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Pollution Characteristics and Decline in Seawater Quality with Rapid Change in Land Use: Case Study of Bima Bay, East Nusa Tenggara, Indonesia

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ABSTRACT

Increased anthropogenic activity in coastal areas has led to a significant decline in marine ecosystem quality, particularly due to the influx of nutrient-rich waste that triggers eutrophication. This study highlights a case of extreme pollution in Bima Bay, West Nusa Tenggara, marked by the appearance of massive brown sea foam in April 2022, covering an area of over 10 hectares. The research was conducted through water quality analysis, acute toxicity testing (LC50), microalgae identification, and satellite image interpretation. Results showed BOD concentrations of 20.8 mg/L, oil and grease at 28.5 mg/L, orthophosphate at 0.037 mg/L, and NO_3-N up to 1.194 mg/L, all exceeding the quality standards set by PP No. 22 of 2021. Toxicity testing yielded an LC50-96 hour value as low as 0.081%, categorized as highly toxic. Microalgae identification revealed a dominance of the Diatom group, such as *Nitzschia sp.*, *Navicula sp.*, and Surirella sp., which thrived due to high nutrient content and favorable water conditions (pH 6.92 - 7.70, high light intensity). Analysis of Sentinel-2 and Landsat 8/9 imagery showed the appearance of foam beginning on April 24 and its disappearance after May 4, 2022. This pollution is closely related to massive land use changes in the upstream area for corn farming expansion, poor domestic sanitation systems, and the semi-enclosed geographical position of Bima Bay, which hinders seawater mixing and accelerates pollutant accumulation. These findings highlight the importance of pollution mitigation based on spatial planning and integrated waste management in tropical coastal areas.

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INTRODUCTION

Anthropogenic pollution is rapidly increasing in many coastal regions worldwide, threatening ecological balance and human well-being. The direct discharge of nutrients into water bodies often leads to eutrophication, altering water chemistry and biological communities (Anderson et al., 2002; Paerl & Huisman, 2008). One of the visible consequences is the occurrence of sea foam, a phenomenon that can disrupt ecosystems and pose risks to humans (Seuront et al., 2006; Shetye et al., 2021). Foam arises when air mixes with water enriched with surfactants

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from organic and inorganic sources, including algae, bacteria, and pollutants (Napolitano & Richmond, 1995).

Large foam events have been documented across the globe, sometimes with severe impacts. In Europe and North America, foam up to a meter thick has caused seabird mortality and even human fatalities (Guo et al., 2015; Schilling & Zessner, 2011). Along Turkey's Marmara Sea, pollution combined with warming seas has triggered extensive "sea snot" outbreaks (Aktan et al., 2008). These cases demonstrate that foam can be generated by both natural and anthropogenic drivers. However, most studies are concentrated in temperate developed regions, while tropical developing countries, where urbanization is accelerating and wastewater management remains limited, are far less studied..

Indonesia, with over 81,000 km of coastline, harbors globally significant coral reefs, mangroves, and seagrass ecosystems (State of the Coral Triangle, 2014; Alongi, 2014). Yet, these ecosystems face growing pressure as human activity intensifies in coastal zones. Despite its vast maritime area, Indonesia is severely underrepresented in international databases that track harmful algal events. The Harmful Algal Event Database (HAEDAT) lists only 70 documented events for Indonesia, compared to 1,274 for the Philippines, 542 for Japan, and 1,076 for France (Hallegraeff, et al., 2021). This discrepancy underscores the lack of systematic monitoring and reporting in Indonesia, despite its high ecological exposure and the increasing frequency of coastal pollution events.

Currently, around 75% of Indonesia's urban areas are located along the coast, accommodating more than 65% of the population. This trend is expected to accelerate, with an additional 1 million people projected to live within 50 km of the coastline by 2035. Population growth increases development activities due to the coast's accessibility for transport, industry, and tourism, driving land use change. Such changes are evident in Jakarta, where from 1996–2007 built-up areas expanded by 7,539.68 ha (11.5% of the province) with an average growth of 750 ha per year (Rizal, 2021). Similarly, in Pekalongan (2003–2016), settlements increased by 171.08 ha while agricultural land declined by 455.36 ha (Wijaya & Susetyo, 2017). These developments have significant environmental consequences, particularly the degradation of surface water quality, which ultimately affects marine ecosystems and sea resources.

In April 2022, Bima Bay in West Nusa Tenggara was blanketed by sea foam covering more than 10 hectares (Asryadin et al., 2022). The phenomenon disrupted fishing, caused illness among residents who consumed contaminated fish, and raised concerns about the sustainability of local coastal ecosystems. As a mid-sized coastal city undergoing rapid land use change, Bima provides a critical case to examine how population growth, development, and weak wastewater management interact to affect seawater quality.

Building on global and national concerns, This study aims to (i) identify pollution sources linked to land use change and waste inputs, (ii) analyze seawater quality and toxicity, and (iii) characterize the biological and temporal dynamics of the sea foam event.

MATERIALS AND METHODS

Description of Study Area

Bima Bay is located in the island of Sumbawa, West Nusa Tenggara Province, Indonesia (seen in Figure 1). Bima Bay is a semienclosed sea, long but narrow at the en- trance point to thesea and is astronomically located between $8^o20'$ $8^o30'$ South Latitude and between $118^o41'$ $118^o48'$ East Longitude. The bay is also the terminus for several rivers flowing through both the heavily agrarian area of Bima Regency and the fast-growing urban center of Bima City (see Figure 1).

