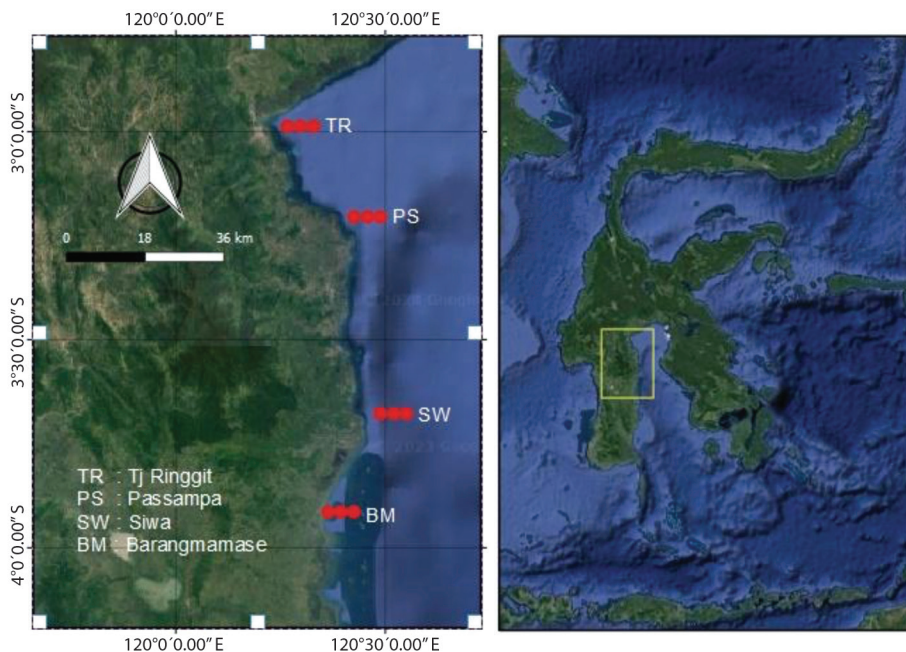


Fig. 1. Research Location in Bone Bay.

from the researchers included the types of phytoplankton HABs and non-HABs.

Analysis of phytoplankton HABs and non-HABs: Seawater filtration was done directly at the research site to enumerate phytoplankton type and abundance. A 50-liter water sample was filtered using a plankton net with a mesh size of 25 μm . The results of the sieve containing phytoplankton in the plankton net bucket were put into a sample bottle with a volume of 100 ml, then preserved with five ml of Lugol one N solution. The sample bottles were placed in a cool box containing ice cubes to be analyzed in the laboratory. The sweeping method (census) calculates the type and abundance of phytoplankton cells (Filatov & Kirkpatrick, 2024). A total of one milliliter of the filtered result was inserted into a 50 mm x 20 mm x 1 mm Sedgwick Rafter Cell (SRC) (de Vries et al., 2024), using a scaled pipette. SRC was observed using a binocular microscope (Olympus CX21) at a magnification scale of 10 x 10. Standard references, such as Tomas (1997)

and Castellani & Edwards (2017), were used for phytoplankton identification.

Measurement of in-situ and ex-situ environmental parameters: Environmental parameters *in situ* include temperature, pH, salinity, and current velocity. Each of these parameters was measured using a thermometer for temperature ($^{\circ}\text{C}$), a pH meter for pH, a refractometer for salinity (ppt), and a drogue that has been calibrated for current speed (m/s). Other parameters were measured in the laboratory, such as turbidity (NTU), which was measured using the nephelometry method, according to the instructions of Strickland and Parsons (1972). The nutrient concentration was measured according to methods developed by APHA (Rice et al., 2017); the nitrate by the brucine method, while nitrite by sulfanilamide, ammonium by phenate, orthophosphate by stannous chloride, and silicate by molybdosilicate.

