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Post-Sea Snot Ecological Assessment: Autoecology of *Ceratium furca* and *Nitzschia longissima* in Bima Bay, Nusa Tenggara Barat, Indonesia

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ABSTRACT

The sea snot phenomenon in Bima Bay, West Nusa Tenggara, has raised significant concerns regarding its ecological implications, particularly in relation to harmful algal blooms (HABs). This study investigates the autoecology of *Ceratium furca* and *Nitzschia longissima*-two phytoplankton species associated with HABs- following the sea snot event in April 2022. Sampling was conducted at ten stations in May 2023 to assess key environmental parameters, including temperature, salinity, pH, dissolved oxygen, nitrate, phosphate, ammonia, and chlorophyll-a, alongside phytoplankton abundance. Canonical correspondence analysis (CCA) revealed a strong correlation between *C. furca* abundance and nitrate concentration, particularly at Station 4 (250.225 × 10^3 cells/L). Conversely, *N. longissima* exhibited the highest abundance at Station 5 (14.837 × 10^3 cells/L), which was positively correlated with elevated phosphate levels. Nutrient concentrations (nitrate: 0.166– 0.431mg/ L, phosphate: 0.272– 0.652mg/ L) exceeded eutrophication thresholds, promoting phytoplankton proliferation. Regression analysis indicated that nitrate significantly influenced C. *furca* abundance (R^2 = 0.78), whereas *N. longissima* was predominantly affected by phosphate levels (R^2=0.69). The weak correlation between phytoplankton abundance and chlorophyll-a suggests that additional factors, such as light intensity and hydrodynamic conditions, also contribute to phytoplankton dynamics. These findings highlight the critical need for continuous monitoring and nutrient management strategies to mitigate future HAB risks and maintain ecological balance in Bima Bay.

INTRODUCTION

The sea snot phenomenon in Bima Bay, Nusa Tenggara, Indonesia, which occurred in April 2022, represents the first recorded instance in Indonesian waters

(BRIDA Bima Kota, 2022). This event has raised concerns regarding its long-term ecological impact, particularly in relation to the potential formation of harmful algal blooms (HABs). Sea snot, or mucilage, is an accumulation of organic mucus produced by phytoplankton in response to eutrophication, a process characterized by increased concentrations of nutrients such as nitrogen and phosphorus in aquatic environments **(Aktan, 2008; Ergul *et al*., 2021; Karadurmuş & Sari, 2022)**. This condition is exacerbated by anthropogenic activities such as agriculture, domestic waste discharge, and aquaculture, which elevate nutrient loading in coastal waters **(Lan *et al*., 2024)**.

Globally, sea snot events have been documented in various regions, including the Gulf of Oman **(Al-Hashmi *et al*., 2014)** and the Marmara Sea in Turkey **(Ergul *et al*., 2021)**. In the Marmara Sea, this phenomenon led to a drastic decline in water quality, adversely affecting the fisheries sector. In the Gulf of Oman, high temperatures and elevated organic matter concentrations were identified as the primary drivers of sea snot formation **(Al-Hashmi *et al*., 2015)**. Compared to Bima Bay, a key difference lies in the dominant nutrient sources. In Bima, nutrient influx is suspected to originate from domestic runoff and aquaculture activities, along with possible contributions from deforestation-driven agricultural land conversion, particularly for maize cultivation. Deforestation reduces vegetation's ability to absorb water, increasing surface runoff that carries sediment and nutrients such as nitrogen and phosphorus into coastal waters **(Satriawan *et al*., 2023)**. Conversely, in Turkey and Italy, intensive agricultural practices are the primary contributors to nutrient enrichment.

This study addresses a critical knowledge gap, as the ecological implications of sea snot in tropical waters remain poorly understood. Understanding how dominant phytoplankton species respond to nutrient enrichment and changing environmental conditions is essential for anticipating the potential recurrence of sea snot and HABs in Indonesian coastal ecosystems **(Sarthou *et al*., 2005; Morton *et al*., 2011; Sholihin *et al*., 2014)**. The novelty of this research lies in being the first documentation of the post-sea snot dynamics of *Ceratium furca* and *Nitzschia longissima* in tropical Indonesian waters. Unlike prior studies conducted in temperate regions, this work provides new insights into the abundance and ecological role of these phytoplankton species in relation to environmental parameters in a tropical setting. These findings contribute to the development of long-term monitoring strategies and region-specific management approaches for mitigating future sea snot and HAB events.

MATERIALS AND METHODS

Time and location

This study employed a quantitative approach, with sampling conducted at ten stations in May 2023, one year after the 2022 sea snot phenomenon. Phytoplankton sampling was performed in the waters of Bima Bay, West Nusa Tenggara, Indonesia

(Fig. 1). Water chemistry analysis, including nitrate, phosphate, and ammonia concentrations, was conducted at the Analytical Chemistry Laboratory, University of Mataram. Chlorophyll-a analysis was performed at the Marine Aquaculture Fisheries Center (BPBL) in Lombok using a Shimadzu UV-Vis UV-1800 spectrophotometer, following APHA protocols **(Rice *et al*., 2012)**. Phytoplankton identification was carried out at the Marine Hydrobiology Laboratory, University of Mataram. Sampling station selection followed a purposive sampling method, considering variations in anthropogenic activities, including an oil fuel terminal, Lawata Beach, a river estuary, and Bima Port. These locations were selected based on their pollution potential, as each activity influences the distribution of nutrients within the aquatic environment.