Bima agricultural transformation

In the past decade, the agricultural sector in Bima Re- gency and Bima City has been growing.

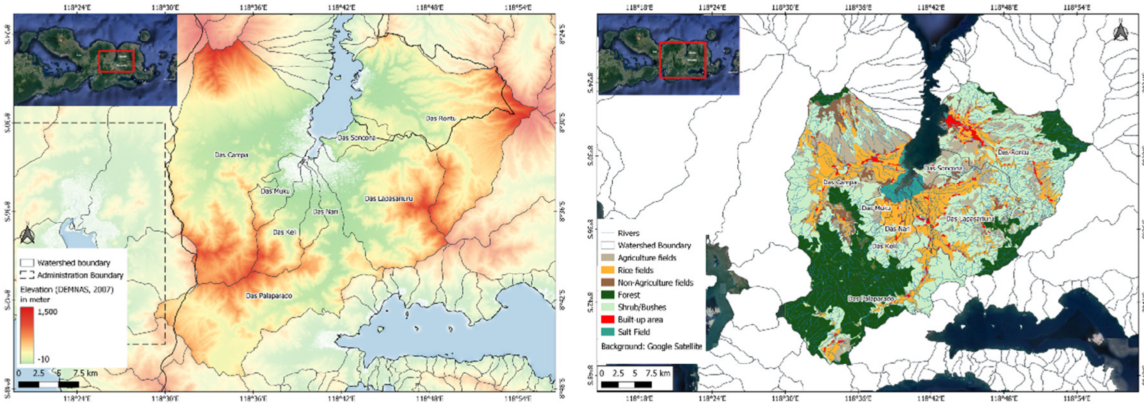

Fig. 1. Watershed and Administrative Boundaries around Bima Bay (Left) and Land Use surrounding Bima Bay (Right)

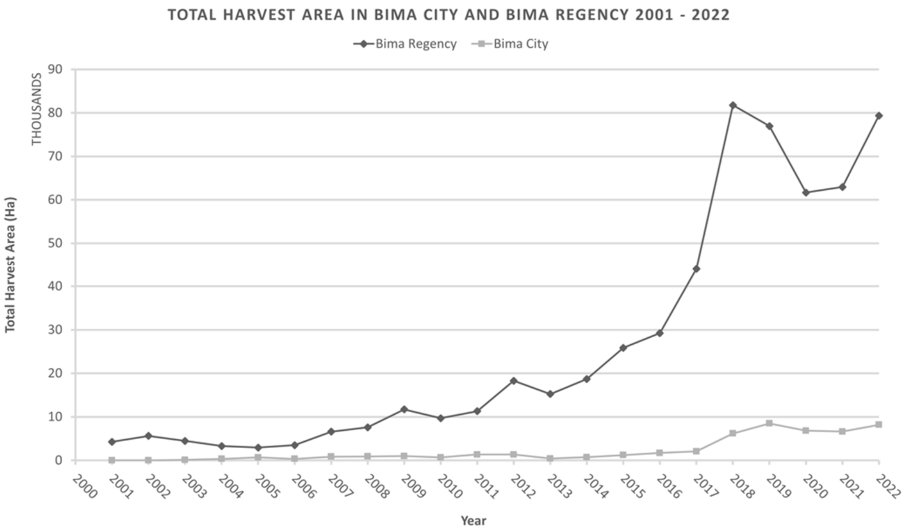

Fig. 2. Total harvest area of Corn in Bima regency and Bima City
Source: Statistics Center Agency of Bima City, 2022

The Indonesian government has been developing the agricultural sector, especially corn, in recent years, dating back to 2012 through the Corporate-Based Agricultural Development Program (Setiasih et al., 2020), and was made into a national priority program in 2020 through the Ministry of Agriculture Strategic Plan 2020- 2024. The program has been made by the government to increase national corn production by optimizing existing cornfield and planning cornfield expansion to meet national demand and exports. Bima City and the Regency both welcome this program and as a result see a significant increase in total harvest area over the past 10 years (see Figure 1and Figure 2).

The intricate urban development of Bima City

Bima City covers an area of 222.25 square kilometers and has a population of 156,224, of whom 8.88% work in agriculture, while the remaining are employed in the commercial sector and as government officials. Like other cities in Indonesia, Bima has experienced population growth and urbanization. The development of the city's infrastructure, including essential aspects such as adequate housing and a safely managed sanitation system, has not kept pace with growth. As a result, impoverished slum areas have expanded, particularly those located near riverbanks. This is evident in the lack of safely managed sanitation access in Bima

City, which increases vulnerability to water-borne disease outbreaks and water quality-related environmental degradation. As of April 2021, only 64% of villages and one in 10 districts have achieved open defecation free status, directly contributing to the degradation of surrounding environmental conditions through the discharge of both black water into rivers and gray water into drainage canals or rivers.

Additionally, Bima City is highly susceptible to flash flooding and other water disasters such as drought (Stanton-Geddes & Vun, 2019). The most significant flash flood recently happened in 2016, with the water level reaching up to 3 meters. The rise in the number of severe floods can be attributed to the transformation of rivers. The development of riverside residential areas, coupled with population growth, has caused the narrowing of some rivers, hindering water flow. As a result, several small rivers transform into primary drainage channels, receiving upstream flow loads and serving as the primary water discharge channels into Bima Bay.