Statistical analysis: The data was analyzed descriptively using tables and figures. One-way

variance analysis (One-way ANOVA) (Chatzi & Doody, 2023) was applied to test the abundance of phytoplankton HABs based on location differences. If ANOVA shows a significant difference at a 95 % confidence level ($\alpha = 0.05$), the analysis continues with Tukey's post-hoc test (Juarros-Basterretxea et al., 2024). Before conducting further tests, the parameters were tested first through a normality test using Kolmogorov-Smirnov and Levene's Test of Equality (Fiandini et al., 2024). Multiple linear regression analysis (Ismail & El Zokm, 2023) was applied to evaluate various parameters that supported the growth of HABs. The entire analysis was done using SPSS 25 software (IBM Corp., 2017) and Excel Stat 2017 (Addinsoft, 2017).

RESULTS

Environmental Parameters: Table 1 presents the results of measuring environmental parameters, including temperature, salinity, pH, current speed, turbidity, and nutrients (nitrate, nitrite, ammonia, orthophosphate, and silicate). Observations of various oceanographic parameters were carried out to analyze the suitability of environmental conditions with the life of HABs in each research location. Based on the measurement results, most of the values of each parameter are within the range that supports phytoplankton growth, including the type of HABs. Based on environmental parameters, particularly nutrients, the water status ranges from mesotrophic (phosphate: orthophosphate) to eutrophic (total nitrogen: nitrate, nitrite, ammonia) (Hakanson & Bryhn, 2008).

Phytoplankton Composition of Non-HABs and HABs: The three classes of phytoplankton identified in this study are Bacillariophyceae, Dinophyceae, and Cyanophyceae. Among the three classes, Bacillariophyceae has the highest number of types, i.e., 19, while Dinophyceae and Cyanophyceae have only four and one type, respectively (Table 2 and Fig. 2).

The dominant types of phytoplankton in this study include *Bacteriastrium*, *Chaetoceros*, *Leptocylindrus*, *Rhizosolenia*, and

Table 1
Results of environmental parameter measurement.

Location	Parameter					Nutrients (mg/L)					
	Station	Temperature (°C)	Salinity (ppt)	pH	Current Speed (m/det)	Turbidity (NTU)	Nitrate	Nitrite	Ammonia	Orthophosphate	Silicate
Tj Ringgit (TR)	TR1	28.0 ± 0.00	15.3 ± 0.58	7.74 ± 0.02	0.39 ± 0.03	2.96 ± 0.23	0.04 ± 0.01	0.04 ± 0.00	0.60 ± 0.03	0.02 ± 0.00	0.00 ± 0.00
	TR2	28.0 ± 0.00	23.3 ± 0.58	7.76 ± 0.01	0.28 ± 0.13	0.80 ± 0.10	0.03 ± 0.00	0.03 ± 0.00	0.70 ± 0.07	0.02 ± 0.00	0.00 ± 0.00
	TR3	28.0 ± 0.00	17.7 ± 0.58	7.76 ± 0.02	0.18 ± 0.10	1.01 ± 0.22	0.02 ± 0.00	0.04 ± 0.00	0.80 ± 0.01	0.02 ± 0.00	0.00 ± 0.00
Passampa (PS)	PS1	30.1 ± 0.00	28.0 ± 0.00	7.78 ± 0.01	0.16 ± 0.09	0.84 ± 0.50	0.05 ± 0.00	0.08 ± 0.02	0.89 ± 0.00	0.02 ± 0.00	0.01 ± 0.00
	PS2	30.1 ± 0.00	28.7 ± 0.58	7.76 ± 0.01	0.21 ± 0.03	0.20 ± 0.14	0.03 ± 0.00	0.08 ± 0.02	0.69 ± 0.00	0.02 ± 0.00	0.01 ± 0.00
	PS3	30.1 ± 0.00	28.3 ± 0.58	7.77 ± 0.02	0.10 ± 0.02	1.02 ± 1.43	0.09 ± 0.01	0.08 ± 0.00	0.65 ± 0.00	0.02 ± 0.00	0.02 ± 0.00
Siwa (SW)	SW1	29.9 ± 0.06	29.3 ± 0.58	7.79 ± 0.02	0.16 ± 0.09	0.96 ± 0.81	0.04 ± 0.00	0.01 ± 0.01	0.63 ± 0.01	0.02 ± 0.00	0.02 ± 0.00
	SW2	30.0 ± 0.06	28.3 ± 0.58	7.78 ± 0.01	0.21 ± 0.03	0.19 ± 0.04	0.03 ± 0.00	0.05 ± 0.01	0.54 ± 0.01	0.02 ± 0.00	0.01 ± 0.00
	SW3	30.4 ± 0.61	30.3 ± 0.58	7.78 ± 0.00	0.10 ± 0.02	0.38 ± 0.16	0.03 ± 0.01	0.05 ± 0.01	0.53 ± 0.00	0.02 ± 0.00	0.01 ± 0.00
Barangmamase (BM)	BM1	29.0 ± 0.00	24.7 ± 0.58	7.81 ± 0.032	0.11 ± 0.037	10.15 ± 0.15	0.05 ± 0.01	0.03 ± 0.02	0.54 ± 0.02	0.02 ± 0.00	0.01 ± 0.00
	BM2	31.0 ± 0.00	23.3 ± 0.58	7.79 ± 0.01	0.07 ± 0.04	5.16 ± 0.14	0.05 ± 0.00	0.05 ± 0.03	0.49 ± 0.05	0.02 ± 0.00	0.01 ± 0.00
	BM3	30.0 ± 0.06	25.3 ± 0.58	7.79 ± 0.01	0.06 ± 0.00	3.65 ± 0.55	0.08 ± 0.00	0.04 ± 0.01	0.86 ± 0.05	0.02 ± 0.00	0.01 ± 0.58

