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Modeling Thermal Plume Dispersion and Its Relationship with Plankton Community Structure in Lombok Coastal Waters

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Abstract

Coastal power plants discharge high-temperature cooling water that forms thermal plumes, potentially imposing thermal stress on marine ecosystems and altering sensitive biological indicators such as plankton. This study aimed to analyze the spatial dispersion of thermal plumes and examine their relationship with plankton community structure in the coastal waters of Lombok. Secondary environmental monitoring data collected in May 2025 were integrated with two-dimensional numerical modeling using MIKE 21 to simulate hydrodynamic circulation and thermal transport. Plankton community structure was evaluated using the Shannon–Wiener diversity, evenness, and Simpson dominance indices, while relationships between environmental variables and plankton metrics were assessed using Spearman rank correlation and correspondence analysis. The simulations indicated that tidal currents, surface winds, and hydrodynamic circulation primarily controlled the spatial distribution of the thermal plume. Under different tidal conditions, the 30.0–30.5 °C temperature class dominated the affected area, covering approximately 62.21–66.06 Km^2, whereas higher temperature zones remained localized near the discharge outlet. Plankton communities exhibited moderate diversity (H' = 1.93–2.21), high evenness (0.86–0.96), and low dominance (0.12–0.17). Water temperature showed no significant relationship with plankton diversity but was strongly correlated with evenness. These findings suggest that plankton community structure was influenced by the combined effects of temperature, nutrient availability, and local hydrodynamic conditions rather than temperature alone. This study provides insight into the ecological response of plankton communities to thermal plume dispersion and supports environmentally sustainable management of coastal power plant cooling-water discharges.

Keywords: coastal waters, heat dispersion, hydrodynamics, plankton community structure, power plant.

1. Introduction

Coastal power plants play an important role in supporting regional electricity demand. Nevertheless, the operation of once-through cooling systems releases heated wastewater into surrounding marine waters, creating environmental concerns related to thermal pollution. This thermal plume effluent is a consequence of the Rankine cycle, in which latent heat from steam must be released to the environment after passing through the turbine so that it can condense back into water (Ashfania et al., 2021). This process generates a thermal plume, namely the distribution of warm water masses in the sea driven by buoyancy resulting from density differences, while mixing with ambient water through turbulent treatment processes (Cushman-Roisin, 2022). Its dispersion dynamics are strongly influenced by local oceanographic conditions such as currents, tides, and wind (Ashfania et al., 2021).

The regulation of heated wastewater discharge in Indonesia is still governed by several regulations with different approaches. Decree of the Minister of Environment No. 51 of 2004 sets the maximum allowable increase in water temperature at 2 °C above natural conditions, while Regulation of the Minister of Environment No. 8 of 2009 sets the effluent temperature limit at up to 40 °C without specific details for the receiving water body (Ministry of Environment, 2004; 2009). Government Regulation No. 22 of 2021 also does not yet establish technical criteria related to spatial dispersion in marine waters. The studies of national environmental law (Rustandi and Pandapotan, 2018) have strongly highlighted the necessity to formulate specific policy frameworks to bridge the regulatory gap on marine thermal effluents. At the international level, the World Bank/IFC EHS Guidelines (World Bank Group, 2007) recommend a maximum increase in temperature of 3 °C outside the mixing zone, which is consistent with Canadian guidelines requiring thermal plume modeling (Environment and Climate Change Canada, 2019). Therefore, the delta temperature (ΔT) approach is considered more relevant for assessing ecosystem responses.

Scientific studies have further demonstrated that elevated temperature can directly influence phytoplankton growth and physiological performance, although the magnitude and direction of the response vary among taxa. Laboratory experiments have shown that temperature affects growth and photosynthetic processes differently among marine microalgae, reflecting species-specific thermal tolerances and optima (Claquin et al., 2008). Experimental studies on marine diatoms have likewise demonstrated contrasting responses to elevated temperature, with some species showing reduced growth while others maintained or increased their growth rates (Hyun et al., 2014). Field observations in coastal waters receiving thermal effluent have also shown that thermal discharge can alter phytoplankton size structure and photosynthetic physiology near power-plant outfalls (Hu et al., 2023). Recent field observations in Daya Bay further indicated that the effects of thermal discharge can vary with season and water-column conditions, with elevated temperature suppressing phytoplankton growth under some conditions but enhancing growth at greater depths under others (Xu et al., 2021). These findings indicate that the ecological response to thermal discharge cannot be interpreted solely from temperature thresholds, but should also consider species-specific thermal sensitivity, nutrient availability, water-column structure, and local hydrodynamic conditions.

