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ECOLOGICAL RISK ANALYSIS OF HARMFUL ALGAL BLOOMS (HABS) IN BIMA BAY, WEST NUSA TENGGARA, INDONESIA

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Abstract
In April 2022, the occurrence of Harmful Algal Blooms (HABs) was first reported in Bima Bay, West Nusa Tenggara, resulting in a mass fish mortality event and the formation of a brown gel-like biomass that covered a significant portion of the Amahami coastal area. Here, we assess the extent of pollution and its associated ecological risk in the aquatic environment of Bima Bay. The assessment is conducted through two scenarios: 1) the vulnerability of the bay and the potential occurrence of HABs and associated pollutant load index (PLI) and water quality index (WQI); 2) the potential ecological impact of HABs related to the structure of the phytoplankton community. The PLI calculation at all stations exceeded 1, indicating an increase in environmental pollution. The pollution index (PI) at eleven stations was classified as moderately polluted, and one station was classified as lightly polluted, with a WQI of 31.67 or in the poor water quality category. Phytoplankton abundance in Bima Bay ranged from 811 – 854,724 individuals/liter. The five most dominant phytoplankton species were identified as *Pseudo-nitzschia* sp., *Chaetoceros* spp., *Lauderia* spp., *Rhizosolenia* spp., and *Chatonella* sp. The level of HAB risk in different areas of Bima Bay is based on the PI value and the proportion of the highest toxic species obtained at stations 2 and 1, with PI values of 5.83 and 5.60, and toxic proportions of 0.41 and 0.38. The distribution of HAB tends to be concentrated in the inner bay, particularly on the east and south coasts. The potential for phytoplankton blooming is relatively higher during the months of the rainy season, as indicated by the results of the chlorophyll index (satellite imagery).

Keywords: coastal water quality, ecological impact, risk assessment, toxic algae, water quality

Introduction

In recent decades, the phenomenon of Harmful Algal Blooms (HABs) has increased significantly worldwide (Zahir *et al*. 2024). According to the IOC-UNESCO (2024), 624 HAB events were documented during 2022–2024. The HABs phenomenon affects the sustainability of coastal ecosystems, fisheries, and other aquaculture industries, and can endanger human health (Anderson *et al*. 2012). Additionally, the HABs phenomenon negatively affects the economy of a region because it can cause the death of fish, increase the cost of monitoring bodies of water, and disrupt tourism activities (Hoagland & Scatasta 2006).

The HABs phenomenon can be categorized into two types: red tide makers, caused by an explosion in the population of pigmented phytoplankton, resulting in a change in the color of seawater; and toxin producers, caused by phytoplankton species that produce certain toxic compounds (Mulyani *et al*. 2012, Wells *et al*. 2020). Toxins produced by phytoplankton can be classified into paralytic shellfish poisoning (PSP), diarrhetic shellfish poisoning (DSP), amnesic shellfish poisoning (ASP), neurotoxic shellfish poisoning (NSP), and ciguatera fish poisoning (CFP) (Grattan *et al*. 2016).

In Indonesia, research on HABs has been conducted since 1979. Most reported HABs phenomena have occurred in bay waters, such as in Jakarta Bay, Hurun Bay, Lampung Bay, Ambon Bay, etc. (Samudra *et al.* 2022, Sidabutar *et al*. 2022). In April 2022, a HABs phenomenon was reported for the first time in Bima Bay, West Nusa Tenggara (Asryadin *et al*. 2022). This event resulted in the mass mortality of fish, and most of the Amahami coastal area was covered with a brown gel-like biomass. This phenomenon is hypothesized to have occurred due to an increase in nutrient levels in the waters of Bima Bay as a result of an increase in agricultural activities, particularly corn farming, in recent years. The use of excessive fertilizers and pesticides on corn farms carried by water runoff has been demonstrated to increase nutrient levels. In addition, the conversion of forests has been shown to reduce natural filter vegetation, thereby further increasing nutrient loads in Bima Bay (Adi & Muladi 2022).

Bima Bay is a semi-enclosed water area that is directly connected to the Flores Sea. Its area is approximately 169.05 km^2, and its coastline is approximately 78 km in length (Munawar 2021). Bima Bay plays a pivotal role in sustaining the socio-economic life of coastal residents by serving as a prolific producer of fish and a significant source of livelihoods for various stakeholders, particularly fishermen, cultivators, and people working on tourism-related activities. However, the increased activities of these residents have the potential to adversely impact the ecosystem of Bima Bay, particularly about elevated levels of pollution. Conversely, disruption or degradation of the aquatic ecosystem of Bima Bay will also exert a deleterious effect, both directly and indirectly, on the socio-economic life of the population.

The pollution levels in the aquatic environment of Bima Bay are influenced by various factors, including anthropogenic activities, topography and bathymetry, meteorology and climatology, and hydrological and oceanographic patterns. The basin-like topography of Bima Bay allows for the accumulation of pollutants from various anthropogenic activities through stormwater runoff and river inflows. The occurrence of HABs in Bima Bay can be attributed to alterations in the quality of seawater, characterized by elevated levels of pollution that surpass the environmental carrying capacity of the bay. This study was conducted to evaluate the extent of pollution and its relationship with the ecological risk of HAB events in the aquatic environment of Bima Bay, to obtain information and basic references for the sustainable management of the bay.