Sea foam phenomenon in Bima Bay

On April 25 2022, pollution began to occur in the Bima Bay area. This pollution is known by residents around the Bima Bay and it is observed that the pollution that appears is in the form of bubbles floating above the waters of the Bima Bay. The froth observed had a characteristic odor, thickened and thick, up to 10 cm thick and brownish in color. When observed from a distance, the pollution in the form of foam that appears is observed to be like a desert because of the massive distribution.

From 26 April, 2022 to 27 April,2022, pollution began to appear massively until foam appeared in an area of 10 Ha and on this date poisoning began after a resident in the Teluk Bima area consumed sea fish originating from the Bima Bay. Based on the poisoning incident, there are indications that this emerging pollution is toxic to the environment because at several points it was also found that there were dead fish.

Based on the pollution phenomenon that appeared in the Bima Bay area, a team from the ITB Faculty of Civil and Environmental Engineering in coordination with the ITB Center for Environmental Studies (PSLH ITB) and the Ministry of Environment and Forestry (KLHK) on 28 April 2022 begin to inspect the area where the contamination occurred. The team began to take samples at 5 points of pollution areas with different area characteristics. On April 28, 2022, the scope of pollution where bubbles appeared from the BimaBay area began to decrease, and large clumps of foam had also shrunk. On April 29, 2022 the team also took drone images of the phenomenon.

Based on the team's observations, it was shown that this pollution phenomenon occurred in a short period of time and was no longer visible one week after the peak of the incident. However, based on the guidance of residents who live in the Bima Bay area, this phenomenon does occur every year at the peak of summer, but the pollution that occurred in 2022 is the largest scale pollution that has ever occurred in the Bima Bay area.

The rapidity of the phenomenon observed on the ground is also strengthened through Satellite imagery from LAND- SAT 8 and SENTINEL 2, seen in Figure 3. Only 6 figures were retrieved as these were the only dates where Bima Bay was clearly visible. Notably, on 24 April 2022 nothing peculiar was visible, on 28 April 2022 thesea foam is visible (this is however past the peak of the phenomenon),while on 29 April it had subsided albeit still visible. Then On 4 May 2022 onwards, no more sea foam is visible.

Points of Grab Sample on Bima Bay

This study examines the sea foam phenomenon in Bima Bay through three main analyses: water quality testing, toxicity level testing, and microalgae characterization. This study collected water samples from five main points in Bima Bay using the grab sampling method with a frequency of three samples taken three times, as shown in Figure 4. A total of 15 samples were