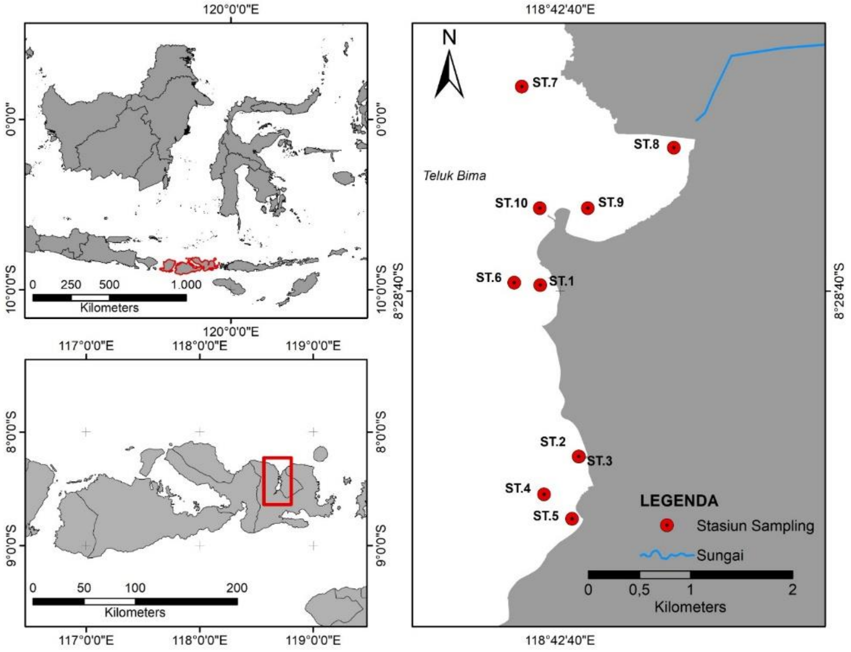

Fig. 1. Research location

Water quality sampling and measurement

Chlorophyll-a samples were collected using a Van Dorn Water Sampler Horizontal from a depth of 5 meters to represent the primary productive zone within the water column **(Ritchie, 2008)**. The samples were stored in 1-liter dark polyethylene bottles to prevent photodegradation and immediately placed in an icebox at 4°C until laboratory analysis **(Parsons, 2013)**. In the laboratory, the samples were filtered using GF/F glass fiber filters (0.7µm pore size) with a vacuum pump. Chlorophyll pigments were extracted using 90% acetone at a low temperature (4°C) for 24 hours. The chlorophyll-a concentration was measured using a Shimadzu UV-Vis UV-1800 spectrophotometer at a wavelength of 664nm following APHA standard methods **(Rice *et al*., 2012)**.

Measurements of physical parameters included current velocity with a Global Water FP Current Meter, temperature with Hanna HI98193 DO Meter, salinity with a handheld refractometer, and water transparency with a Secchi disk.

Chemical parameters measured included pH and dissolved oxygen (DO) using a Hanna HI98193 DO Meter. Water samples for nutrient analysis (nitrate, phosphaate, and ammonia) were collected at each sampling station using a horizontal Van Dorn sampler from a depth of up to 5m. At each station, three replicate water samples (1L each) were transferred into pre-cleaned sterilized glass bottles. Each 1L bottle was immediately stored in an icebox at approximately 4°C to minimize biological and chemical changes during transportation. In the laboratory, nutrient concentrations were analyzed using a Shimadzu UV-Vis UV-1800 spectrophotometer following the standard procedures described by the APHA **(Rice *et al*., 2012)**.

Phytoplakton sampling and handling

Phytoplankton samples were collected by taking 50 liters of seawater using a Van Dorn sampler Horizontal and then filtered manually through a plankton net with a 20µm mesh size, 30cm mouth diameter, and 100cm length (nylon material). The filtered samples were transferred into 100mL polyethylene bottles and preserved with 1% Lugol's solution **(Sahu *et al*., 2012)** before being transported to the laboratory for analysis. Phytoplankton identification was performed using a Sedgwick-Rafter counting chamber under an Olympus CX-23 microscope at 100× magnification **(Larasati *et al*., 2015)**. Plankton abundance was determined following APHA standard methods **(Rice *et al*., 2012)**. Species identification was conducted using established taxonomic references, including **Davis (1955)**, **Yamaji (1984)** and **Hasle *et al*. (1996)**. Additionally, potentially harmful algal bloom (HAB)-forming taxa were verified using the AlgaeBase online database **(Guiry *et al*., 2014)**.

Statistical analysis

Canonical correspondence analysis (CCA) was employed to investigate the ecological relationships between the abundance of *Ceratium furca* and *Nitzschia longissima* and key environmental parameters, including temperature, salinity, dissolved oxygen (DO), pH, water transparency, chlorophyll-a, nitrate, and phosphate. CCA was selected due to its robustness in capturing complex interactions between biotic and abiotic variables, enabling a comprehensive visualization of species' ecological preferences under multifactorial influences **(Ter Braak & Šmilauer, 2018)**. In the resulting biplot, vector length represents the strength of association between environmental factors and phytoplankton abundance, while vector direction indicates the gradient along which each factor influences species distribution **(Lepš & Šmilauer, 2003)**.

To further quantify these relationships, polynomial regression analysis was applied to model the non-linear associations between nutrient concentrations and phytoplankton abundance, as these interactions often deviate from linear trends in aquatic ecosystems **(Zuur *et al*., 2007)**. The use of polynomial regression allows for a more precise depiction of threshold effects and saturation dynamics in nutrient uptake and phytoplankton proliferation. All statistical analyses were conducted using PAST3 software for CCA and XLSTAT for polynomial regression modeling, ensuring methodological rigor and reproducibility in ecological data interpretation.

RESULTS

Abundance of *Ceratium furca* and *Nitzschia longissima*

Based on the phytoplankton abundance data obtained (Table 1), the average abundance of *Ceratium furca* reached 71,849.59 cells/L, significantly higher than *Nitzschia longissima*, which recorded an average abundance of only 3,709.28 cells/L. The abundance of *C. furca* exhibited considerable variation, ranging from 401 to 250,226 cells/L. Such high variability and dominance of a single species indicate its potential role in bloom formation, a characteristic feature of Harmful Algal Blooms (HABs). In comparison, the maximum abundance of *C. furca* recorded in Pago Pago Harbor, American Samoa, was only 9,200 cells/L in 2007 **(Morton *et al.*, 2011)**. HAB events are typically recognized not solely by a fixed numerical threshold but by rapid increases in phytoplankton biomass and dominance of particular species that surpass the natural regulating capacity of the ecosystem **(Smayda, 1997; Anderson *et al.*, 2012)**. Excessive blooms of *C. furca* may lead to oxygen depletion in the water column, disrupt ecological balance, and threaten marine biodiversity **(Somsap *et al.*, 2015)**.