Studies on the thermal dispersion of cooling-water discharge in Indonesian coastal waters have been widely conducted. Extensive studies have been conducted on the thermal dispersion of cooling-water discharge in Indonesian coastal waters. The spatial variability of the thermal plume dispersion in Benete Bay is from 50 m to 5 km depending on the tidal phases (Panalaran et al., 2012). Previous studies in Indonesian coastal waters have indicated that the dispersion of thermal effluent is strongly related to both discharge characteristics and the local oceanographic conditions. Research in Semarang Harbour (Subardjo et al., 2016) and Jeneponto (Hafid, 2015) highlighted the role of discharge flow and hydrodynamic processes on the plume behaviour. Other remote sensing approaches using Landsat-8 imagery (Utama et al., 2020) and numerical simulations using MIKE software (Wibowo and Asvaliantina, 2018) have also been widely used to evaluate and optimise the outfall location. Discharge temperatures in the Paiton steam power plant were reported to be 34–35 °C (Pintubatu et al., 2020), highlighting the importance of continuous environmental monitoring. In general, the distribution of thermal plumes is strongly affected by operational discharge, seasonal variability, and surrounding hydrodynamic conditions. However, most of the existing studies are mainly concentrated on the physical behaviour of thermal dispersion, and the ecological consequences are less explored. Where thermal effects decrease quickly after mixing, the high temperatures at outfall locations could still cause ecological pressure (Deabes, 2020; see multiple studies). Also changes in the composition of the planktonic community were noticed, particularly in the regions adjacent to the discharge points (Muthulakshmi et al., 2019).

As well as their physical impacts on coastal waters, thermal plumes can influence marine ecological processes, particularly plankton communities which constitute the base of aquatic food webs. The distribution and productivity of both phytoplankton and zooplankton are strongly related to environmental conditions and temperature is one of the main controlling factors for metabolism, growth and reproduction. Variations in water temperature can affect phytoplankton dynamics by influencing growth performance and competition among species (Paerl et al., 2011), but also affect stratification and biogeochemical processes in the water column (Boyd et al., 2019). Higher temperatures may also drive metabolic activity and change the dominance of some plankton taxa. Thermal discharge is also shown to affect size structure of phytoplankton and responses of photosynthesis especially in areas close to power plant outfalls (Hu et al., 2023).

Research on thermal discharge in Indonesian coastal waters has been conducted in several locations, including Paiton, East Java (Fikri et al., 2020; Pintubatu et al., 2020), Semarang Harbour (Subardjo et al., 2016), and Jeneponto (Hafid, 2015). These studies have mainly focused on the spatial distribution and hydrodynamic behaviour of heated effluent, while investigations combining hydrodynamic modelling with plankton community analysis remain relatively limited. This is particularly relevant in the coastal waters of Lombok, where thermal plume dispersion is influenced by tides, surface currents, and regional circulation, while plankton communities can respond to short-term environmental changes. Therefore, an integrated assessment of thermal plume dispersion and plankton community structure is important to improve understanding of the potential ecological implications of thermal discharge in coastal waters. This study addresses two main questions: (1) how does the thermal plume disperse under the prevailing hydrodynamic conditions in the coastal waters of Lombok? and (2) how is the spatial variation in thermal exposure associated with plankton community structure? We hypothesized that thermal plume dispersion varies with hydrodynamic conditions and that plankton community structure is associated with thermal exposure in combination with other environmental factors. Accordingly, the present study aims to analyse the spatial distribution of thermal plumes and assess their relationship with plankton community structure in the coastal waters of Lombok. The results are expected to improve understanding of the interaction between hydrodynamic processes and biological responses in coastal ecosystems and provide scientific support for more sustainable thermal discharge management.