Materials and methods

Location. This research was conducted in August of 2023. The selected study sites were the inner, middle, and outer Bima Bay, which were divided into 12 stations as listed in Sup. Table 1.

Data Collection. The in situ parameters measured include transparency, currents, tides, temperature, pH, salinity, and dissolved oxygen (DO). The ex-situ parameters encompass total suspended solids (TSS), biochemical oxygen demand (BOD), total phosphorus (TP), total nitrogen (TN), orthophosphate, nitrate, ammonia, and phytoplankton. The ex-situ parameters were measured by extracting water samples vertically using a water sampler and a plankton net. This sampling technique was used to obtain composite samples from each layer of the water column (1–20 m, determined based on water clarity measurement) at each station (Rosada & Sunardi 2021). Sediment samples for TN and TP parameter measurements were collected using an Ekman grab sampler. Subsequently, the water and sediment samples were transferred into sample bottles and preserved for subsequent analysis in the laboratory. The identification of phytoplankton species was conducted by observing their morphological structure under a microscope (400–1000x magnification) using reference books. The phytoplankton community structure was analyzed using several indices, including abundance, diversity index (Shannon-

Wiener), uniformity index (Evennes), and dominance index (Simpson).

The oceanographic conditions in Bima Bay were simulated using the Finite Volume Community Ocean Model (FVCOM) numerical model. FVCOM is a three-dimensional (3D) marine water model with an unstructured triangular grid system, which has been demonstrated to provide accurate results for highly complex coastal conditions (Chen *et al.* 2006). The data used in this modeling consists of shoreline data, bathymetry, tidal elevation, and current components. The model implementation comprises two distinct stages. Initially, the numerical modeling of hydrodynamics is conducted to solve the equations of motion and thereby ascertain the current movement patterns within the model domain. Subsequently, the numerical modeling of particle tracking is performed using a forward scheme to calculate the particle residence time.

Data Analysis. The determination of ecological risk is based on two scenarios: 1) the vulnerability of the bay and the potential occurrence of HABs in relation to the pollutant load index (PLI) and water quality index (WQI); and 2) the potential ecological impacts of HABs related to phytoplankton community structure.

The PLI is determined by calculating the root *n* value of the contamination factor of each pollutant, as the following expression (Ferreira *et al.* 2022):

$$PLI = (CF1 \times CF2 \times \ldots \times CFn)^{\frac{1}{n}}$$

Where, CF_1, CF_2, and CF_n are the contamination factors of the pollutants 1, 2, and n. The pollutant parameters used in this calculation are TN and TP in sediments. A PLI value greater than 1 indicates an increase in environmental pollution.

The calculation of the WQI involves determining the pollutant index (PI) value and establishing the quality status of each location, as the following expression (MEF 2021):

$$PI = \sqrt{\frac{\left(\frac{C_i}{L_{ij}}\right)_M^2 + \left(\frac{C_i}{L_{ij}}\right)_R^2}{2}}$$

Where, C_i is the sample concentration of water quality parameter (i), L_{ij} is the concentration of water quality standard (j), $(C_i/L_{ij})_M$ is the maximum value of C_i/L_{ij}, and $(C_i/L_{ij})_R$ is the average value of C_i/L_{ij}. The PI value is transformed into WQI by multiplying the index value's weight by the percentage of quality standard fulfillment. The percentage of quality standard fulfillment is derived from the ratio of sample stations meeting quality standards to the total number of samples, expressed as a percentage. The parameters used in this index calculation include TSS, DO, BOD, orthophosphate, nitrate, ammonia, and pH.

Statistical analysis involves Spearman's rho correlation analysis to determine the relationship (correlation) between PLI, WQI, and phytoplankton community structure.

Results

Hydrodynamics pattern. Bima Bay has a relatively short, intense rainy season. The annual mean precipitation is 92 mm, with 15 days of rain (BPS 2023). The distribution of rainfall is characterized by unevenness with minimal precipitation during May–October (Fig. 1).

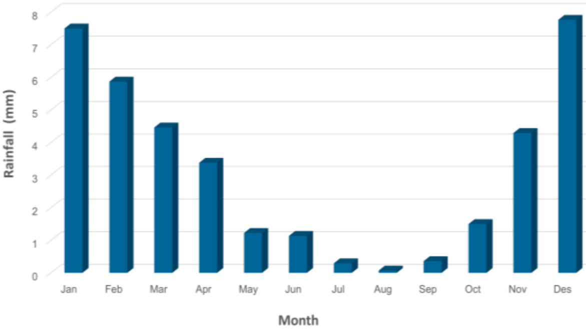

Figure 1. Average monthly rainfall (2013–2022)

The tidal type of Bima Bay is classified as mixed semidiurnal, meaning it exhibits two high tides and two low tides within a 24-hour period. The high tides occur at 1–2 a.m. and 1–2 p.m., while the low tides occur at 7–8 a.m. and 7–8 p.m. Central Indonesian Time. The current speed in Bima Bay ranges from 0.007 to 1.793 m/s. During periods of high tide, the current flows into the bay, while during low tide, it flows out of the bay (Fig. 2). The current conditions at depths of 0–6 m are relatively similar due to the presence of the mixed layer.