Table 1. Mean abundance of *Ceratium furca* and *Nitzschia longissima* as potential HAB-forming species in Bima Bay

No	Species pf Phytoplankton	Mean Abundance (Cells/L)
1	*Ceratium furca*	71.849,59
2	*Nitzschia longissima*	3.709,28

The boxplot in Fig. (2) illustrates distinct differences in the abundance of *Ceratium furca* and *Nitzschia longissima* across the sampling stations. The median abundance of *C. furca* was consistently higher than that of *N. longissima* at most stations, indicating that *C. furca* is the dominant species in the study area. Additionally, *C. furca* exhibited a larger interquartile range, reflecting greater variability in its abundance compared to *N. longissima*.

The longer whiskers observed for *Ceratium furca* indicate that its abundance varied much more widely across stations compared to *Nitzschia longissima*. This suggests that *C. furca* not only maintained a consistently higher median abundance, but also frequently exhibited sudden population increases, as reflected by the presence of extreme outliers. In contrast, *N. longissima* showed relatively low and stable abundance across most stations. For example, at Station 4 the abundance of *C. furca* far exceeded that of *N. longissima*, while at Station 8, despite some variation, *C. furca* remained the dominant species. These findings confirm that *C. furca* exhibits a more dynamic population structure and is more responsive to environmental fluctuations, thereby reinforcing its potential role in harmful algal bloom (HAB) development.

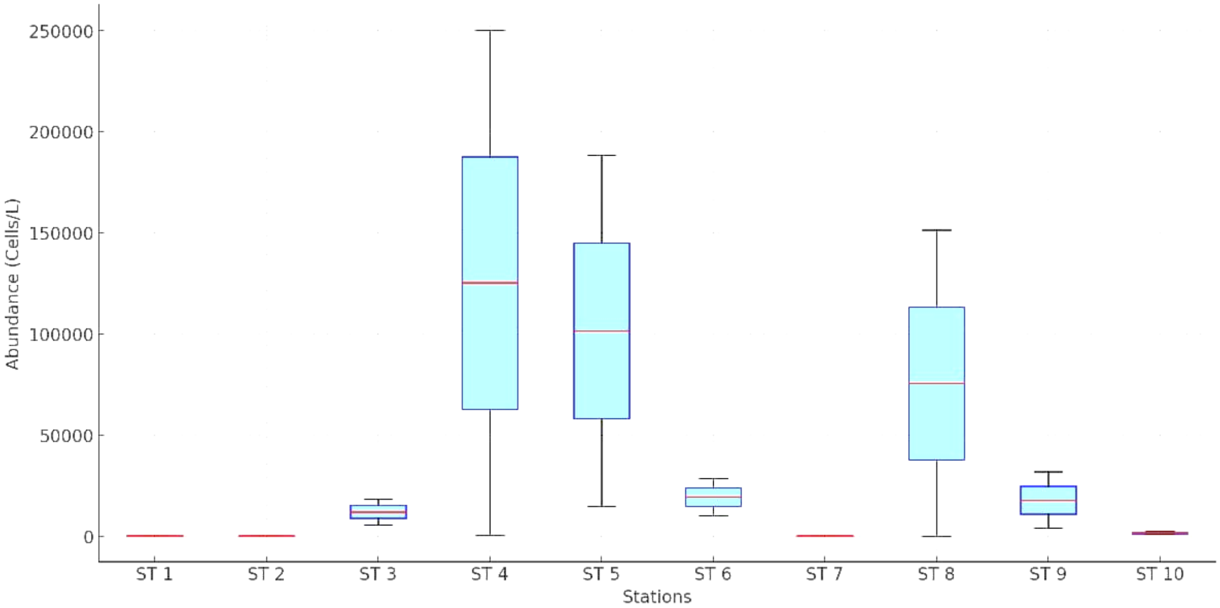

Fig. 2. Boxplot of *C. furca* and *N. longissima* abundance

The marked differences between these two species reflect contrasting ecological strategies. As a dinoflagellate, *C. furca* is considered opportunistic, capable of rapid responses to changing environmental conditions and thus prone to sudden increases in abundance under favorable circumstances. In contrast, *N. longissima* follows a more conservative growth strategy, resulting in relatively stable populations even under variable conditions. Such disparities are common within phytoplankton communities, where spatial heterogeneity, driven by factors such as nutrient availability, water column stability, or light penetration can produce highly divergent abundance patterns among co-occurring species **(Anderson *et al.*, 2012)**.

Water environment factor

As presented in Table (2), key water quality parameters such as nitrate, phosphate, ammonia, chlorophyll-a, temperature, and salinity play a crucial role in regulating the abundance of specific phytoplankton species, including *Ceratium furca* and *Nitzschia longissima*. These environmental factors influence species distribution, growth rates, and overall ecosystem dynamics by determining nutrient availability and primary productivity. Understanding the interactions between these parameters and phytoplankton abundance is essential for assessing potential harmful algal bloom (HAB) risks and implementing effective ecosystem management strategies.

Table 2. Water quality parameters

Water Quality Parameter	**ST 1**	**ST 2**	**ST 3**	**ST 4**	**ST 5**	**ST 6**	**ST 7**	**ST 8**	**ST 9**	**ST 10**
Nitrate (mg/l)	0.431	0.275	0.198	0.327	0.251	0.227	0.166	0.242	0.184	0.195
Phosphate (mg/l)	0.445	0.621	0.272	0.55	0.322	0.276	0.352	0.652	0.314	0.304
Ammonia (mg/l)	0.497	0.646	0.482	0.518	0.646	0.626	0.472	0.537	0.762	0.726
Chlorophyll-a (mg/l)	2.967	0.593	4.153	5.933	2.967	4.747	4,153	356	4.153	6.527
Clarity (m)	1.75	0.75	0.8	2.4	09	1.75	1.45	0.9	1.5	1.75
Temperature (^{o}C)	31	31.7	31.6	31.3	31.5	31	31.4	31.9	31.5	31.3
pH	7.48	7.3	8.19	8.25	8.1	8.22	8.22	8.23	8.23	8.21
DO (mg/l)	7.95	6.8	7.87	8.46	7.35	8.35	8.68	8.41	8.6	8.18
Salinity (ppt)	29	28.6	29	29	28.9	28.8	28.8	28.6	28.8	29.1

As detailed in Table (2), nitrate concentrations in Bima Bay ranged from 0.166 to 0.431 mg/L, falling within the optimal range for phytoplankton proliferation (0.01–1 mg/L), as defined by **Agustiadi *et al.* (2013)**. As a key nitrogen source, nitrate plays a fundamental role in protein synthesis and nucleic acid formation, thereby facilitating phytoplankton growth. The elevated nitrate concentrations observed in Bima Bay may provide favorable conditions for the proliferation of *Ceratium furca*, a dinoflagellate commonly associated with nutrient-enriched coastal waters and frequently reported during bloom events. Previous studies support this linkage, where the growth and vertical migration of *C. furca* in Sagami Bay, Japan, were closely related to nutrient availability **(Baek *et al*., 2011)**, and periods of elevated nitrate in tropical estuaries along the west coast of India coincided with increased abundances of dinoflagellates, including *C. furca* **(Pednekar *et al*., 2012)**.