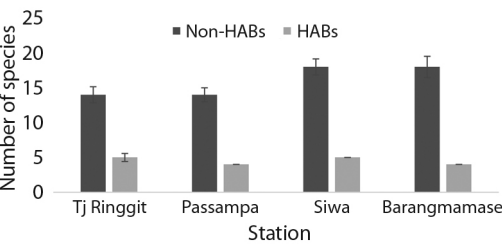


Fig. 2. Number of taxa from Non-HABs and HABs.

Thalassionema from the class Bacillariophyceae, as well as *Ceratium* from the class Dinophyceae (Table 2). All type identified are classified as Non-HABs type phytoplankton.

From Table 2 and Fig. 2, it can be seen that there was no single dominant type of HABs during the study. Also, several taxa type of phytoplankton HABs were detected, although not in dominant amounts, such as *Pseudo-nitzschia* of the class Bacillariophyceae,

Table 2
Number and Abundance of HABs and Non-HABs.

Type Number	Class	Type	Abundance (cell/L)			
			Tj Ringgit (TR)	Passampa (PS)	Siwa (SW)	Barangmamase (BM)
1	Bacillariophyceae	<i>Bacteriastrum</i> *	222	1 583	16	18
2		<i>Chaetoceros</i> *	5 555	21 091	525	794
3		<i>Coscinodiscus</i> *	12	20	54	12
4		<i>Cyclotella</i> *	23	23	9	15
5		<i>Dactyliosolen</i> *	1		9	2
6		<i>Ditylum</i> *	5	12	11	10
7		<i>Guinardia</i> *	3	15	4	17
8		<i>Hemiaulus</i> *			2	24
9		<i>Lauderia</i> *				2
10		<i>Leptocylindrus</i> *	111	271	36	1 262
11		<i>Nitzschia</i> *	1	6	8	61
12		<i>Odontella</i> *			1	2
13		<i>Pleurosigma</i> *		1	6	14
14		<i>Pseudo-nitzschia</i> **	29	310	33	272
15		<i>Rhizosolenia</i> *	189	596	49	74
16		<i>Skeletonema</i> *	20	25	22	1 122
17		<i>Synedra</i> *	10	13	9	31
18		<i>Thalassionema</i> *	282	747	402	479
19		<i>Triceratium</i> *			1	
Abundance of Type			6 463	24 713	1 197	4 211
Number of Type			14	14	18	18
20	Dinophyceae	<i>Ceratium</i> *	125	7	71	29
21		<i>Dinophysis</i> **	31	3	11	
22		<i>Prorocentrum</i> **	6	1	10	13
23		<i>Protoperidinium</i> **	33	27	27	33
Abundance of Type			195	38	119	75
Number of Type			4	4	4	3
24	Cyanophyceae	<i>Oscillatoria</i> **	3	3	2	36
Abundance of Type			3	3	2	36
Number of Type			1	1	1	1
Total Abundance			6 661	24 755	1 318	4 322
Total Type			19	19	23	22