2. Materials and Methods

2.1. Study Area and Data Collection

This study used a combination of secondary data analysis and two-dimensional numerical modelling in the coastal waters of Lombok, particularly around the cooling-water discharge outlet of a coastal power plant. Water quality and plankton community characteristics were evaluated using routine environmental monitoring data collected in May 2025 from four observation stations (TP1, TP2, TP3, and TP4) around the outfall area (**Figure 1**). The four stations represented the spatial gradient of potential thermal influence, with TP3 located closest to the outfall and representing the initial thermal mixing zone. Plankton samples and physicochemical parameters, including dissolved oxygen (DO), pH, BOD_5, total suspended solids (TSS), total ammonia, nitrate, and orthophosphate, were analyzed by an accredited external laboratory. Field sampling followed the Indonesian National Standard SNI 9064.3:2022. Because this study relied exclusively on secondary environmental monitoring data, detailed information on plankton sampling equipment, sample size, filter volume, and sampling orientation was unavailable. Bathymetric data were obtained from the National Bathymetry System (BATNAS) managed by the Geospatial Information Agency (BIG), while tidal, surface current, and wind data were obtained from Lembar Station and Marine Copernicus reanalysis products (CMEMS). Surface water temperature was measured on 1 May 2025, while regional sea surface temperature (SST) data from Marine Copernicus were used to characterize background thermal conditions. These SST data were not used for direct model validation because of their coarser spatial resolution and the absence of synchronous model outputs.

The numerical design represented a conservative worst-case discharge condition, with an outlet temperature of 36 °C and ambient seawater temperature of 30 °C (ΔT = 6 °C). Previous laboratory studies have shown species-specific responses of marine microalgae to elevated temperature (Claquin et al., 2008; Hyun et al., 2014), which provided ecological context for interpreting plankton responses. The model was simulated for 15 days (1–15 May 2025) to capture spring–neap tidal variability. As monitoring data were available only for May 2025, the results represent plume behaviour during this period and do not capture seasonal variability.

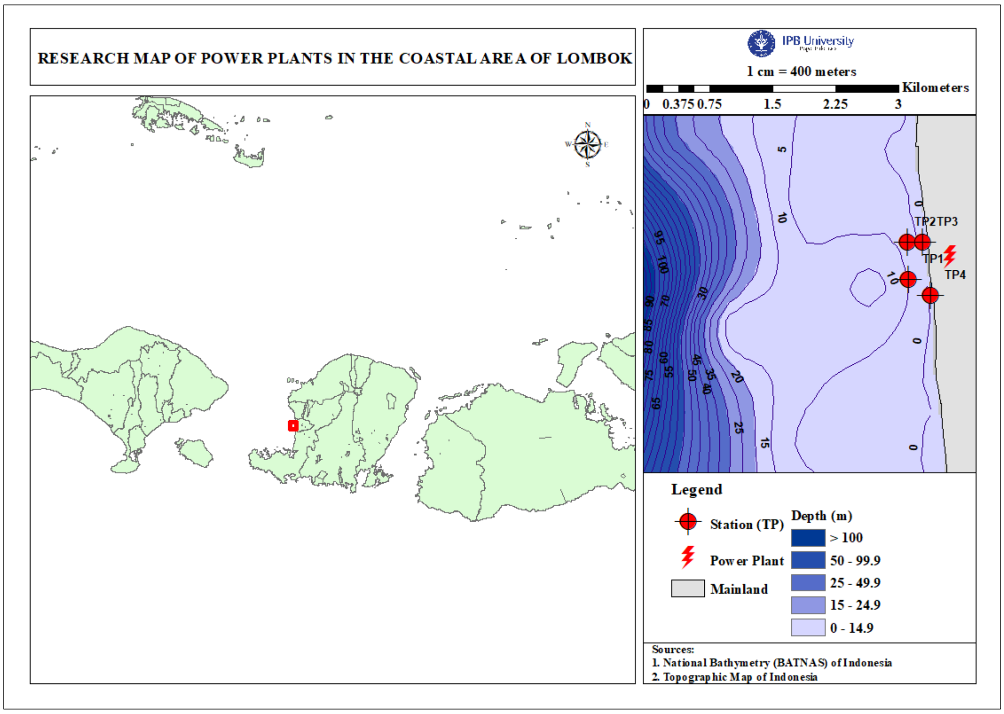

Figure 1. Geographical location of the study area and the distribution of environmental monitoring stations (TP1–TP4) in the coastal waters of Lombok during the May 2025 field survey. Station TP3 is positioned closest to the thermal outfall and represents the initial mixing zone affected by the power plant discharge, while the other stations capture spatial gradients away from the source.