The particle simulation results demonstrate that particles tend to exit the bay more easily under initial conditions (Figs. 3, 4). Approximately 24% of the particles remain in the bay while the remaining 76% successfully exit. The particles located near the open water boundary or within the central region of the bay depart within 10–20 days. In contrast, particles residing in deeper areas of the bay take approximately 40–59 days to depart, and some of these particles remain in the bay.

Plate 15

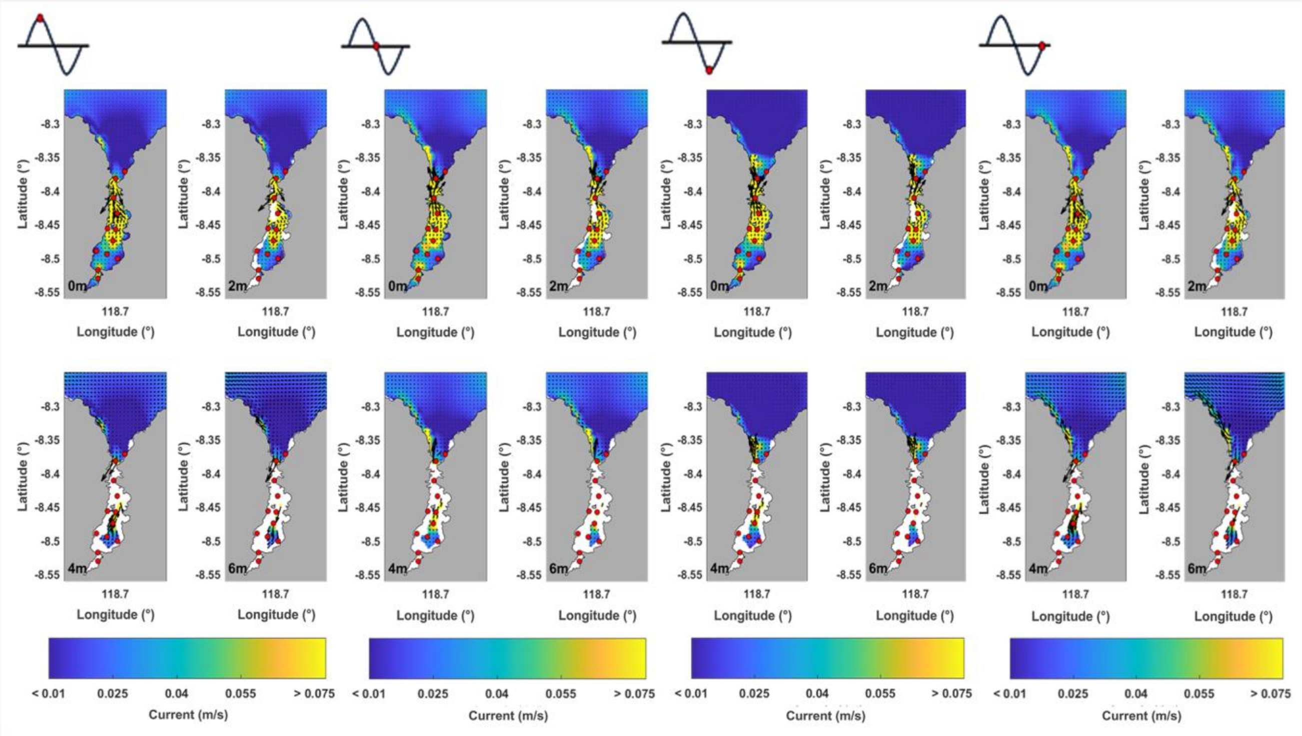

Figure 2. Characteristics of current patterns in Bima Bay: current condition, high tide, and low tide are indicated by the red dot).