* Non HABs; ** HABs

Table 3
ANOVA results of the abundance of HABs during the study.

ANOVA					
	The sum of Squares	df	Mean Square	F	Sig.
Between Groups	198582.917	3	66194.306	3.057	0.092
Within Groups	173214.000	8	21651.750		
Total	371796.917	11			

Dinophysis, *Prorocentrum*, *Protoperidinium* of the class Dinophyceae, and *Oscillatoria* of the class Cyanophyceae.

Proportion of HAB abundance: The results showed that the proportion of HABs abundance was lower than that of non-HABs (Fig. 2). In the TR and PS locations, the abundance of HABs only reached 1.53 and 1.39 %, while the abundance of Non-HABs reached 98.47 and 98.61 %, respectively. In SW and BM locations, the proportion of HABs increased to 6.25 and 8.18 %, although non-HABs remained dominant with a proportion of 93.75 and 91.82 % (Table 3 and Fig. 3).

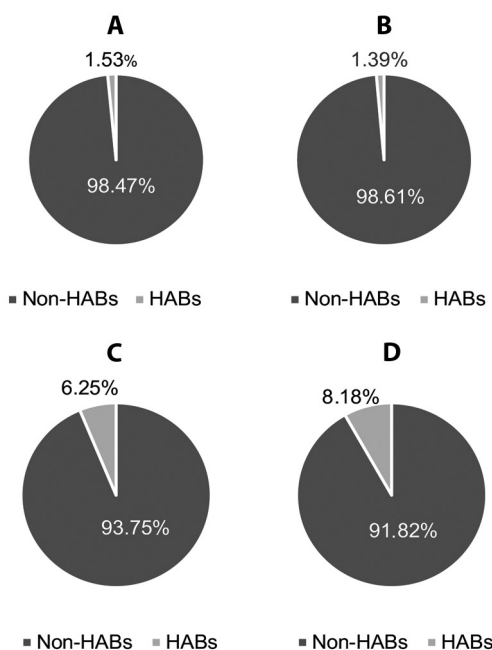


Fig. 3. Proportion of abundance of Non-HABs and HABs: (A) Tj Ringgit (TR); (B) Passampa (PS); (C) Siwa (SW); (D) Barangmamase (BM).

There was no statistically significant difference ($p > 0.05$) based on the results of the analysis of the variance of HABs abundance between the locations studied (Table 3). These findings indicate that the abundance of HABs was considered uniform across sites during the study.

Detection of Environmental Parameters Affecting the Emergence of Phytoplankton HABs: To ascertain the factors that cause the emergence of phytoplankton HABs in Bone Bay in the Northern part of South Sulawesi, a multiple linear regression analysis has been carried out between the abundance of phytoplankton HABs and various environmental parameters such as temperature, salinity, pH, turbidity, current speed, nitrate, and orthophosphate. The test results showed that the environmental parameters had a real relationship ($p = 0.14$) with HABs (Table 4). Based on verifying environmental parameters that affect HABs, orthophosphate and salinity were found with a determination coefficient (R^2) of 61.1 %.