2.2. Hydrodynamic and Thermal Dispersion Modeling

Hydrodynamic and thermal plume dispersion modeling was done by MIKE 21 software with two-dimensional (2D) approach applied to the sea surface layer (**Figure 2**). The simulation was run for 15 days (May 1–15, 2025) to capture present variability over a full spring–neap tidal cycle. The model scenario used the maximum operating conditions (worst case scenario) with input parameters (**Table 1**) of outlet discharge of 4.32 m 3 /s, outlet temperature of 36 °C and ambient seawater temperature of 30 °C. The basic equations of the model integrated continuity equation, momentum equations (for horizontal water mass movement dynamics) and the advection-diffusion heat equation to simulate the transport and dilution mechanisms of the discharged water. Surface current circulation was visualised using Ocean Data View (ODV) and wind characteristics were processed in Python to generate wind rose representation.

The spatial analysis was mainly based on the description of the horizontal dispersion pattern of the thermal plume, the dominant direction of movement and the extent of the affected area in relation to the neighbouring waters. Here, the modeled temperature distribution was considered as a representation of the plume dispersion behaviour rather than an accurate representation of actual field conditions of temperature. The temperature distribution was visualised in the form of surface temperature contour maps and analyzed with respect to the modeled surface-current patterns from the hydrodynamic (HD) model. This view is supported by previous studies confirming that the direction and extent of plume dispersion in coastal waters are mainly governed by the interaction between power-plant discharge flow, tides and local hydrodynamic conditions (Wang et al., 2022; Wang et al., 2025). Furthermore, this analysis also takes into account the variability in plume distribution and intensity, which can vary significantly due to dynamic interactions between currents and plant operational activities (Jiang et al., 2025).

Table 1. Summary of model input parameters, boundary conditions, and operational datasets used in the two-dimensional thermal plume dispersion simulation. The model is configured under a worst-case scenario with a maximum cooling-water discharge of 4.32 m³/s and outlet temperature of 36 °C against an ambient temperature of 30 °C, allowing assessment of maximum plume dispersion and dilution over a spring–neap tidal cycle.

Parameter	Data / Nilai	Sumber
Bathymetry	BATNAS	National Bathymetry Information System
Tides (Lembar Station)	15 days	Indonesian Geospatial Reference System, Meteorology Climatology and Geophysics Agency (BMKG)
Wind	30 days	*European Centre for Medium-Range Weather Forecasts* (ECMWF), Marine Copernicus
Surface currents	30 days	Copernicus Marine Environment Monitoring Service (CMEMS), Marine Copernicus
Outlet Discharge	4.32 m^3/s	Power plant operational data
Ambient seawater temperature	30°C	Field data
Outlet temperature	36°C	Worst-case scenario
Simulation time	15 days	1 – 15 May 2025