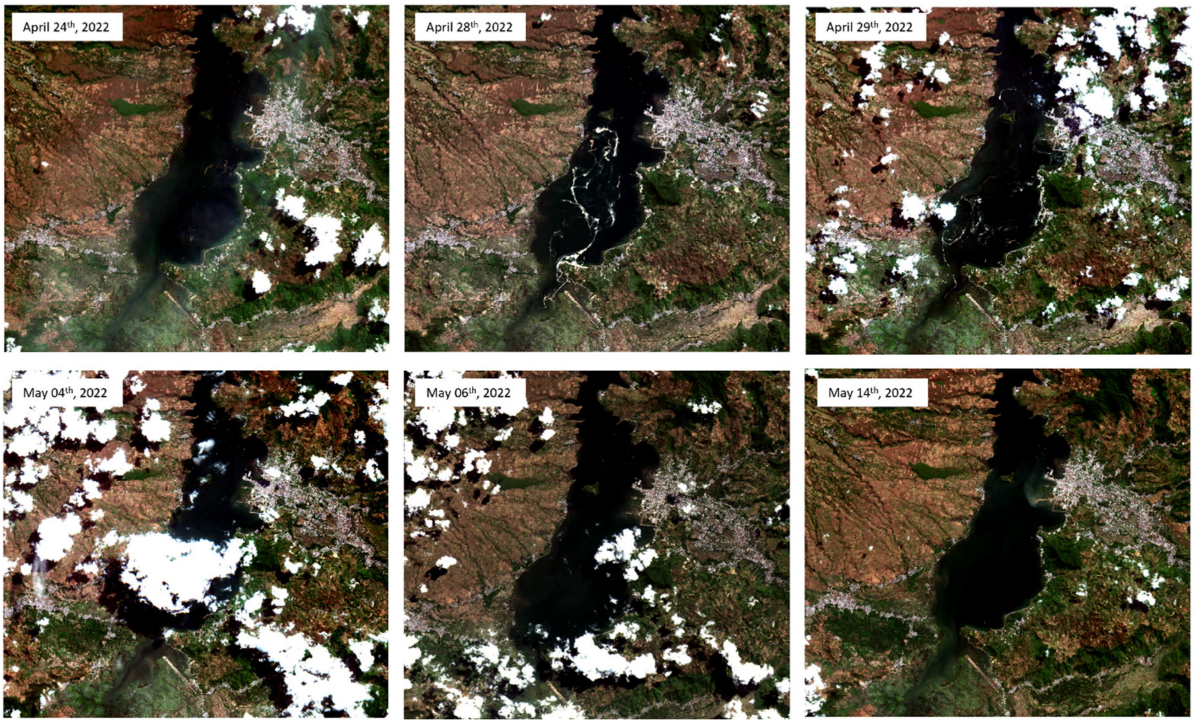

Fig. 3. True color combination on satellite image dataset

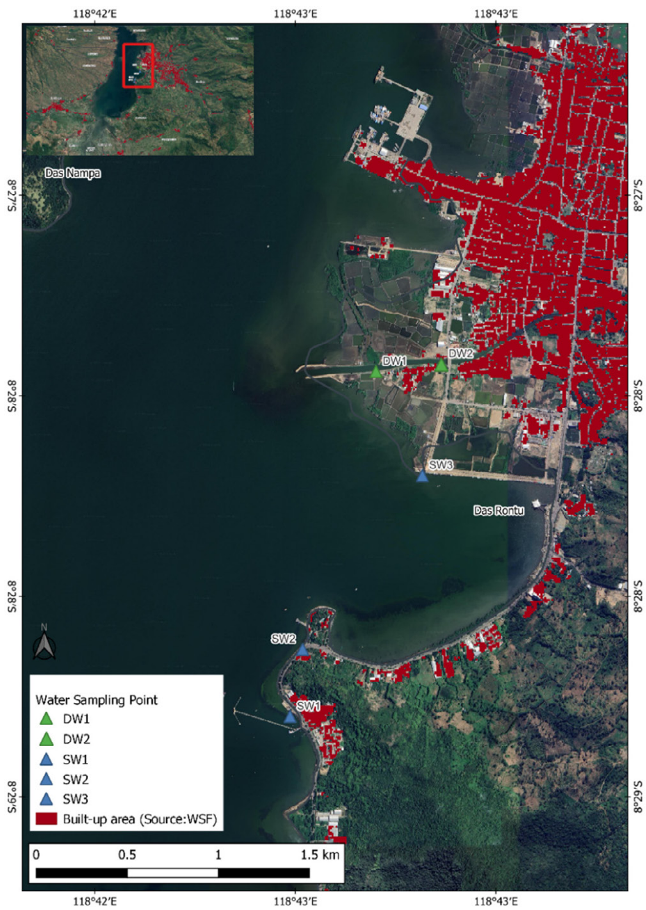

Fig. 4. Points of Grab Sample on Bima Bay

Table 1. Level of Toxicity Based on LC50-96 hours Value

LC50-96 hours Value	Toxicity Level
<1 mg/L	Very Toxic
1 – 10 mg/L	Toxic
10 – 100 mg/L	Moderate Toxic Low Toxic
>100 mg/L	Low Toxic

collected. Water sampling was conducted on April 28, 2022, at the end of the rainy season. Additionally, around 6 months prior to the sea foam phenomenon on December 2021, the team conducted a river water quality investigation, using grab method to take the water sample.

The selection of sampling locations was based on the assumption that the presence of sea foam phenomenon in the bay is attributable to contaminants originating from rivers that discharge into the bay. To address this, sampling points were strategically chosen along the coastal waters and at the mouth of the river. There are 3 samples of seawater (SW) taken around Lawata Beach (SW1 and SW2) and Amahami floating mosque of Bima City (SW3), along with 2 samples of downstream river water (DW) which were taken at the mouth of the Padolo River (DW1 and DW2). Meanwhile, the selection of river sampling location in December 2021 was based on the location of a riverside slum settlement in Paruga sub-district (masukin peta sampel).

The three main analyses were conducted to investigate the link between the phenomenon of pollution. By analyzing the results of each analysis, the study aimed to identify the potential main sources of pollution. Below the detailed description of each methodology is presented.

Water Quality Test

The water quality tests was analyses with the water quality standards of the Indonesian Government Regulation Number 22 of 2021 Appendix VIII. Based on these regulations, water quality standards are used for Marine Tourism and Marine Ecosystems. In addition to the water quality standards mentioned, marine tourism and ecosystem quality standards were also utilized in the study to evaluate the water quality in Bima Bay. This is because, the bay is a busy area used by both fishermen and tourists. By comparing the water quality to the standards for marine tourism, the study assessed if the bay is suitable for such activities. Additionally, the study assessed if the pollution has impacted the marine ecosystem in the area, which is important for both the residents who depend on marine products and fishermen who rely on the bay for their livelihood.

Acute Toxicity Test

In order to assess the potential impact of pollution on the marine ecosystem in Bima Bay, an acute toxicity test was conducted. This approach was chosen as acute toxicity refers to the ability of a chemical or biological parameter to induce harmful effects within a short timeframe. The outcome of the acute toxicity test was expressed as the Lethal Concentration 50 (LC50), which indicates the concentration of the toxic substance that causes 50% of the tested organisms to perish (*Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms Fifth Edition*, 2002). The level of toxicity based on the LC50-96 hour value is divided into several criteria (*PART 4 ENVIRONMENTAL HAZARDS*, n.d.) which are shown in Table 1.

The toxicity test was conducted following the standard protocols outlined by the Environmental Protection Agency (EPA) (*Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms Fifth Edition*, 2002). The concentration used for the LC50 assay was 25.6%; 12.8%; 6.4%; 3.2%; 1.6% (Weber, 1991). Ten Artemia speci- mens were employed in each test container, and the experi- ment was conducted three times. The

Table 2. Satellite dataset

Satellite	Acquisition Date
Sentinel 2A	April 24th, 2022
Landsat 8/9	April 28th, 2022
Sentinel 2B	April 29th, 2022
Sentinel 2A	May 04th, 2022
Landsat 8/9	May 06th, 2022
Sentinel 2A	May 14th, 2022

following parameters were monitored at 24-hour intervals: mortality rate of the test subjects, pH level, dissolved oxygen (DO), ambient temperature, humidity, and lighting conditions

Microalgae taxonomic characterization

To determine the microalgae characteristics present in the Bima Bay waters, water samples were collected from the area. Water sampling was conducted from the surface layer at a depth of 50 cm, which was determined by the intensity of sunlight at the study site. This method ensured that the microalgae collected were those that were living near or above the water surface and floating in the water. The water sample for microalgae observation was then filtered using a plankton net with a mesh size of 35 nm which was pulled horizontally by the towing method for 2 minutes and then the filtered water sample at the codend was poured into a sample bottle. The abundance of microalgae samples was calculated by adding 4% formalin and 3 drops of iodine. However it is important to note that the microalgae samples for character- ization were isolated and stored without preservatives.