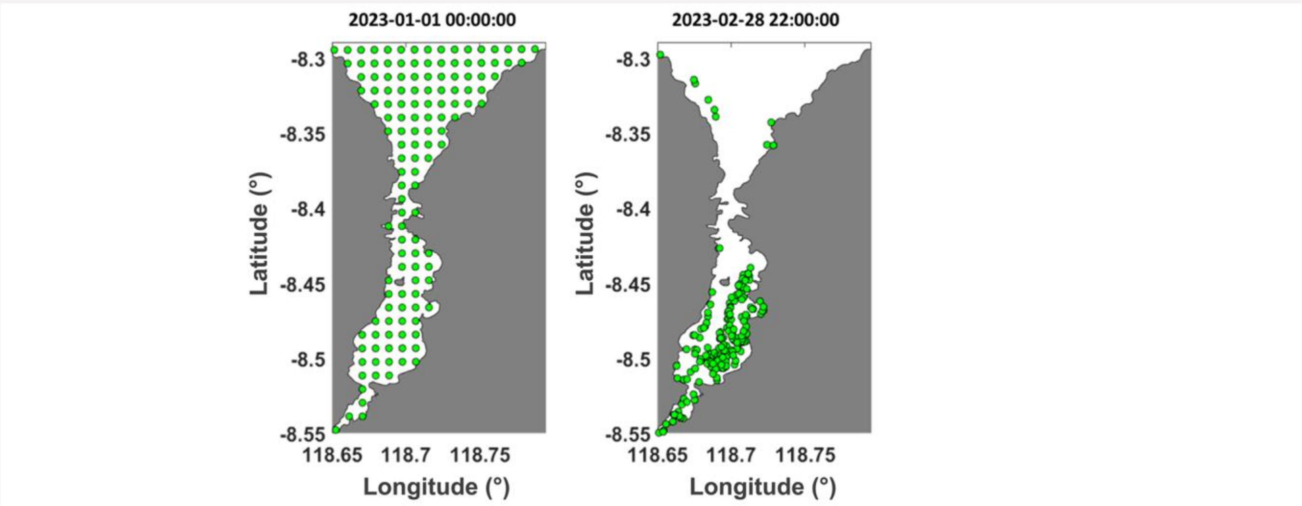

Figure 3. Particle state at the beginning and end of the simulation

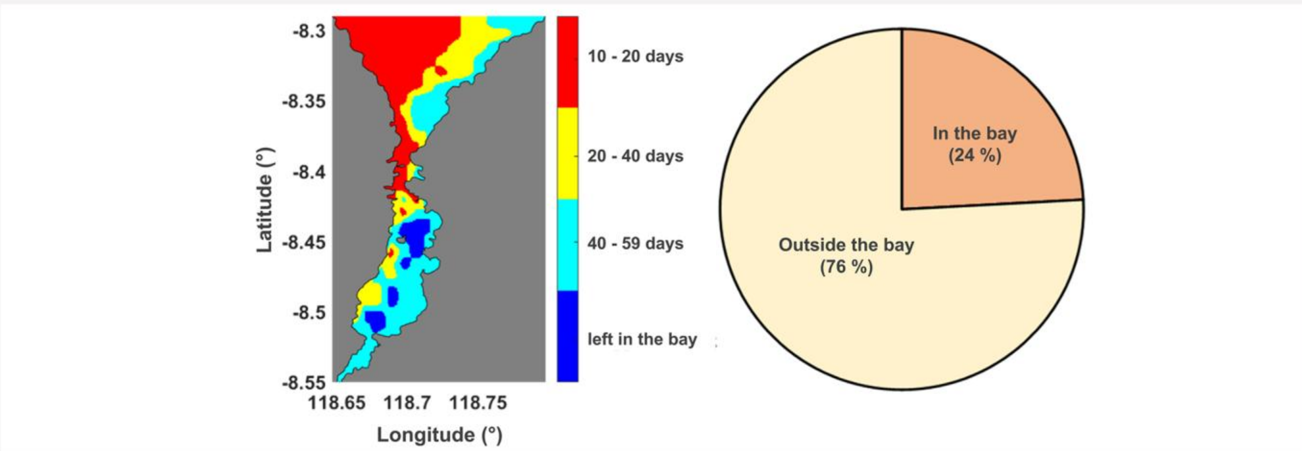

Figure 4. **(A)** Particle residence time and **(B)** Percentage of particles at the end of the simulation

Water and sediment quality. The seawater temperature in Bima Bay ranges from 27 to 31°C. The salinity of Bima Bay is 34 ± 0.13 PSU, classified as medium salinity/mesohaline waters (Sup. Table 2). The measured pH value is 8, indicating an alkaline environment. The dissolved oxygen (DO) concentration ranges from 6 to 8 mg/L, which is within the normal range for marine waters. The biochemical oxygen demand (BOD) level in Bima Bay meets the seawater quality standards. However, the total suspended solids (TSS) value exceeds the specified quality standards (except station 12). The measured ammonia level was below the specified quality standard. Nitrate concentrations in Bima Bay ranged from 0.88 to 1.44 mg/L, not meeting quality standards, while orthophosphate concentrations ranged from 0.011 to 1.06 mg/L, partially meeting quality standards. The highest TN level was measured at station 1 with a concentration of 526 mg/kg, while the highest TP level was measured at station 10 with a concentration of 2.32 mg/kg.

Phytoplankton community structure. There are 57 species and 42 families of phytoplankton identified, with abundance varying from one station to another. The highest abundance of phytoplankton was found at station 3 with 854,724 individuals/liter. This station is located in the inner bay between two river estuaries originating from the Bolo district. The lowest abundance of phytoplankton was found at station 12 with 811 individuals/liter. This station is located in the outer bay at the mouth of the bay in the Asakota district, which borders directly onto the Flores Sea. The proportion of phytoplankton that has the potential to cause HABs was as much as 51% of the total phytoplankton species found, including the red tide maker group (18%) and toxin producer group (33%). The phytoplankton community structure can be seen in Fig. 5.