DISCUSSION

The results of the enumeration of phytoplankton type showed that the number of type from the Bacillariophyceae class was more than that of the Dinophyceae and Cyanophyceae classes. The abundance of Bacillariophyceae type is due to their ability to adapt to a variety of aquatic environments, including freshwater (Quevedo-Ortiz et al., 2024), marine (Hochfeld & Hinnern, 2024), and estuaria (Solórzano, 2024). This adaptability allows them to colonize diverse habitats and respond to varying environmental conditions. They can grow well



Table 4
Summary model and regression analysis of HABs phytoplankton abundance with various environmental parameters.

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.595 ^a	0.354	0.289	0.29644
2	0.782 ^b	0.611	0.525	0.24243

a. Predictors: (Constant), Orthophosphate.
b. Predictors: (Constant), Orthophosphate, Salinity.

ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.482	1	0.482	5.479	0.041 ^b
	Residual	0.879	10	0.088		
	Total	1.360	11			
2	Regression	0.831	2	0.416	7.073	0.014 ^c
	Residual	0.529	9	0.059		
	Total	1.360	11			

a. Dependent Variable: HABs (Log10).
b. Predictors: (Constant), Orthophosphate.
c. Predictors: (Constant), Orthophosphate, Salinity.

in a wide range of nutrients and temperatures (as in the case of this study), which supports their rapid growth. In reproducing, they reproduce asexually through continuous cell division (Krueger-Hadfield, 2024). In unfavorable environmental conditions, they turn to sexual reproduction, increasing cell counts and type diversity (Persson et al., 2024). This is very important for survival in a changing environment. The combination of asexual and sexual reproduction contributes to a type of higher diversity, which can enhance ecosystem stability and resilience.

In contrast, the Dinophyceae and Cyanophyceae experience growth restriction that depends on environmental conditions (Goven-der & Jury, 2024; Lajnef et al., 2023). The type of phytoplankton in these two classes are usually abundant in waters with low concentrations of nutrients and warmer temperatures (Dory et al., 2024). Thus, the diversity of the type tends to be lower. In addition, their reproductive ability is also slower than Bacillariophyceae (Hara-guchi et al., 2023).

Research conducted indicates that species within the Bacillariophyceae class dominate

phytoplankton communities during certain seasons, demonstrating their ability to adapt to seasonal changes (Bouma-Gregson et al., 2024). Selph et al. (2022) also noted that Bacillariophyceae exhibit better growth in nutri-ent-rich conditions, with a rapid reproduction capability through cell division. In contrast, Dinophyceae and Cyanophyceae grow more slowly and depend more on specific environ-mental conditions. Furthermore, a study found that Bacillariophyceae dominate phytoplankton communities in estuaries, with a significantly higher abundance compared to Dinophyceae and Cyanophyceae, highlighting their reliance on more specific environmental conditions (Essa et al., 2024).

During the study, phytoplankton type such as *Bacteriastrium*, *Chaetoceros*, *Leptocylin-drus*, *Rhizosolenia*, and *Thalassionema*, which are members of the class Bacillariophyceae (diatoms), were predominantly found. This dominance occurs because these type of phy-toplankton can adapt to high concentrations of nutrients (Kim et al., 2023). Under nutrient-rich environmental conditions, they can bloom rapidly in coastal waters (Zhu et al., 2024),

including bays (Shaika et al., 2023), as in this study. They can reproduce quickly through cell division (asexual) and are highly resistant to temperature fluctuations and salinity to thrive in various conditions. These multiple factors make them the most competitive and dominant type of phytoplankton in coastal and marine environments (Stewart et al., 2012).

Another ability of the class Bacillariophyceae phytoplankton species is to form dormant spores, especially *Chaetoceros*, when environmental conditions become unfavorable (for example, when nutrients are depleted or temperatures change drastically). According to Ishii et al. (2022), this type can form spores to survive in poor environmental conditions and remain on the seafloor or water column until conditions improve. When nutrients are abundant again, or temperatures return to optimal conditions, these spores return to active cells ready to multiply. This adaptation provides a significant competitive advantage in coastal waters, including bays (Command et al., 2023), where environmental changes are frequent, as it allows *Chaetoceros* to survive for long periods and restart growth when conditions improve (Kazmi et al., 2022).