Satellite imagery observation

Satellite imagery has been utilized to detect the phe- nomenon of sea foam in Bima Bay. The satellite images used in this study were obtained from Sentinel-2A, Sentinel- 2B, and Landsat 8/9 satellites, covering the period from 24th April 2022 to 14th May 2022. The use of multiple satellite constellations was necessary to obtain daily imagery due to their differing temporal resolutions. Despite this, obtaining daily imagery of the Bima Bay region remains unfeasible. The data set used in this research is presented in Table 2.

In order to provide an overview of the distribution of sea foam in Bima Bay, a simple satellite image processing approach was employed. This involved the application of true color combination (red, green, and blue) to all satellite images in the dataset (4). In addition, false color combination (near infrared, red, and green) and Normalized Pigment Chlorophyll Ratio Index (NPCRI) were employed to differ- entiate between sea foam and water in those images depict- ing clear instances of sea foam in the true color combination. NPCI indices were defined as the combination of satellite bands.

$$\frac{Red - Blue}{Red + Blue} \quad (1)$$

RESULTS AND DISCUSSIONS

Water Quality

The results of the water quality analysis for all 5 points are shown in Table 3, where the quality standard for both marine tourism and marine ecosystems are also presented. The water quality for Biochemical Oxygen Demand (BOD), Oil and Grease, Orthophosphate, Surfactant (MBAS), NH_3-N, Cu and Total Coliform does not meet the quality standards for marine tourism. While, The water quality for Biochemical Oxygen Demand (BOD), Oil and Grease, TPH, Orthophosphate, Surfactant (MBAS), NH_3-N, NO_3-N, Cu and Total Coliform also do not

Table 3. Water Quality Analysis Results on Bima Bay Water Sample

Parameter	Unit	Lab Results					Quality Standards	
		SW 1	SW 2	SW 3	DW 1	DW 2	Marine Tourism	Marine Ecosystem
pH	-	6.92	7.55	7.39	7.68	7.7	7 – 8.5	7 – 8.5
COD	mg/L	32	16	16	16	32	-	-
BOD	mg/L	20.8	10.4	10	10	20	10	20
Oil and Grease	mg/L	11.3	12	28.5	7.58	12.5	1	1
TPH	mg/L	3.58	1	12.2	<1	1	-	0.02
Total Phosphate	mg/L	0.035	0.028	0.027	0.063	0.058	-	-
Orto Phosphate	mg/L	0.024	<0.01	<0.01	0.032	0.037	0.015	0.015
Surfactan (MBAS)	mg/L	0.395	0.275	0.274	0.249	0.235	0.001	1
NH_3-N	mg/L	0.487	0.255	0.24	0.311	0.43	0.02	0.3
NO_3-N	mg/L	0.046	0.022	0.824	0.821	1.194	-	0.06
NO_2-N	mg/L	0.058	0.015	0.059	0.051	0.06	0.06	-
N Organic	mg/L	6.99	5.85	16.2	3.02	3.73	-	-
Benzene	mg/L	<0.10	<0.10	<0.10	<0.10	<0.10	-	-
Toluene	mg/L	0.166	0.159	0.167	0.132	0.17	-	-
Ethyl Benzene	mg/L	<0.10	<0.10	<0.10	<0.10	<0.10	-	-
Xylene	mg/L	<0.10	<0.10	<0.10	<0.10	<0.10	-	-
Cu	mg/L	0.023	<0.005	<0.005	<0.005	<0.005	0.05	0.08
Zn	mg/L	0.063	<0.001	<0.001	<0.001	<0.001	0.095	0.05
Total Coliform	MPN/ 100 mL	240	240	24,000	43	1,100	1,000	1,000
Fecal Coliform	MPN/ 100 mL	0	0	20	43	43	200	-
Algae							-	-

:xceeding quality standard

Table 4. River water quality testing results December 2023

Parameter	Unit	Standard	Analysis Result			
			Station 1	Station 2	Station 3	Station 4
TSS	mg/L	40	49	39	37	37
Ammonia	mg/L	10	0.066	0.047	0.06	< 0.038
BOD	mg/L	2	10.2	8.80	10.0	5.80
COD	mg/L	10	15	13.0	15.0	10.0
Oil and Grease	mg/L	1	2.5	2.33	2.17	2.33
Total Coliform*	MPN/100 mL	0	> 23	> 23	> 23	> 23
Fecal Coliform	MPN/100 mL	0	>23	> 23	> 23	> 23

Exceeding quality standard

meet the quality standards for marine ecosystem. The analysis showed that the standards were not met, indicating the presence of pollution sources.