The phytoplankton diversity index in Bima Bay falls into the low to medium species diversity category. The highest diversity index was found at station 12 with H'= 2.02 (42 species), and the lowest was found at station 3 with H'= 0.15 (26 species). The phytoplankton uniformity index in Bima Bay falls into the unevenly to evenly distributed category. The highest uniformity index was found at station 12 with E = 0.6, and the lowest was found at station 3 with E = 0.04. The highest dominance index was found at station 3 with D = 0.95, and the lowest was found at station 12 with D = 0.2.

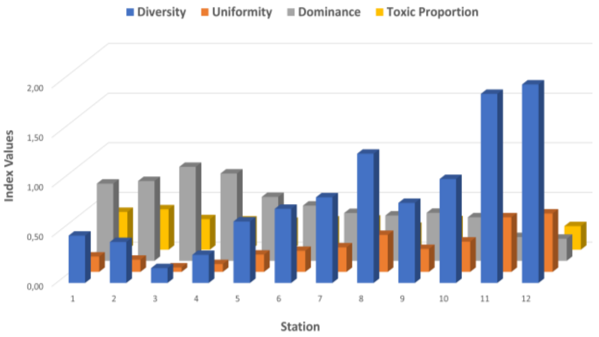

Figure 5. Phytoplankton community structure

Potential HAB events. Eleven stations were classified as moderately polluted (with the highest PI value at station 4), and one was classified as lightly polluted (station 8) (Fig. 6). The WQI obtained is 31.67, which is in the lower category. The level of pollution in Bima Bay was also evaluated using the pollutant load index (PLI). The PLI obtained at all stations is greater than 1, indicating an increase in pollution compared to previous environmental conditions. The highest pollution levels were observed at station 10, followed by stations 7 and 2. Spearman's rho correlation test revealed a strong positive relationship between PLI and PI, with a correlation coefficient of 0.488.

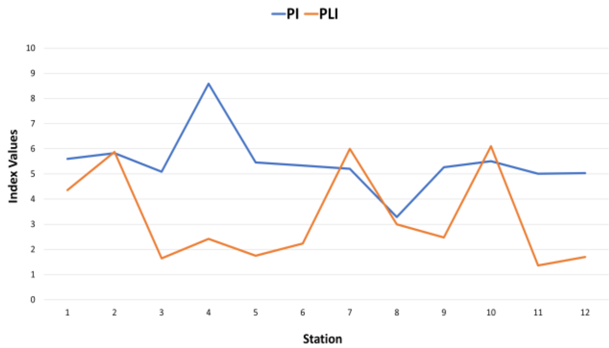

Figure 6. Pollutant index values

Potential impact of HAB. The five most dominant phytoplanktons in Bima Bay are species of *Pseudo-nitzschia*, *Chaetoceros*, *Lauderia*, *Rhizosolenia*, and *Chatonella* (Sup. Table 4). The highest proportions of toxic species were identified at stations 1 and 2, with values of 0.38 and 0.41, respectively (Fig. 7). Spearman's rho correlation test revealed a positive relationship between the proportion of toxic species and the dominance index with a correlation coefficient of 0.621. A negative relationship was obtained between the proportion of toxic species and diversity index and uniformity index with correlation coefficients of 0.623 and 0.603, respectively. In addition, the