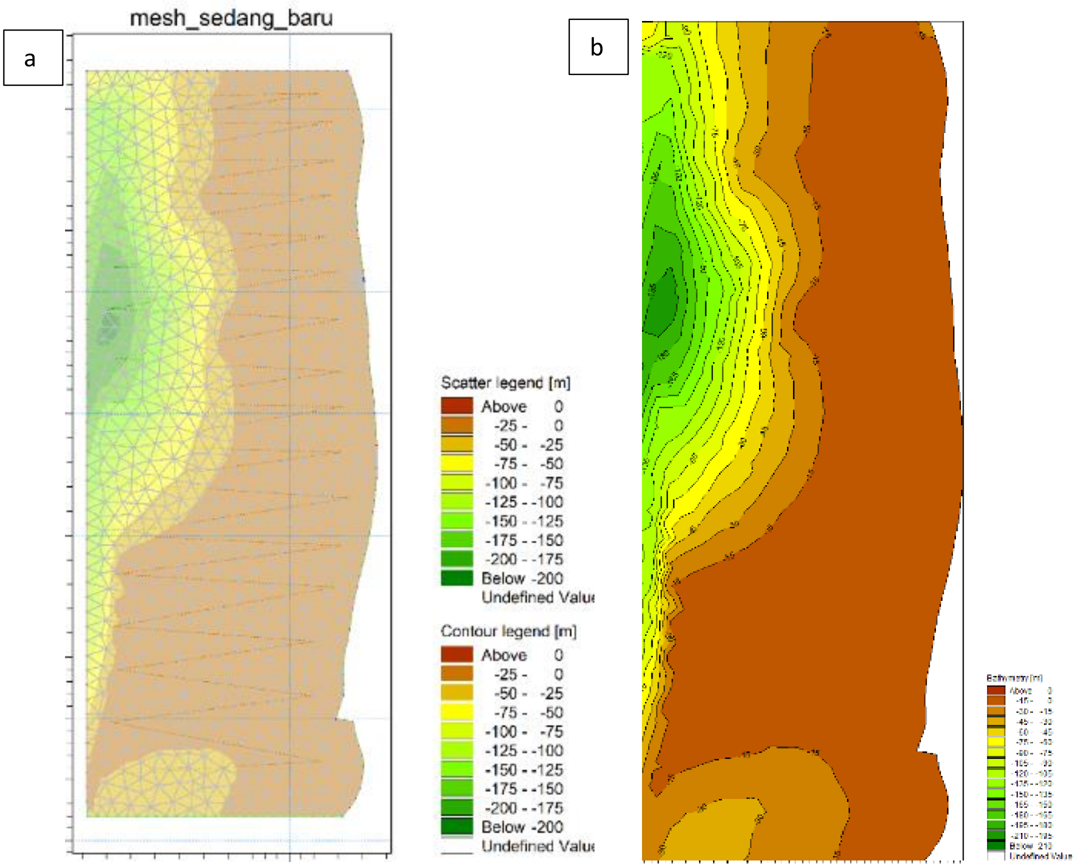

Figure 2. Unstructured flexible mesh grid (a) and interpolated bathymetry (b) used in the MIKE 21 two-dimensional hydrodynamic model for the Lombok coastal domain. The mesh is refined near the coastline and thermal outfall to better resolve near-field hydrodynamic processes, while the bathymetry shows gradual offshore deepening based on BATNAS data, which influences local water volume availability for plume dilution.

2.3. Fundamental Model Equations

Hydrodynamic and thermal plume dispersion modeling in this study was conducted using a two-dimensional (2D) horizontal approach to represent the surface-layer dynamics of the coastal waters. In general, the model formulation was based on the equations of mass conservation, momentum conservation, and temperature transport commonly used in physical oceanography (Stewart, 2008). Under the assumption of incompressible flow, the continuity equation can be written as follows:

$$\frac{\partial \eta}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{\partial (Hv)}{\partial y}=0 \tag{1}$$

where η is the sea surface elevation (m), h is the water depth (m), and u and v are the depth-averaged current velocity components in the x and y directions (m/s).

The horizontal momentum equations were derived from the equations of fluid motion by considering local acceleration, advection, pressure gradient, Earth's rotation, and external forcing. In 2D form, the equations are expressed as:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}+F_x \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}+F_y \tag{3}$$

Where f is the Coriolis parameter, g is gravitational acceleration (m/s^2), and F_x and F_y represent external forces such as bottom friction, wind stress, and horizontal turbulent mixing.

Thermal plume dispersion was simulated using the advection-diffusion equation for temperature, as surface temperature is controlled by advection, diffusion, and heat input. In 2D form, the temperature transport equation is given by:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=K_x\frac{\partial^2 T}{\partial x^2}+K_y\frac{\partial^2 T}{\partial y^2}+S \tag{4}$$

where T is the surface water temperature (°C), K_x and K_y are the horizontal turbulent diffusion coefficients (m^2/s), and S is the heat source representing the cooling-water discharge from the power plant (Talley et al., 2011). This set of equations was used to simulate the lateral transport and dilution of thermal effluent in the Lombok coastal waters.

2.4. Plankton Community and Statistical Analysis

Plankton community structure was evaluated using total plankton abundance, the Shannon–Wiener Diversity Index (H'), the Evenness Index (E), and the Simpson Dominance Index (D). Plankton abundance data were obtained from the accredited laboratory analytical report and expressed as total plankton abundance (ind. L^{-1}), representing the combined abundance of phytoplankton and zooplankton. Separate abundance data for phytoplankton (cells L^{-1}) and zooplankton (ind. L^{-1}) were not available because this study relied on secondary environmental monitoring data. Spatial and statistical relationships between physicochemical parameters (including modeled and observed temperature) and plankton community indices were analyzed using XLSTAT software. Due to the limited number of samples (n = 4), correlation was tested using Spearman rank correlation (ρ) at a significance level of α = 0.05. In addition, Correspondence Analysis (CA) was applied to map asymmetric relationships and associations between observation stations (rows) and plankton species composition (columns) in a two-dimensional factorial space. Visual representation in the form of a symmetric plot was used to interpret similarities in species composition among stations based on the proximity of their coordinate positions in the main dimensions (Bengen and Boer, 2023). Increased water temperature due to thermal plumes modifies local biogeochemical dynamics and consistently triggers persistent changes in plankton community structure, particularly through shifts in dominance between taxa that are tolerant and sensitive to thermal stress (Kibria, 2024; Beng et al., 2025; Lin et al., 2025). In addition to affecting plankton, this warming may also influence the broader structure of aquatic organism communities, especially among groups with low temperature tolerance (Leng et al., 2024).