Phosphate concentrations varied between 0.272 and 0.652mg/ L, underscoring its critical role in cellular energy metabolism through adenosine triphosphate (ATP) production, which significantly influences phytoplankton biomass in tropical marine ecosystems **(Mishbach *et al*., 2021)**. Phosphate enrichment in Bima Bay originates from both natural (rock weathering, fluvial input) and anthropogenic sources, including agricultural runoff (fertilizer leaching), aquaculture effluents, industrial discharges, and domestic wastewater **(Purba & Pranowo, 2015)**. The recorded phosphate levels in Bima Bay substantially exceeded the phytoplankton growth threshold of < 0.015mg/ L **(Sholihin *et al*., 2014)**, potentially fueling episodic algal blooms, particularly of *Ceratium furca* and *Nitzschia longissima*.

Ammonia concentrations ranged from 0.472 to 0.762mg/ L, further enhancing phytoplankton growth, particularly in regions subjected to high organic matter input from anthropogenic activities. This pattern is consistent with observations in Pago Pago Harbor, American Samoa, where excessive agricultural runoff contributed to *Ceratium furca* bloom events **(Morton *et al*., 2011)**.

From a physicochemical perspective, water temperature ranged from 31 to 31.5°C, aligning with the optimal thermal range for tropical phytoplankton metabolism and reproduction. Water column clarity varied between 0.8 and 2.4m, conditions that favor the proliferation of dinoflagellates such as *Ceratium furca*, which are well-adapted to low-light environments **(Armiani & Harisanti, 2021)**. Salinity levels remained relatively stable, ranging from 28 to 29.1ppt, while pH values were measured between 7.48 and 8.25, indicating a neutral to slightly alkaline environment, suitable for the growth of both *C. furca* and *N. longissima*.

Dissolved oxygen (DO) concentrations ranged from 6.8 to 8.68mg/ L, supporting active phytoplankton photosynthesis and metabolic processes. However, excessive phytoplankton proliferation, particularly during bloom events, can induce localized oxygen depletion due to increased microbial respiration and organic matter decomposition, potentially leading to hypoxic conditions **(Irawan *et al*., 2015)**.

Chlorophyll-a concentrations exhibited spatial variability across sampling stations, with the highest levels recorded at Station 10 (6.527mg/ L) and the lowest at Station 2 (0.592mg/ L). This variation reflects heterogeneity in primary productivity across the bay, driven by localized differences in nutrient fluxes, hydrodynamic processes, and phytoplankton community structure. The observed environmental conditions indicate that Bima Bay is characterized by nutrient enrichment conducive to phytoplankton proliferation, necessitating continuous monitoring to assess potential ecological shifts and mitigate the risk of recurrent HABs.

The autoecological characteristics of *Ceratium furca* and *Nitzschia longissima* in Bima Bay waters

The autoecological characteristics of *Ceratium furca* and *Nitzschia longissima* in Bima Bay reveal distinct environmental preferences, as evidenced by the canonical correspondence analysis (CCA). *Ceratium furca* is a dinoflagellate characterized by its brownish-yellow pigmentation and unique morphological features, including a sulcus and epitheca, which enable adaptation to diverse environmental conditions **(Kraberg *et al*., 2010; Baek *et al*., 2011)**. This species possesses an elongated, horn-like structure with a segmented cellulose theca, providing structural protection. The species is distinguished by two unequal posterior (hypothecal) horns, with the right horn being shorter than the left, which aids in buoyancy and stabilizes its position within the water column **(A'IN *et al*., 2017)**. Additionally, a thin connecting strand can be observed between the two horns. *C. furca* exhibits a mixotrophic lifestyle and has the capacity for rapid population expansion under favorable conditions, contributing to HAB formation **(A'IN *et al*., 2017; Karlson *et al*., 2021)**. This species is frequently associated with HAB events that deplete dissolved oxygen levels, cause mass mortality of marine organisms, and produce harmful toxins affecting both marine life and humans.

Nitzschia longissima, a diatom commonly found in eutrophic waters, exhibits high growth rates in environments with abundant nitrogen and phosphorus supply **(Hasani *et al*., 2022)**. This pennate diatom has an elongated, needle-like shape with a silica-based frustule that exhibits bilateral symmetry. The presence of a raphe structure on one side of the frustule enables *N. longissima* to move along substrates such as sediment surfaces. Adapted to high-nutrient conditions, particularly in eutrophic waters, *N. longissima* thrives in environments enriched with phosphorus, often originating from anthropogenic sources such as agricultural runoff, aquaculture effluents, and domestic wastewater **(Sarthou *et al*., 2005; Wang *et al*., 2020)**. Despite their different ecological niches, both species have the potential to contribute to HAB events, albeit with distinct responses to environmental factors.

Based on our CCA analysis, *Ceratium furca* abundance was strongly associated with nitrate concentration, particularly at Stasion 4, where the highest density was recorded (250.226 x 10^3 cells/L). At this station, nitrate (0.327mg/ L), chlorophyll-a (5.933mg/ L), and temperature (31.3°C) elevated, providing favorable conditions for *C. furca* proliferation. This supports previous findings that *C. furca* exhibits optimal metabolic and reproductive activity in nitrogen-enriched tropical waters **(Morton *et al*., 2011)**. Interestingly, although nitrate reached its maximum value at Station 1 (0.431 mg/L) and ammonia at Station 9 (0.762 mg/L), the peak abundance of *C. furca*was was not observed at these stations. This suggests that the combination of nitrate availability, warmer temperature, and higher chlorophyll-a levels at Station 4 played a more important role than absolute nutrient concentrations in supporting its growth **(Paerl *et al*., 2016)**. This indicates that this species adapts well in nitrogen enriched environments. This finding is consistent with previous studies reporting that *C. furca* exhibits optimal metabolic and reproductive activity under high nutrient and warm tropical conditions **(Morton *et al*., 2011)**.