Water quality analysis showed high concentration of nitrate (NH_3-N and NO_3-N) and high concentrations of phosphate in the form of Orthophosphate. These nitrates and phosphates are nutrients that support water fertility and determine the quality of waters. Excessive concentrations of nutrients in the form of nitrates and phosphates can have negative impacts such as decreasing oxygen levels in the waters and the development of phytoplankton types that can disrupt biodiversity in aquatic biota (Gypens et al., 2009).

When the parameters that do not meet quality standards were grouped, three possible sources were identified: domestic waste (containing nitrate, phosphate, organic, and coliform), agricultural and fishery waste (containing nitrate and phosphate), and waste oil content (containing TPH, toluene, and oil and grease). As many of the pollution sources are from the shore, it is clear that this is a byproduct of Bima Bay's semi-enclosed sea area that makes it more prone to pollution from sources along the shore, as it has limited ability to disperse and dilute the pollutants. This is exaggerated by the sanitation conditions in Bima City where in

Table 5. The LC50-96 hours Toxicity Test Results Value

Water Samples	LC50 (%) Value	
	1st Stage	2nd Stage
SW 1	0.081	4.668
SW 2	0.088	5.034
DW 1	0.181	10.64
DW 2	0.297	12.268

Table 6. Algae Groups Around Bima Bay

Division	Class	Ordo	Family	Genus	Species
Bacillariophyta	Bacillariophyceae	Surirellales	Surirellaceae	Surirella	Surirella sp.
		Pennales	Achananthaceae	Achanthes	Achantes sp.
		Bacillariales	Bacillariaceae	Nitzchia	Nitzchia sp.
		Bacillariales	Bacillariaceae	Nitzchia	Nitzchia longisima
		Incertae sedis	Chaetocerotaceae	Bacteriastrum	Bacteriastrum sp.
		Naviculales	Amphipleuraceae	Amphiprora	Amphiprora sp.
		Naviculates	Naviculaceae	Navicula	Naviculla sp.

practice both black and gray water are disposed into the river. In addition, the rapid increase in agriculture and fishing industry also adds to the potential pollutant in the area.

Acute Toxicity Level

The results of the analysis of the acute toxicity test LC50- 96 hours around Bima Bay are shown in Table 5. The results showed that there were variations in the outcomes depending on whether the test biota were not acclimatized (1st stage) versus when they were (2nd stage).

Without acclimatization, samples from both coastal ar- eas (SW 1 and SW 2) and river areas (DW 1 and DW 2) have high level of toxicity (very toxic). But when compared coastal areas have a higher level of toxicity than samples in river areas. However with acclimatization, samples from coastal areas (SW 1 and SW 2) still have high level of toxicity (Very Toxic), but samples from river areas (DW 1 and DW 2) have only moderate level of toxicity. However over all, coastal areas show higher level of toxicity than the river areas.

Microalgae taxonomic characterization

The previously depicted water quality analysis showed a high abundance of algae growth. Algae groups observed around Bima Bay in general were *Surirella sp, Achanthes sp, Nitzchia sp, Bacteriastrum sp, Nitzchia longisima, Am- phiprora sp, and Naviculla sp*.

The types of algae found around Bima Bay were identi- fiedas belonging to the Diatom group. This diatom is a type of algae that belongs to the Bacillariophyceae class which is a single cell (unicellular) organism that lives solitarily and in some species lives in colonies (Kale & Karthick, 2015). Algae from the Diatom group can be detected on substrates with slimy characteristics and have a golden brown thin film covering the substrate. Under certain conditions or at certain times, this membrane can become thicker (Taylor et al., 2007). The characteristics of each group of algae observed around Bima Bay based on their taxonomic level are shown in table 6.

Table 7 shows that each location has different phytoplankton community characteristics. Jakarta Bay is dominated by diatoms such as Skeletonema and Chaetoceros and harmful dinoflagellates such as Alexandrium and Pseudo-nitzschia, indicating a high potential for HABs. Lampung Bay has high diversity with many harmful species such as Cochlodinium polykrikoides and Dinophysis, which are often associated with mass fish deaths. Ambon Bay

Table 7. Algae Groups Around Bima Bay

p	Algae Species	Reference
Jakarta Bay	Skeletonema sp, Chaetoceros sp, Thalassiosira sp, Trichodesmium sp, Noctiluca (green), Ceratium furca, Alexandrium sp, Pseudo-nitzchia sp, Dinophysis sp, Coscinodiscus sp, Leptocylindricus sp, Thalassiotrix sp, Bacteriastrum sp, Pyrodinium (Pbc), Gymnodinium sp	Sidabutar et al., 2024
Lampung Bay	Trichodemium sp, Thalassiotrix sp, Rhizosolenia sp, Chaetoceros sp, Skeletonema sp, Noctiluca sp, Ceratiun furca Harmful Fish mortality 8 Pseudo-nitzchia, Phaeocystis sp, Dinophysis sp, Prorocentrum sp, Pyrodinium bah. var. compressum, Cochlodinium polykrikoides, Alexandrium sp	Sidabutar et al., 2024
Ambon Bay	Pyrodinum bahamense (Pbc), Trichodesmium sp, Noctiluca sp, Chaetoceros sp, Skeletonema sp, Alexandrium affine, Noctiluca scintillans, Pyrodinium (Pbc), Pyrodinum (Pbc)	Sidabutar et al., 2024
Bima Bay (This Research)	Surirella sp., Achantes sp. Nitzchia sp., Nitzchia longisima, Bacteriastrum sp., Amphiprora sp., Naviculla sp.	This Research

is relatively more specific, with Pyrodinium bahamense dominating as the main cause of HAB in the region. Meanwhile, Bima Bay differs significantly as it is more dominated by non-HAB diatoms such as Surirella, Nitzschia, and Navicula, resulting in a more normal community despite still being susceptible to nutrient enrichment.