Several type of phytoplankton in the class Bacillariophyceae have been known to have endosymbiotic relationships with nitrogen-fixing cyanobacteria, for example, *Rhizosolenia* (Mutalipassi et al., 2021). This endosymbiosis allows *Rhizosolenia* to take advantage of nitrogen from the atmosphere, especially when it is less available in the water column (Manigandan et al., 2024). This makes it superior in nitrogen-deficient environments, especially in more oligotrophic (nutrient-poor) open ocean waters. Its ability to obtain nitrogen from this symbiosis allows *Rhizosolenia* to thrive in environments where other phytoplankton may be limited by nitrogen deficiency (Martínez-Pérez et al., 2024), making them more competitive and often dominant.

Ceratium is a type of phytoplankton from the class Dinophyceae, which was also predominantly found during the study. These organisms can assimilate the available nutrients

available in the waters (Jachniak & Jaguś, 2023). This causes it to develop quickly when an abundant supply of nutrients, such as nitrogen and phosphate, is often available in coastal waters, including bays. Although they are not as fast as diatoms in absorbing nutrients, *Ceratium* can survive in nutrient-deficient environments, which helps it thrive over extended periods, especially when environmental conditions change (Albin et al., 2022). These microorganisms are commonly found in marine environments and can contribute to the occurrence of algal blooms, which may impact aquatic ecosystems. Additionally, they serve as primary producers in the food chain within these aquatic ecosystems.

As a mixotroph (Yang et al., 2021), *Ceratium* can perform photosynthesis while obtaining nutrients by consuming organic particles or other microorganisms through phagocytosis. This flexibility in nutrient acquisition allows it to survive and even dominate in coastal waters during nutrient scarcity. Under adverse conditions, the organism can form cysts that enable it to enter a dormant state and resume growth when conditions improve (Trottet et al., 2018). Nevertheless, its abundance is often lower than diatoms (Vajravelu et al., 2018). *Diatoms* are more efficient in utilizing nutrients such as silica and have a faster reproduction rate in nutrient-rich waters (Demir & Turkoglu, 2022).

During the study, several types of HABs were detected, such as *Pseudo-nitzschia* of the class Bacillariophyceae, *Dinophysis*, *Prorocentrum*, *Protoperdinium* of the class Dinophyceae, and *Oscillatoria* of the class Cyanophyceae. These HABs can produce toxins that harm humans (Sha et al., 2021), disrupt ecosystems, and degrade water quality (Heil & Muni-Morgan, 2021). Its growth can be rapid because it is triggered by nutrient-rich environmental conditions caused by human activities, such as agriculture and waste disposal. These blooms can cause significant economic impacts, especially on fisheries and tourism (Igwaran et al., 2024).

Pseudo-nitzschia is a diatom that can produce domoic acid, a neurotoxin harmful to humans and animals. Blooms of *Pseudo-nitzschia*



are often associated with the phenomenon of Amnesic Shellfish Poisoning (ASP) (Twiner et al., 2008). When shellfish consume this organism and store ASP toxins in their bodies and then ingest them by humans, this can cause health problems (Marques et al., 2010).

Dinophysis is known for its ability to produce okadaic acid, which causes Diarrhetic Shellfish Poisoning (DSP) disease (Henigman et al., 2024), while *Prorocentrum* is also associated with the same disease (Camacho-Muñoz et al., 2021). Some of these two types can cause seafood poisoning, such as shellfish, thus threatening human health. Both growths are often associated with increased nutrient availability, such as agricultural waste. When blooms occur (10^4 cell/L) (Sidabutar et al., 2024), they can also damage aquatic ecosystems through decreased water quality and reduced oxygen levels, potentially affecting the balance of the ecosystem (Griffith & Gobler, 2020).