In contrast, *Nitzschia longissima* exhibited a strong association with phosphate concentrations, with the highest abundance observed at Station 5 (14,837 × 10^3 cells/L), where phosphate levels peaked (0.322mg/ L). This pattern indicates that *N.*

longissima efficiently utilizes phosphorus inputs, likely derived from aquaculture activities and organic waste, to sustain its growth. Such a relationship between diatoms and phosphorus enrichment has been widely reported, as phosphorus plays a central role in diatom energy production and physiological functions **(Lepš & Šmilauer, 2003; Sarthou *et al*., 2005)**.

These nutrient preferences align with the ecological traits of each phytoplankton group. Dinoflagellates, such as *C. furca*, primarily rely on nitrogen compounds for metabolic processes and protein synthesis, whereas diatoms, such as *N. longissima*, utilize phosphorus for energy production and physiological functions **(Sarthou *et al*., 2005)**.

The response of *C. furca* and *N. longissima* to environmental factors and nutrient availability as potential HAB-forming species in Bima Bay was elucidated through CCA (Fig. 3). The analysis accounted for 100% of the variance along a single axis, with an eigenvalue of 0.098. The results indicated that *C. furca* was predominantly associated with Stations 1, 4, and 8, responding to eight environmental parameters: nitrate, phosphate, chlorophyll-a, water transparency, temperature, pH, dissolved oxygen (DO), and salinity. In contrast, *N. longissima* exhibited a strong association primarily with ammonia levels. These findings are consistent with in-situ abundance data, which showed the highest concentration of *C. furca* at Station 4, whereas *N. longissima* reached its peak abundance at Station 5.

The distinct ecological preferences of *C. furca* and *N. longissima* highlight their differential responses to nutrient availability and environmental conditions, reinforcing their roles as key contributors to HAB events in Bima Bay. Continuous monitoring and nutrient regulation strategies are imperative to mitigate potential ecological disruptions caused by phytoplankton blooms in tropical coastal ecosystems.

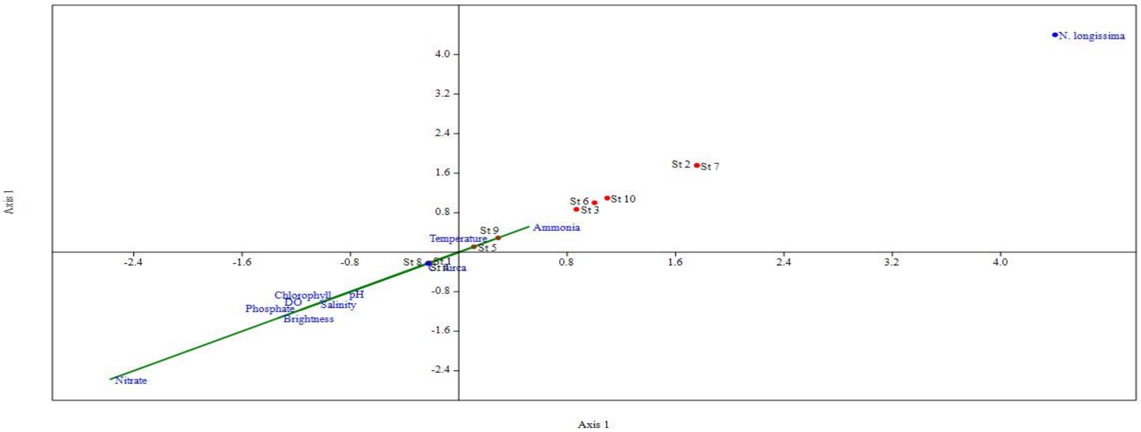

Fig. 3. CCA biplot analysis of *Ceratium furca* and *Nitzschia longissima* in relation to environmental factors in Bima Bay, West Nusa Tenggara

Relationship between nutrients and the abundance of *Ceratium furca* and *Nitzschia longissima*

Polynomial regression analysis revealed significant correlations between the abundance of *Ceratium furca* and *Nitzschia longissima* and key environmental parameters, including nitrate, phosphate, chlorophyll-a, and ammonia. Fig. (4) presents the polynomial regression analysis between *C. furca* abundance and the concentrations of nitrate, ammonia, phosphate, and chlorophyll-a in Bima Bay. A strong positive correlation was observed between *C. furca* abundance and nitrate concentration ($R^2 = 0.78$, $P < 0.05$), indicating that nitrate plays a crucial role in supporting the growth of this species. However, this relationship follows a saturation curve, where *C. furca* abundance increases with rising nitrate levels up to a certain threshold, after which further increases in nitrate concentration lead to a decline, likely due to physiological limitations or competitive interactions.

Similarly, *C. furca* abundance exhibited a significant but weaker correlation with ammonia concentration ($R^2 = 0.63$, $P < 0.05$), suggesting that while ammonia serves as an alternative nitrogen source, its contribution to *C. furca* proliferation is less pronounced compared to nitrate. Conversely, phosphate concentration demonstrated a weaker and statistically insignificant relationship with *C. furca* abundance ($R^2 = 0.42$, $P = 0.07$), reinforcing the dominance of nitrogen-based nutrients in regulating the population dynamics of this dinoflagellate in eutrophic waters.

The relationship between *C. furca* abundance and chlorophyll-a concentration ($R^2 = 0.71$, $P < 0.05$) further highlights the link between primary productivity and the proliferation of this species. High chlorophyll-a levels indicate increased phytoplankton biomass, which is consistent with the high abundance of *C. furca* in nutrient-enriched waters. These findings suggest that *C. furca* thrives in environments characterized by high nitrogen availability and elevated primary productivity, reinforcing its potential role in harmful algal bloom (HAB) formation in Bima Bay.