The observed group of algae belongs to the Class Bacil- lariophyceae. This Algae class has the ability to adapt to strong currents because this Algae group has an adhesive device on the substrate in the form of gelatinous stalks (Effendy et al., 2017, 2018). This ability of the Bacillariophyceae Class supports its relatively high density around the Bima Bay.

The abundance of algae groups from the Class Bacillar- iophyceae around the Bima Bay area indicates that there are certain factors that result in supporting the growth of these algae. Based on table3, it can be seen that nitrate, phosphate, BOD, oil and grease exceeded the quality standard. So that the dissolved organic compounds in the seawater greatly influences the growth of these algae (Harmoko et al., 2019). Moreso, the pH level of Bima Bay is between 6.92 to 7.7, indicating an alkaline condition. Therefore the existance of the diatom class Bacillariophyceae, which requires a pH that tends to be alkaline and avoids water containing acids (Roito et al., 2014), is in accordance to the ph level recorded. Even a slight change in the pH value and organic compounds will affect the abundance of the diatoms in these waters (Gualtieri & Barsanti, 2022).

Other environmental factors such as light intensity are also important for the growth of algae used to carry out photosynthesis. The aforementioned information is in line with the climate situation in Bima Bay, which is catego- rized as tropical waters having extended periods of sunlight throughout the day (Arthington et al., 2006).

Satellite Imagery

The true composition of satellite imagery has revealed that the occurrence of sea foam in Bima Bay began on April 24th , 2022. This finding is consistent with the initial reports from residents of Bima City, who first mentioned the occurrence of sea foam on April 25th , 2022. The sea foam was observed to peak on April 28th, 2022,as indicated by satellite images, and gradually decreased in intensity on April 29th, 2022, eventually disappearing completely on May 04th , 2022. It is important to note that the disappearance of the sea foam in Bima Bay may have occurred prior to May 04th, 2022, but due to dataset limitations, this date is the latest for which it is shown. The use of true color image composition was found to be effective in clearly

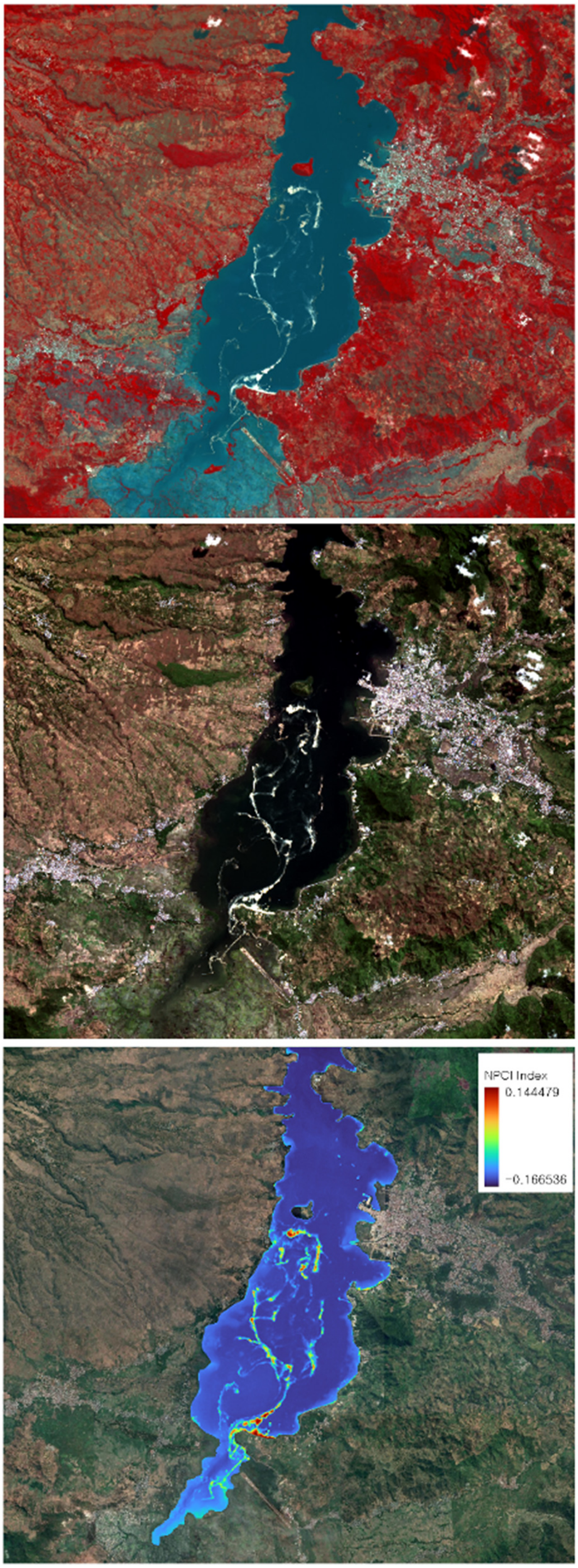

Fig. 5. False color combination, true color combination, and NPCRI indices on April 28th, 2022 satellite imagery

displaying the appearance of sea foam in Bima Bay, without the need for complex satellite image processing such as atmospheric correction or sun glint correction. It is worth noting that atmospheric correction is not always necessary for change detection from satellite imagery.