Plate 16

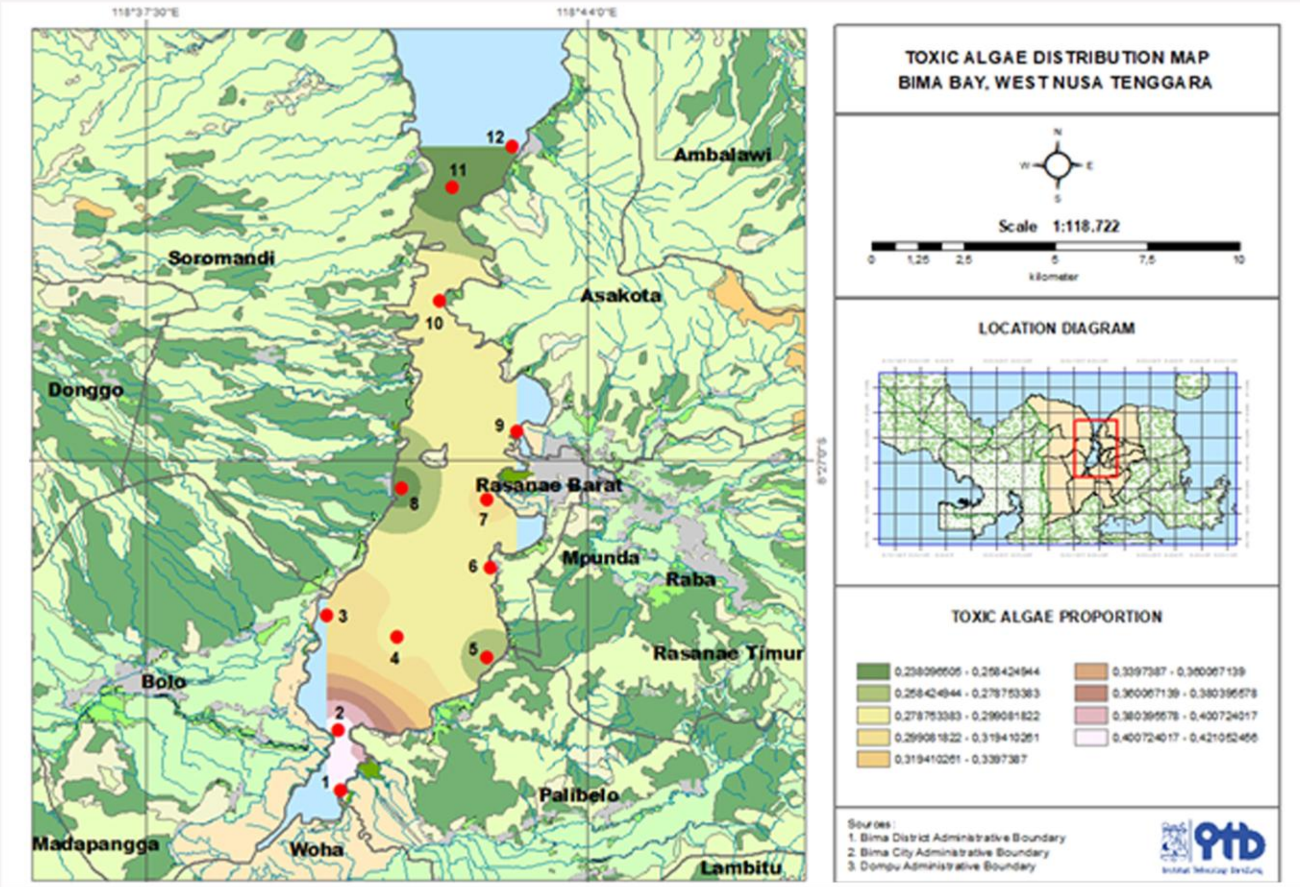

Figure 7. Proportion toxic species (illustrated in October 2023)