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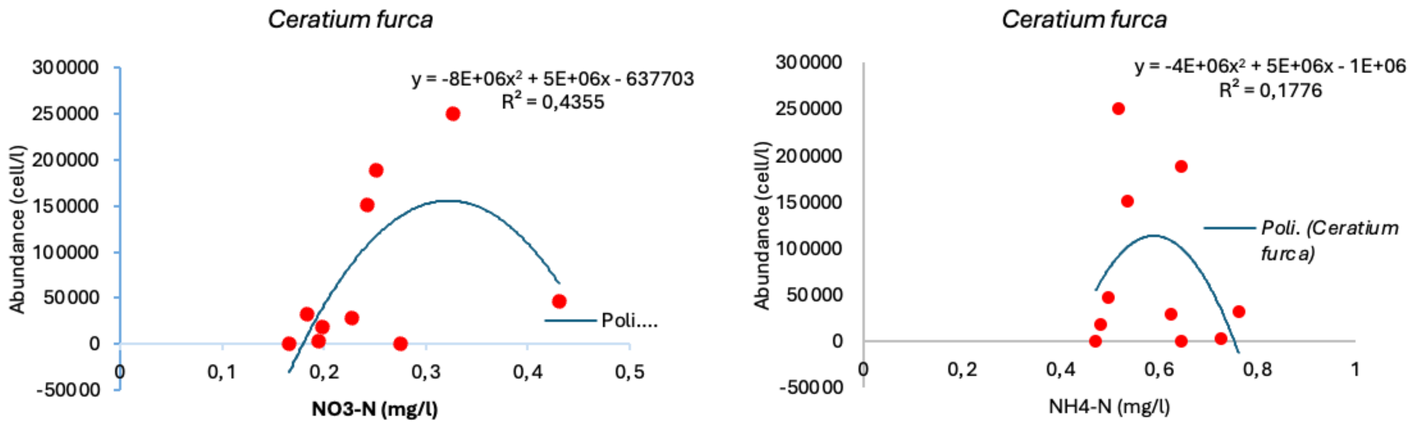
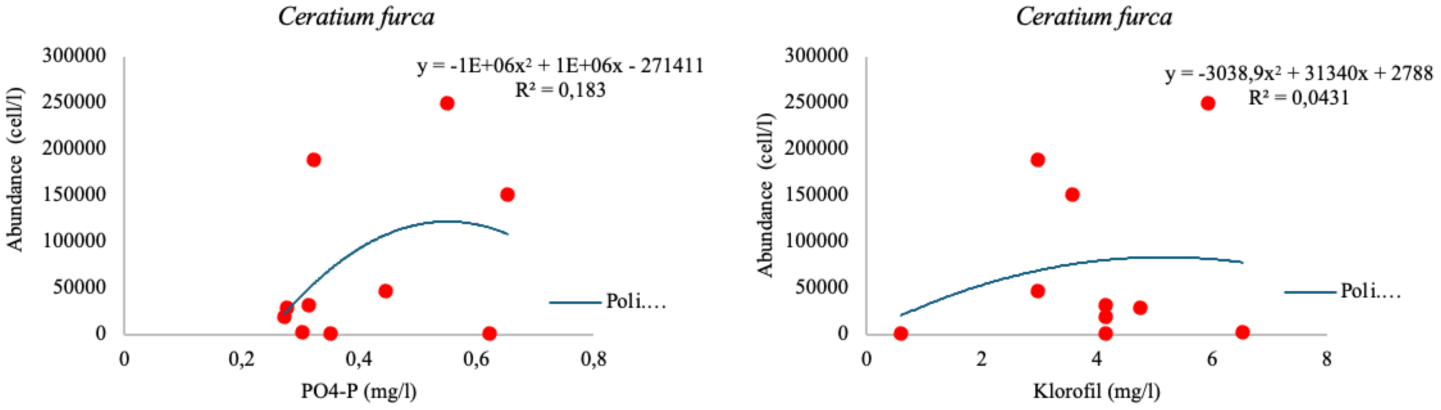


Nitrate

Ammonia



Phosphate

Chlorophyll

Fig. 4. Polynomial regression analysis between *Ceratium furca* abundance and key environmental parameters in Bima Bay, West Nusa Tenggara

Fig. (5) presents the polynomial regression analysis examining the relationship between *Nitzschia longissim*a abundance and key environmental parameters in Bima Bay. The results indicate that phosphate availability plays a pivotal role in regulating the population dynamics of this diatom, with secondary influences from ammonia and primary productivity indicators.

A strong positive correlation was observed between *N. longissima* abundance and phosphate concentration (R^2= 0.69, $P < 0.05$), highlighting phosphorus as the primary limiting nutrient for this species. The polynomial regression model suggests a non-linear response, where increasing phosphate concentrations promote *N. longissima* proliferation up to a certain threshold, beyond which growth may plateau due to resource saturation or competitive interactions. This finding is consistent with previous studies indicating that phosphorus availability is a key driver of diatom bloom formation, particularly in eutrophic marine environments.

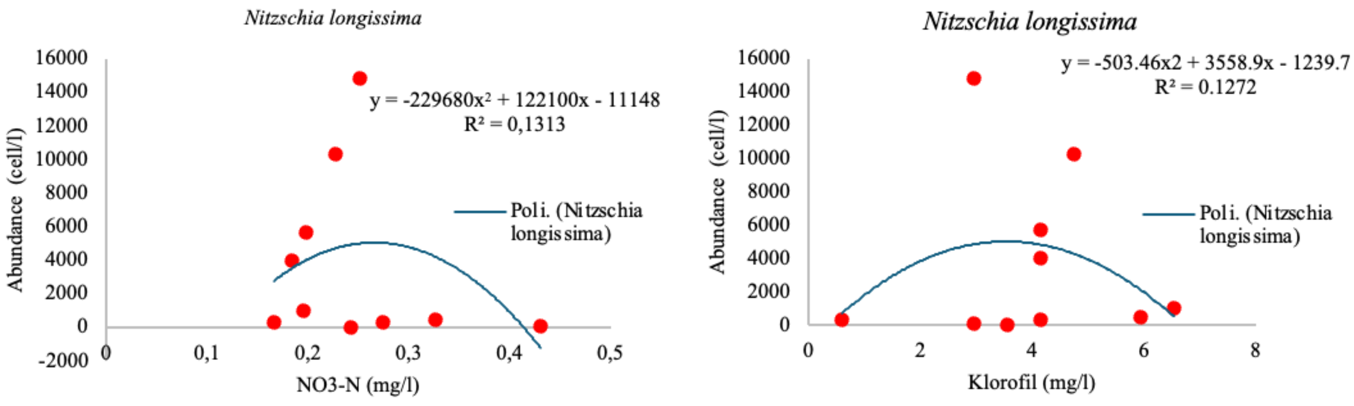
A significant relationship was also detected between *N. longissima* abundance and ammonia concentration ($R^2 = 0.61$, $P < 0.05$), suggesting that ammonia serves as an additional nitrogen source facilitating growth. The regression model indicates that *N. longissima* abundance increases in areas characterized by elevated ammonia levels, particularly near aquaculture sites where organic nitrogen inputs are high. This aligns with findings in other eutrophic coastal systems, where diatoms have been shown to efficiently assimilate ammonia as a readily available nitrogen source, particularly under conditions of high phosphorus availability.