3. Results and Discussion

3.1. Oceanographic Conditions

Based on the results of sea surface elevation observations over 15 days, the waters at the study site experienced two high tides and two low tides within a single day, with different heights and periods. These characteristics show that the study area is dominated by a mixed tide with a semi-diurnal pattern, where there are two high tides and two low tides every day with different heights. The tidal period is the time taken for the sea level to complete one cycle and is closely related to the dominant tidal type (Fadilah, 2021). The harmonic analysis resulted in a Formzahl of 0.327 and a tidal range of up to 2.28 m (**Figure 3**). The tidal movement is one of the main mechanisms controlling water circulation in coastal environments (Triatmodjo, 2014). Variation in the dilution capacity of thermal effluent is also affected by the tidal range. The volume of water at high tide is higher and this promotes mixing and dilution. At low tide, water volume is less and this can increase the chances of localised heat accumulation near the outfall area because of the lower relative depth.

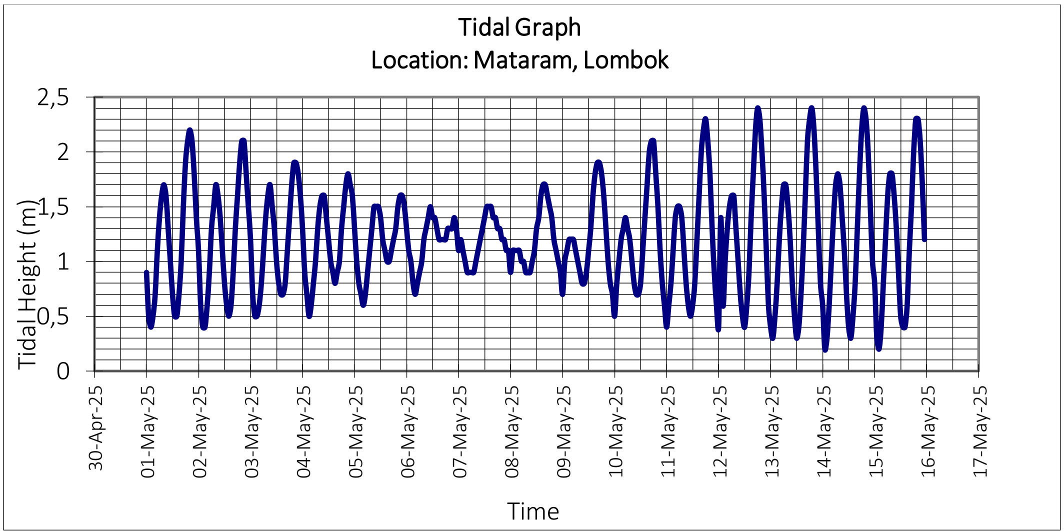

Figure 3. Sea surface elevation variability over a 15-day simulation period (1–15 May 2025) at Lembar Station. The tidal signal is mixed, dominated by a semi-diurnal regime, with a maximum tidal range of 2.28 m, controlling the coastal circulation and influencing the potential for dilution of thermal plumes.

Surface wind is another contributor to local hydrodynamic conditions besides tidal forcing. Wind rose analysis (**Figure 4**) showed that the dominant wind direction was from the southeast with usual wind speeds of 4–8 m/s. These wind conditions favour the formation of surface wind-driven currents (Sprintall et al., 2014) which in turn interact with the tidal circulation and help to dictate the initial movement pattern of the thermal plume.