Oscillatoria is a cyanobacterium that can produce toxins, such as microcystins, that harm human health (Manganelli et al., 2023). Blooms of *Oscillatoria* are frequent in nutrient-rich waters and can result in a decrease in water quality, as well as affect aquatic ecosystems (Rattner et al., 2022).

In Indonesia, research on harmful algal blooms (HAB) in coastal waters has been conducted regularly since 1990. However, many instances of algal blooms remain unrecorded or unpublished. This highlights a gap in our understanding of this phenomenon and underscores the need for better documentation to identify potential patterns and trends. Several studies have successfully documented the occurrence of algal blooms and identified the key factors that trigger these events. One significant finding is that algal species can unexpectedly shift from non-toxic to toxic, adding complexity to managing and mitigating HAB impacts in Indonesian waters (Sidabutar et al., 2024).

The emergence of HABs is important to observe because they can produce dangerous toxins and threaten human health and aquatic ecosystems (Zingone et al., 2021). Its rapid growth can disrupt the balance of ecosystems,

reduce water quality, and damage the fishing industry. By understanding the factors that trigger them to bloom, mitigation strategies can be designed to minimize their adverse impacts, protect public health, and maintain aquatic biodiversity (Pal et al., 2020).

The results showed that the proportion of HABs abundance in all locations studied was lower than that of Non-HABs, with the abundance of HABs in TR and PS locations only reaching 1.53 and 1.39 %, respectively. The dominance of non-HABs in these two locations, which reached 98.47 and 98.61 %, indicates that environmental conditions are suspected to be more supportive of the growth of non-HABs.

In contrast, in SW and BM locations, the proportion of HABs increased to 6.25 and 8.18 %. However, non-HABs still dominate with proportions of 93.75 and 91.82 %. Although there was an increase in the abundance of HABs in the SW and BM locations, based on the results of the variance analysis, the abundance of HABs was considered uniform in all locations during the study.

The increase in the proportion of HABs in SW and BM locations indicates a change in environmental conditions that can trigger their growth. Although the abundance of HABs was still relatively low, this increase must be observed as an early sign of more significant bloom potential. It is important to know that negative impacts, such as seafood poisoning and ecosystem damage, can be anticipated (Organización de las Naciones Unidas para la Agricultura y la Alimentación, la Comisión Oceanográfica Intergubernamental & el Organismo Internacional de Energía Atómica, 2023). A better understanding of the patterns and factors influencing the growth of HABs is crucial for the sustainable management of aquatic resources (Obaid et al., 2024).

The increase in the proportion of HABs in aquatic waters indicates that various environmental parameters support their growth. In this context, the regression analysis presented in Table 3 provides strong evidence of the relationship between environmental conditions and the

occurrence of HABs (*Pseudo-nitzschia* of the class Bacillariophyceae, *Dinophysis*, *Prorocentrum*, *Protoperidinium* of the class Dinophyceae, and *Oscillatoria* of the class Cyanophyceae). Two key parameters identified, namely orthophosphate and salinity, play an important role in facilitating the growth of this harmful algae. A deep understanding of these relationships is essential to formulate more effective strategies for managing aquatic resources.

Orthophosphates, as one of the forms of phosphorus available to phytoplankton, including HABs, serve as the primary nutrients that support their growth. The availability of orthophosphate often increases due to human activities (Tambaru et al., 2024), such as intensive agricultural activities, domestic waste, and pollution from industry. When phosphorus accumulates in large quantities in the waters, conditions become ideal for the growth of HABs (Glibert et al., 2020). This process can lead to rapid proliferation, thereby increasing the risk of blooms (Brown et al., 2020). In many cases, high orthophosphate concentrations can contribute to the development of HABs, resulting in seafood poisoning and adverse ecosystem impacts (Dammak-Walha et al., 2021), among other negative consequences.

In addition to orthophosphates, salinity is an important parameter that can influence the appearance of HABs. Appropriate salinity can affect the growth of HABs, allowing them to adapt and thrive in different environments (Shi et al., 2024). Some HABs show a high tolerance to salinity variations to survive and reproduce under changing conditions (Giesler et al., 2023).