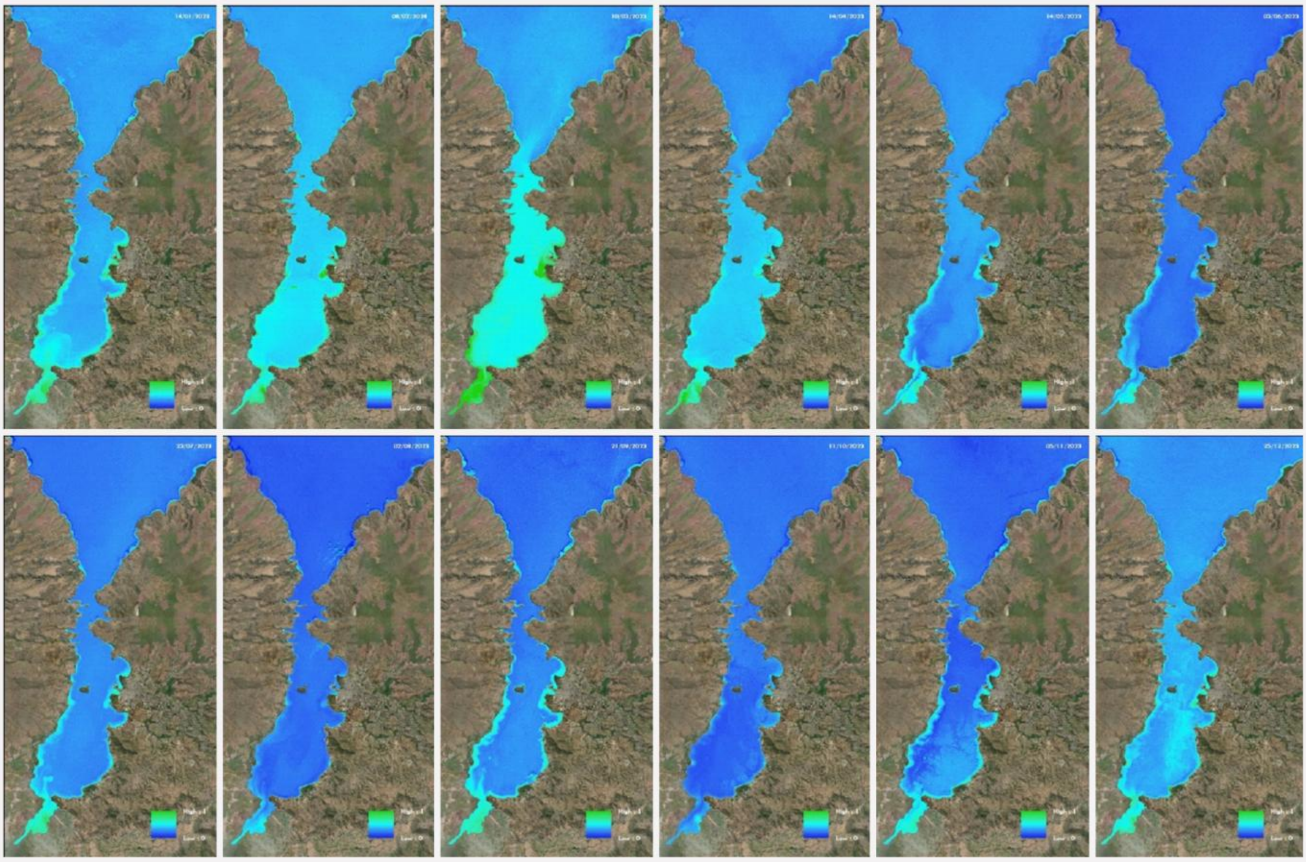

Figure 8. NPCRI in Bima Bay

proportion of toxic species was positively correlated with PI and PLI values with correlation coefficients of 0.66 and 0.49, respectively. PI was positively correlated with the dominance index (0.59) and negatively correlated with the diversity index (0.65) and uniformity (0.65).

Discussion

Hydrodynamics pattern. According to the Schmidt and Ferguson climate classification system, climate types D, E, and F, which characterise Bima Bay, represent increasingly drier conditions based on the percentage of dry months in a year—defined as months with less than 60 mm of rainfall (Lakitan 2002). However, there are significant environmental implications of its rainfall, which can occur with high intensity over short periods. Rainfall affects pollutant distribution by carrying runoff from the land into the bay waters. Additionally, heavy rain can influence temperature stratification in the water column and, combined with wind, may trigger upwelling (Weeks *et al.* 2024). Frequent flooding during the rainy season also contributes to increased accumulation of pollution in the bay (Adi & Muladi 2022). The hydrodynamics of Bima Bay, shaped by a mixed semidiurnal tidal regime, play a crucial role in transporting these pollutants and sediments. Tidal currents drive water inflow during high tides and outflow during low tides, resulting in efficient flushing near the bay's open boundaries. However, circulation slows in the deeper, more enclosed parts of the bay, leading to longer water retention and localized accumulation of pollutants. This dynamic interplay between tidal flushing and retention zones strongly influences the bay's water quality and ecosystem health.

Water and sediment quality. Marine water and sediment quality are key indicators of ecosystem health, especially in Bima Bay, where limited circulation leads to pollutant accumulation. The bay's seawater temperature (27–31°C) supports optimal phytoplankton growth (Behrenfeld & Boss 2014, Zainuri *et al.* 2023), while its moderate salinity may inhibit phytoplankton by affecting osmoregulation (Redden & Rukminasari 2008, Chakraborty *et al.* 2011). The decomposition of organic matter, as reflected in biochemical oxygen demand (BOD), releases nitrogen and phosphorus that stimulate phytoplankton growth. However, elevated total suspended solids reduce light penetration, thereby limiting photosynthesis and phytoplankton distribution. Nutrients such as ammonia, nitrate, and orthophosphate significantly influence phytoplankton dynamics. Ammonia levels stay below inhibitory thresholds (Collos & Harrison 2014), but nitrate and orthophosphate exceed standards, increasing the risk of eutrophication (Mahmudi *et al.* 2020). High sediment total nitrogen and phosphorus suggest pollution sources and potential internal nutrient loading, influenced by hydrodynamics. Together, these factors indicate Bima Bay's vulnerability to nutrient enrichment and turbidity.

Phytoplankton community structure. The community structure of phytoplankton in Bima Bay is strongly influenced by local hydrodynamics, nutrient availability, and water quality. Stations near river estuaries, particularly in the inner bay, recorded the highest phytoplankton abundance, which is consistent with elevated nutrient concentrations and limited circulation. As noted by Yusuf *et al.* (2012) and Mahmudi *et al.* (2020), such conditions tend to promote phytoplankton growth, particularly in nutrient-rich zones such as river mouths. Similar findings by Peng *et al.* (2023) confirm that areas receiving terrestrial inputs or influenced by upwelling often support dense phytoplankton populations. However, despite the high abundance of phytoplankton, diversity was low and dominance was high, suggesting the prevalence of a few opportunistic species that are better adapted to eutrophic and turbid environments. Ignatiades (2020) supports this pattern, noting that competitive advantages in nutrient uptake or allelopathic interactions can drive species dominance.

By contrast, the outer bay station exhibited lower phytoplankton abundance, but higher diversity and uniformity. This aligns with more stable hydrodynamics and lower nutrient stress. The temperature ranges observed in the bay are also conducive to phytoplankton metabolism and reproduction (Feng *et al.* 2018), which further influences spatial abundance. Notably, over half of the identified phytoplankton species were associated with HABs, including red tide makers and toxin-producing species. As Yan *et al.* (2022) emphasise, the risk posed by HABs is related not only to abundance, but also to species type and toxin production. This highlights the ecological vulnerability of Bima Bay, particularly in areas with high nutrient levels and limited flushing, where the risk of HABs is increased.