During the observation period, the surface current velocities varied between 0.1 and 0.3 m/s, with periodic fluctuations related to tidal cycles (**Figure 5**). Though these currents are moderate, they are still relevant for the horizontal advection, one of the main processes controlling the thermal dispersion (Zhang et al., 2023). The Lombok Strait is also part of the Indonesian Throughflow system, an active and continuously moving water mass transport pathway driven by regional circulation and tides (Gordon et al., 1999). That means the warm discharged water is driven by the prevailing current, making it less likely that heat will build up near the outfall for extended periods.

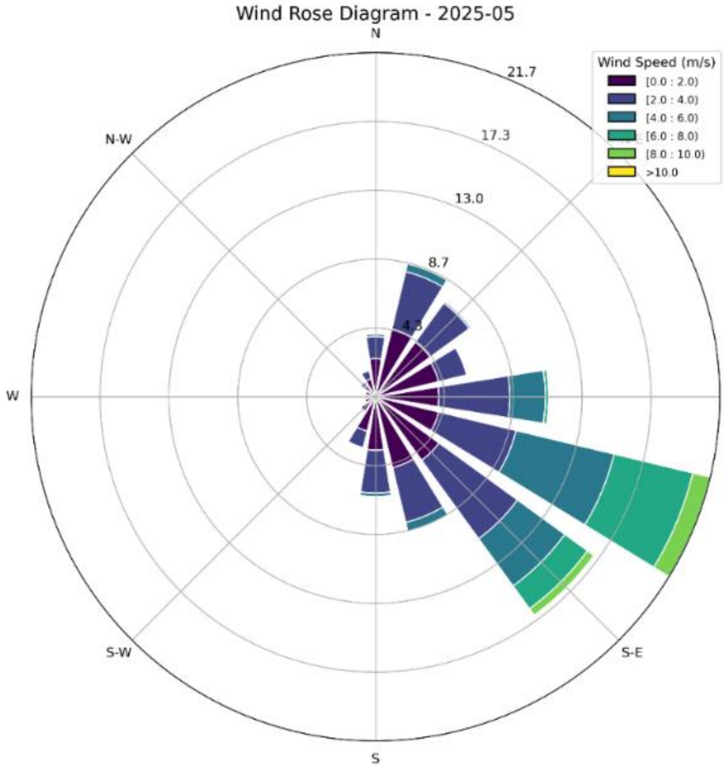

Figure 4. Wind rose showing the frequency of surface wind direction and speed over the study area for the simulation period, using Marine Copernicus reanalysis data. The prevailing winds are southeasterly with speeds of 4–8 m/s, which contribute to the formation of surface currents and determine the initial direction of transport of the thermal plume.

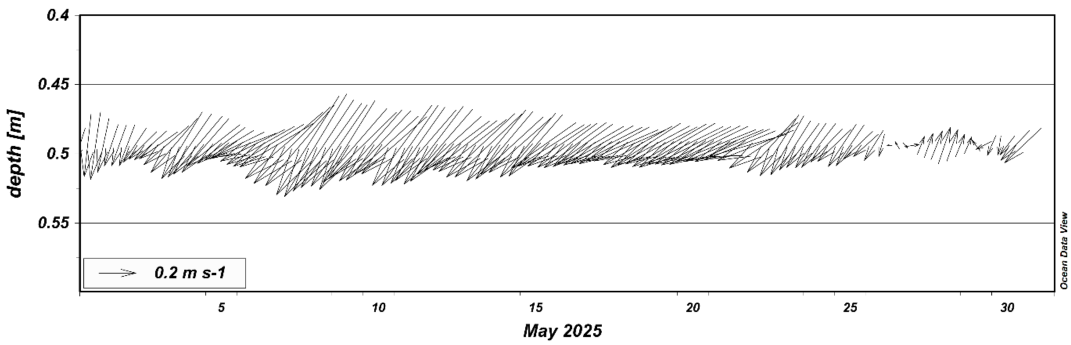

Figure 5. Stick plot of surface current velocity and direction during observation period with 0.1–0.3 m/s fluctuations associated with semi-diurnal tidal forcing. These oscillatory currents maintain a continuous advective transport along the coast line, reducing water mass stagnation and favouring horizontal dispersion of the thermal plume.