The relationship between *N. longissima* abundance and nitrate concentration was weaker and not statistically significant ($R^2 = 0.47$, $P = 0.06$), suggesting that nitrate is not a primary determinant of *N. longissima* growth. This result contrasts with the nitrogen-driven proliferation observed in *Ceratium furca*, indicating a fundamental difference in nutrient assimilation strategies between these two phytoplankton species. The reduced dependence on nitrate reinforces the ecological adaptation of *N. longissima* to phosphorus-enriched environments, where it may outcompete other species under conditions of high phosphate availability.

A significant correlation was found between *N. longissima* abundance and chlorophyll-a concentration ($R^2 = 0.66$, $P < 0.05$), indicating a close association between its population dynamics and overall primary productivity. The polynomial trend suggests that *N. longissima* proliferation contributes to phytoplankton biomass accumulation, particularly in regions where phosphorus enrichment sustains high levels of chlorophyll-a. This finding reinforces the role of phosphorus in promoting diatom-dominated phytoplankton assemblages in nutrient-rich coastal waters.

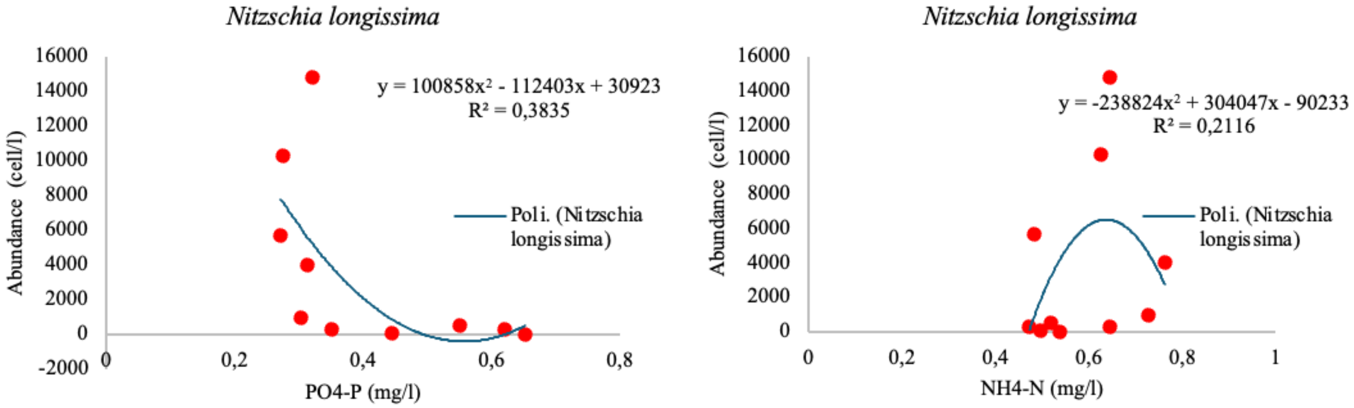
The polynomial regression analysis underscores the differential nutrient preferences of *N. longissima* and *C. furca*, revealing contrasting ecological strategies in response to nutrient availability. While *C. furca* exhibits a nitrogen-dependent growth pattern, *N. longissima* is primarily regulated by phosphate concentrations, with ammonia serving as a secondary nitrogen source. These findings highlight the fundamental role of phosphorus in structuring diatom communities in eutrophic tropical waters and emphasize the need for targeted nutrient management strategies to mitigate the risk of bloom formation.

Understanding species-specific nutrient dynamics is crucial for predicting phytoplankton succession patterns and assessing the potential impacts of anthropogenic nutrient loading on coastal ecosystems. Given the significant role of aquaculture and terrestrial runoff in contributing to phosphorus and ammonia inputs, continuous monitoring of nutrient fluxes and their effects on phytoplankton community composition is essential to safeguard ecosystem stability in Bima Bay.



Nitrate

Chlorophyll



Phosphate

Ammonia

Fig. 5. Polynomial regression analysis between *Nitzschia longissimi* abundance and key environmental parameters in Bima Bay, West Nusa Tenggara

DISCUSSION

Nutrient dynamics and phytoplankton abundance post-sea snot

The results indicate that nitrate and phosphate concentrations in Bima Bay are within the range that supports phytoplankton growth. Nitrate concentrations ranged from 0.166 to 0.431mg/ L, while phosphate levels were between 0.272 and 0.652mg/ L. These values exceed the coastal eutrophication threshold of < 0.015mg/ L for phosphate **(Sholihin *et al.*, 2014)**, highlighting that nutrient enrichment in Bima Bay may significantly contribute to the risk of harmful algal blooms.

Such nutrient enrichment has direct ecological implicatons. The high nitrate availability in Bima Bay suggests elevated water fertility, supporting increased phytoplankton biomass. Elevated phosphate levels also contribute to cellular energy production via ATP; However, excessive concentrations beyond phytoplankton requirements may trigger population explosions and algal blooms **(Sholihin *et al.*, 2014).**

This nutrient driven dynamic is further reflected in the distribution of specific phytoplankton taxa. The dominance of *Ceratium furca* at Station 4 indicates that elevated nitrate concentrations in Bima Bay strongly support dinoflagellate proliferation. This pattern is consistent with the metabolic strategy of dinoflagellates, which primarily depend on nitrogen availability **(Azis *et al.*, 2020)**. Conversely, the prevalence of *Nitzschia longissima* at Station 5 reflects its greater reliance on phosphate, as diatoms are known to utilize phosphorus more intensively for their physiological processes **(Sarthou *et al.*, 2005)**. The contrasting responses of these taxa to different nutrient inputs suggest that shifts in nutrient dynamics can directly influence phytoplankton community structure, thereby altering ecosystem stability and the potential risk of harmful algal blooms in Bima Bay.