Sea foam is primarily caused by the development or bloom of phytoplankton in water bodies. False color combination and NPCRI were employed in this study to detect the presence of phytoplankton or chlorophyll substrate on the water surface. NPCRI indices were applied to the satellite images from April 24th to 29th, 2022, and were found to be capable of estimating the chlorophyll content on the water surface. The results obtained from false color combination, true color combination, and NPCRI indices revealed that sea foam was most prevalent on the satellite image captured on April 28th , 2022. Both false color and true color combinations were found to be effective in clearly identifying the presence of sea foam in Bima Bay (see Figure 5). However, it was challenging to distinguish the color differentiation between clouds and sea foam, as they appeared identical in false and true color combinations. In contrast, NPCRI indices were able to clearly differentiate between sea foam and water, and also indicated the level of chlorophyll present in thesea foam, which may indicate high concentrations of this substance.

Discussion on Land Use Changes in Bima Bay

When analyzing problems with a focus on the specific conditions of a particular area, such as geographical characteristics, types of community activities, land use patterns, and sources of pollution in the area, it is possible to see how human activities directly affect the quality of seawater in that location. Land use change and anthropogenic emission are known to cause deterioration of the water quality (Vijayakumar, 2022; Makubura, 2022; Siriwardhana, 2023). Decline in water quality in the Bay area due to organic matter and nutrients carried by rivers, such as nitrogen and phosphate (Ator et al., 2020). Both land use change and anthropogenic activities are not inherently harmful, however organic matters and nutrient occurrences in river water might indicate mismanagement -or lack thereof- in the source point of these pollutants. In the case of Bima Bay, two major pollutant sources are suspected to be the cause of the sea foam phenomenon: massive agriculture development in the upstream watershed area and the absence of safely managed sanitation system in Bima City. Therefore, it is also necessary to analyze the microplastic content in Bima Bay, as domestic wastewater is one of its major sources (Fauzi et al., 2024).

Sea foam formation is tightly related to the production of dissolved organic matter in water (B Velimirov, 1980). High nutrient levels that accumulate in the bay act as fertilizers for microscopic algae, promoting rapid growth and reproduction. In Bima Bay context, several algae groups are identified in seawater samples,further confirming the prevalence of said organism, as can be seen in Table 6. As the accumulated algae near the coastline die off and decay, it contributes to the increase of organic matter to the water. The decomposition of organic matter from decaying algae, along with organic matter from untreated sewage, releases Dissolved Organic Carbon (DOC) and triggers the formation of surfactant, reducing surface tension and leading to the formation of sea foam. Limited water circulation, wind and wave interaction, and tidal exchange can exacerbate this phenomenon, such can be found in Bima Bay as an enclosed body of water.

In agricultural practices, land clearing can lead to soil erosion, while deforestation along with sedimentation that happens due to erosion can alter the natural flow patterns of rivers, leading to increased runoff during heavy rainfall events. This sudden increase in water volume, coupled with excessive use of pesticides and fertilizers, can carry contam- inants in the form of nutrients like nitrogen and phosphate downstream, impacting the bay's water quality. This can be seen in Bima, where there have been rapid changes in the upstream areas for the development of the agricultural sec- tor, especially for cornfields (data source: increase in corn production and/or images of upstream land use).

In urban areas, land use changes driven by population growth may involve clearing land for residential areas. Increased population leads to more waste generation, espe- cially wastewater. If not properly managed, untreated sewage may be discharged into rivers, contributing to increased nutrient levels and oxygen depletion due to organic decom- position. This disrupts river carrying capacity and further, its water quality.

Taking into account the process of which sea foam formation in great quantities can occur, the sea foam phe- nomenon happening in Bima can all be traced back to the land use change phenomenon. According to water qual- ity checking (Table 3), BOD and COD (representation of organic matters) along with orthophosphate and nitrogen (representation of nutrients) are particularly high in the downstream sampling points (DW). Similarly, based on the previous river water quality monitoring on December 2021 (see Table 4), BOD and COD are found to be higher then the supposed quality standards. This indicates that the accumu- lation of both organic matter and nutrients are carried by the river. This pollution then can be traced back to the respective activities that may cause them as previously explained.

CONCLUSION

Pollution in Bima Bay originates from domestic, agricultural, fishery, and industrial wastewater that exceeds the ecosystem's carrying capacity, further aggravated by upstream corn farming expansion, poor sanitation, and the bay's semi-enclosed setting that restricts seawater circulation. Water quality analysis recorded BOD at 20.8 mg/L, oil and grease at 28.5 mg/L, orthophosphate at 0.037 mg/L, and NO_3-N at 1.194 mg/L, all exceeding the standards set by PP No. 22/2021. Acute toxicity testing (LC50-96 hours) yielded 0.081% (highly toxic), indicating a severe threat to the marine ecosystem. The massive brown sea foam observed in April 2022 (>10 ha) was linked to high levels of organic matter, nitrogen, and phosphate, triggering blooms of diatoms such as *Nitzschia*, *Navicula*, and *Surirella*, further supported by tropical light intensity. Sentinel-2 and Landsat 8/9 imagery showed the foam appearing on April 24 and disappearing after May 4, 2022. These findings emphasize the urgent need for mitigation through spatial planning and integrated waste management in tropical coastal areas.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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