Each type of phytoplankton, including HABs, has an optimal salinity range to multiply efficiently (Jiang et al., 2022). A change in salinity can trigger the proliferation of certain type of phytoplankton that are more resistant to these conditions (Röthig et al., 2023). For example, in waters with low salinity due to river runoff from land, there is often an increase in nutrients supporting adaptive HAB-type growth, such as *Dinophysis* and *Prorocentrum*. In contrast, other type are more resistant to salinity

that may predominate in high-salinity environments. These factors interact with temperature, light, and nutrient changes, all of which affect the dynamics of aquatic ecosystems.

HABs have a wider salinity tolerance and can take advantage of more extreme environmental conditions than non-HABs (Hernando et al., 2020). Some HAB type can survive and reproduce in less-than-ideal conditions, such as high or low salinity and fluctuations in temperature and nutrients. In contrast, non-HABs grow in more stable waters with a more consistent salinity range (Xu et al., 2024). These differences make HABs type more flexible in responding to environmental changes, often causing blooms that damage ecosystems and human health. Salinity values recorded in the study area ranged from 15.3 to 30.3 ppt.

The combination of the high availability of orthophosphate and extreme changes in salinity creates a very conducive environment for the growth of HABs (Bouma-Gregson et al., 2024). Therefore, monitoring these two parameters is crucial to understanding the dynamics of HABs and formulating appropriate mitigation measures. By monitoring changes in orthophosphate concentrations and salinity, we can identify the potential for early *blooms*. This allows authorities and stakeholders to manage water quality and protect ecosystems proactively. Given the negative impacts that HABs can have, such as seafood poisoning and habitat destruction, a better understanding of the factors influencing their growth is key to the sustainable management of aquatic resources. Thus, more effective prevention and management measures can be implemented to reduce the negative impact of this phenomenon.

Comprehensive mitigation measures are needed to maintain the ecosystem's sustainability in Bone Bay. Reducing nutrient sources from agricultural, fishery, and industrial waste is essential. Regular monitoring of water quality, education, and community engagement are also crucial to addressing the negative impacts of HABs. With collaborative efforts, we can restore and protect coastal aquatic ecosystems to remain productive and healthy for



the sake of marine survival and human welfare in the future.

In conclusion, this study shows that the phytoplankton that caused Harmful Algal Blooms (HABs) identified included *Pseudo-nitzschia* (Bacillariophyceae), *Dinophysis*, *Prorocentrum*, *Protoperidinium* (Dinophyceae), and *Oscillatoria* (Cyanophyceae). Although the proportion of HABs abundance was lower than that of non-HABs phytoplankton across sites, the increased abundance of HABs in some areas, such as SW and BM, indicated the potential for future blooms. Therefore, monitoring environmental parameters, especially orthophosphate concentration and salinity as the two main factors influencing the occurrence of HABs, is very important. Through this monitoring, mitigation measures can be formulated, such as reducing nutrient sources from agricultural, fishery, and industrial waste and implementing regular water quality monitoring. This step aims to protect the aquatic ecosystem while maintaining public health. This research provides important insights into the need for sustainable management of marine resources in Bone Bay.

Activities in Bone Bay that can increase the nutrient load discharged into the waters include aquaculture, agriculture, and household activities. Agricultural runoff, such as fertilizers and pesticides, can flow into the waters, increasing nutrient levels such as nitrogen and phosphorus. Agricultural areas near Bone Bay, especially those using chemical fertilizers, can potentially contribute nutrient waste to the waters. Waste from household activities and ports also contributes to the increased nutrient load. Data on nutrient levels in runoff from agricultural land and domestic waste are crucial for understanding the risks of Harmful Algal Blooms (HAB) in Bone Bay, as increased nutrients can trigger the growth of harmful phytoplankton that negatively impacts ecosystem and food health.

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