Ecological implications of post-sea snot conditions in Bima Bay

The dominance of *Ceratium furca* and *Nitzschia longissima* observed in Bima Bay provides an illustration of how post-sea snot conditions may reshape ecological dynamics in the region. The dependence of *C. furca* on nitrate and *N. longissima* on phosphate indicates that nutrient enrichment derived from anthropogenic activities may favor certain taxa, potentially reducing phytoplankton diversity **(Sarthou *et al.*, 2005; Azis *et al.*, 2020)**. Such shifts in community composition can decrease ecosystem resilience and increase vulnerability to harmful algal blooms **(Sholihin *et al.*, 2014)**.

In Bima Bay, where small pelagic fisheries are an important source of livelihood, changes in phytoplankton structure have broader ecological consequences. Dominance by one or two species may disrupt zooplankton populations, thereby affecting prey availability for higher trophic-level organisms such as carnivorous fish **(Paerl *et al.*,**

2018). This scenario suggests that nutrient-driven phytoplankton proliferation is not only an environmental issue but also a socio-economic risk for coastal communities dependent on fisheries **(Diaz & Rosenberg, 2008).**

Thus, the ecological implications of post-sea snot conditions in Bima Bay should be considered in the context of both ecosystem stability and local resource sustainability. Without proper management of nutrient sources, Bima Bay may experience recurrent phytoplankton blooms that reduce biodiversity, lower fishery productivity, and threaten the long-term sustainability of coastal resources **(Irawan *et al*., 2021; Aktan *et al*., 2022; Lan *et al*., 2024)**.

Interconnection between sea snot, eutrophication, and HABs: Key drivers of sea snot formation

Eutrophication results from excessive nutrient inputs (nitrate and phosphate) from anthropogenic activities, accelerating phytoplankton growth, including species such as *Ceratium furca* and *Nitzschia longissima*, which produce extracellular polysaccharides (EPS). These EPS secretions contribute to the formation of organic mucus on the water surface, a primary factor in sea snot development **(Aktan, 2008; Karadurmuş & Sari, 2022)**. In Bima Bay, the first sea snot phenomenon was observed in April 2022, followed by another occurrence in February 2023. However, this study was conducted after these events, focusing specifically on post-sea snot conditions to assess their ecological implications.

Beyond sea snot formation, eutrophication also creates favorable conditions for harmful algal blooms (HABs). The sea snot layer at the water surface reduces light penetration and oxygen diffusion into deeper layers, promoting hypoxic conditions. Low-oxygen, nutrient-rich environments enable certain harmful phytoplankton species to thrive, exacerbating the ecological impact of HABs **(Kumar *et al*., 2023)**. Without intervention, this cycle will persist, where eutrophication continuously triggers sea snot and HABs. This could result in prolonged ecosystem degradation and economic losses, particularly in coastal areas reliant on fisheries and tourism **(Lan *et al*., 2024)**. Therefore, understanding the causal relationship between these phenomena is critical for designing effective mitigation strategies.

Initial community observations linked the sea snot occurrence in Bima Bay to an oil spill. However, scientific analysis and sea snot characteristics indicate that this phenomenon is more closely associated with eutrophication due to increased nutrient loads from anthropogenic activities such as deforestation, domestic waste discharge, and aquaculture **(Hasani *et al*., 2022)**. No direct evidence was found linking oil spills to sea snot formation in this region. Similar studies in the Marmara Sea also concluded that sea snot formation was primarily driven by excessive nutrient enrichment and favorable environmental conditions **(Aktan, 2008; Ergul *et al*., 2021; Karadurmuş & Sari, 2022)**.

The conversion of forested areas into maize agricultural land surrounding Bima Bay is suspected to play a significant role in increasing nutrient loads in coastal waters. Deforestation reduces soil water retention capacity, leading to surface runoff carrying sediment and nutrients, such as nitrogen and phosphorus, directly into coastal waters **(Satriawan *et al*., 2023)**. This process accelerates eutrophication, serving as the primary driver of sea snot formation in the region.

Key factors contributing to sea snot formation in Bima Bay

a. Increased Nutrient Load: Domestic waste discharge and aquaculture activities elevate nitrate and phosphate concentrations in coastal waters **(Sholihin *et al*., 2014)**.

b. Warm Water Temperatures: High temperatures accelerate phytoplankton metabolism and enhance extracellular polysaccharide secretion **(Al-Hashmi *et al*., 2014)**.

c. Potential Water Column Stratification: Although this study did not measure vertical profiles of temperature and salinity, previous studies have shown that limited vertical mixing in coastal waters can create stable surface layers that facilitate phytoplankton accumulation and bloom formation **(Paerl *et al.*, 2019)**. Such mechanisms may also operate in Bima Bay under calm hydrodynamic conditions, further supporting sea snot formation.

This study primarily focused on the physicochemical parameters of surface waters. Further research is necessary to explore the role of ocean currents and microbial communities in sustaining HAB-forming species in Bima Bay **(Huang *et al*., 2020)**. Additionally, a long-term monitoring approach integrating hydrodynamic modeling and molecular analysis would provide a more comprehensive understanding of sea snot and HAB dynamics in tropical coastal ecosystems.

CONCLUSION

This study reveals distinct ecological preferences between *Ceratium furca* and *Nitzschia longissima* in Bima Bay. The abundance of *C. furca* is significantly influenced by nitrate concentration, whereas *N. longissima* thrives in high-phosphate environments. Although nitrate and phosphate concentrations exceed eutrophication thresholds, other environmental factors (such as light intensity, temperature, and hydrodynamics) also affect phytoplankton dynamics. These findings emphasize the importance of routine monitoring and nutrient source regulation from anthropogenic activities such as agriculture and domestic waste to prevent recurrent HABs. Effective ecosystem management strategies are essential to maintaining the ecological integrity of Bima Bay and mitigating the long-term impacts of sea snot phenomena.

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