Potential HAB events. The pollution status of Bima Bay, as indicated by both Pollution Index (PI) and Pollutant Load Index (PLI), reflects a deteriorating environmental condition that exceeds the natural carrying capacity of the bay. Most stations were categorized as moderately polluted, with consistently elevated PLI values across all sites, indicating long-term pollutant accumulation, particularly of nitrogen and phosphorus in sediments. Unlike PI, which captures short-term fluctuations influenced by hydrodynamics and temporal variability in water quality, PLI provides a more stable and historical perspective (Ferreira *et al.* 2022). This highlights Station 10 as a hotspot for sedimentary nutrient buildup. Thus, while certain areas may appear less polluted based on water column data, their sedimentary load could still pose long-term ecological risks. The elevated PLI values support the hypothesis that historical and continuous pollutant input, primarily from terrestrial runoff, has surpassed the bay's self-purification capacity. Pollution that occurs in Bima Bay waters has the potential to induce ecological problems, including phytoplankton blooms and inhibition of growth or even death of marine organisms. In relation to blooming, the worst-case scenario can be estimated by considering the level of rainfall in the waters of Bima Bay. It is estimated that during periods of rainfall, the influx of pollutants into the bay will be amplified. Consequently, the probability of blooming is expected to be higher during the rainy season, when nutrients are presumed to be plentiful. This hypothesis is corroborated by the findings of remote sensing employing SENTINEL 2 satellite imagery, which demonstrate comparatively elevated chlorophyll-a concentrations (as indicated by normalized pigment chlorophyll ratio index/NPCRI) during the months of the rainy season (Fig. 8).

High levels of nutrients in sediments have the potential to increase aquatic nutrients if released into the water column, a phenomenon known as upwelling (Peng *et al.* 2023). Upwelling occurs when a mass of colder and/or higher-density water moves from the seafloor to the surface due to the movement of winds above it. The factors that can trigger this phenomenon include sea breezes, the Coriolis effect (a force generated by the Earth's rotation), and changes in water column temperature stratification (Kampf & Chapman 2016). According to the MCGA (2024), the maximum wind speed in the Bima Bay area reached 10 m/s. According to the findings of Rahayu *et al.* (2023), a robust correlation has been identified between wind speed and the magnitude of upwelling phenomena, both under conditions of La Nina and in typical climates. In the context of Bima Bay, upwelling events are expected to manifest during the rainy season, a period characterized by high rainfall intensity, leading to a decline in sea surface temperature relative to the underlying layer. Furthermore, the presence of rain leads to a reduction in the density of the seawater at the surface, thereby facilitating its displacement by sea breezes.

Potential impact of HAB. The dominance of *Pseudo-nitzschia* sp., *Chaetoceros* spp., and *Chattonella* sp., three known HAB-forming species (Sup. Table 3), suggests a heightened ecological risk in Bima Bay, particularly with *Pseudo-nitzschia* sp. recognized globally for producing domoic acid (DA), a neurotoxin responsible for Amnesic Shellfish Poisoning (ASP) (Suthers & Rissik 2009, Hallegraeff 2021). This toxin-producing species poses a monitoring challenge due to its lack of visual bloom indicators such as discoloration or fish mortality. Nevertheless, its presence has been associated with over 128,000 cases of ASP worldwide (Hallegraeff 2021).

The correlation analysis reveals that areas with a higher proportion of toxic phytoplankton have lower diversity and uniformity, and a higher dominance index, indicating ecological imbalance (Spearman's $\rho > 0.6$). This pattern suggests that toxic species may outcompete other phytoplankton through allelopathy or superior physiological adaptability under stressful conditions (Ignatiades 2020). Furthermore, significant positive correlations between the proportion of toxic species and both PI and PLI ($\rho = 0.66$ and 0.49, respectively) suggest a potential association between pollution and the proliferation of HAB-associated species. This is consistent with findings that nutrient enrichment, especially nitrogen and phosphorus, can shift community structure toward harmful species (Mahmudi *et al.* 2020).

The distribution of toxic phytoplankton species in the waters of Bima Bay is influenced by several complex environmental factors. Physical water conditions, including temperature, salinity, and water clarity, have been identified as pivotal factors in the distribution and development of these toxic phytoplankton species (Redden & Rukminasari 2008, Chakraborty *et al.* 2011, Behrenfeld & Boss

2014). The dynamics of ocean currents also play a role by carrying nutrients and phytoplankton to various locations. Interactions between phytoplankton species and other organisms in the food chain also affect their distribution (Ignatiades 2020). Competition or predation among phytoplankton species can lead to alterations in population composition and abundance. Stations 1 and 2, located near anthropogenic inputs, displayed the highest proportions of toxic species. Toxins potentially produced at both stations include domoic acid (cause of ASP), saxitoxin (cause of Paralytic Shellfish Poisoning/PSP), okadaic acid (cause of Diarrhetic Shellfish Poisoning/DSP), brevetoxin (cause of Neurotoxic Shellfish Poisoning/NSP), ciguatoxin (cause of Ciguatera Fish Poisoning/CFP), cooliatoxin, microcystin, and cyanotoxin. The distribution or dispersal of these toxins tends to be concentrated within the inner bay, particularly along the east and south coasts.

Author contributions

JJ designed, performed data collection, analyzed, and prepared the manuscript; SS, BSM and PS guided during the planning and implementation of this study, including the preparation and supervision of the manuscript.

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Supplemental data

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