3.2. Thermal Dispersion Pattern

To investigate the spatial distribution of surface water temperature associated with cooling water discharge from the power plant, thermal plume modeling was performed. The simulation results (**Figure 6**) show that surface currents, mixed semidiurnal tides and wind conditions are the main controlling factors for plume dispersion in the Lombok coastal waters. The discharged warm water is generally advected parallel to the coast and the highest temperatures are near the outfall with a gradual decrease into offshore waters. The distribution pattern indicates the significance of local hydrodynamics-driven alongshore transport and mixing processes in controlling the plume direction and spatial extent. Similar conditions were reported by Hu et al. (2023), who found that thermal plumes were mainly propagated along the coastline in Daya Bay, resulting in significant temperature differences between the inlet and outlet areas.

Similarly, Deabes (2020) also reported similar findings, reported that the elevated temperatures were mostly confined to the immediate area of the outfall and decreased gradually due to mixing with the surrounding seawater.

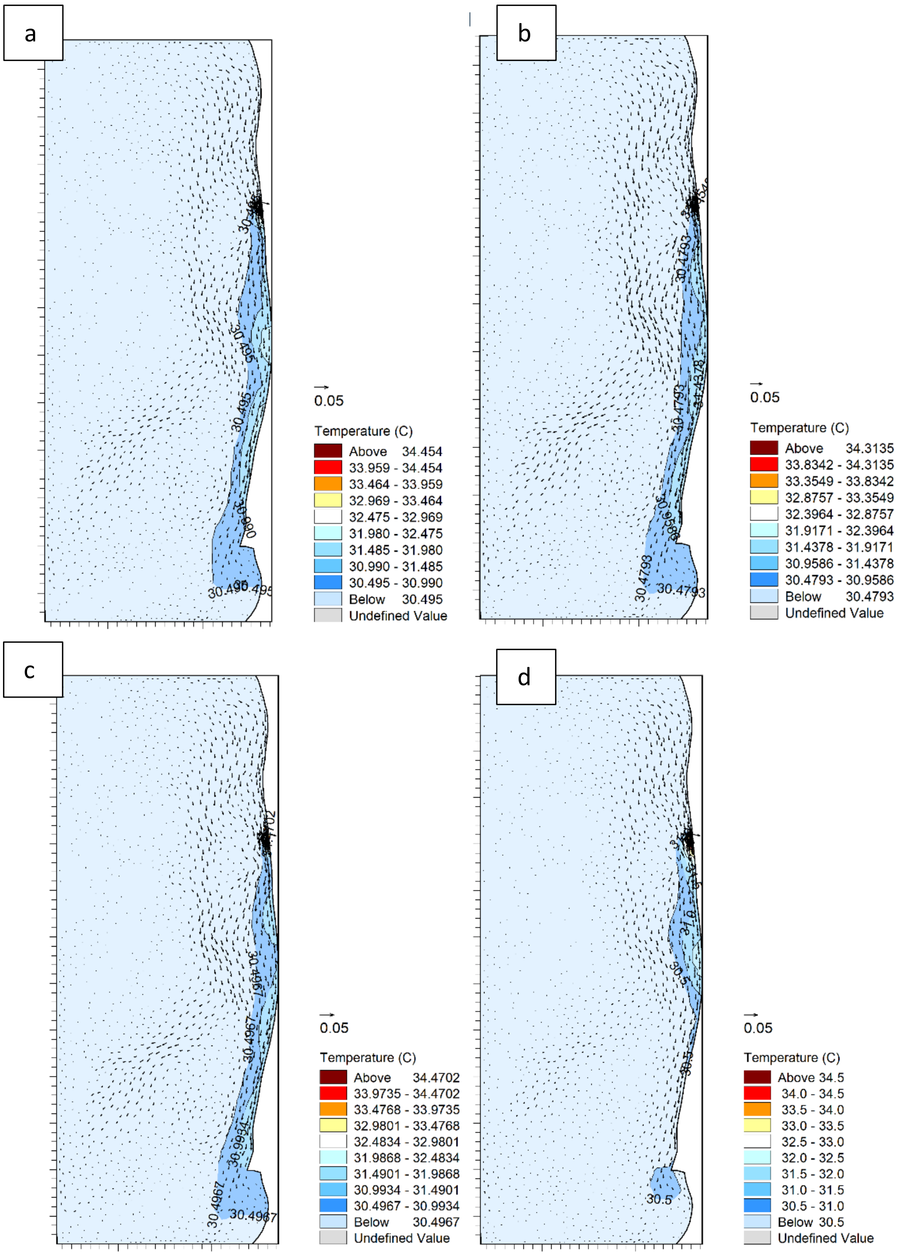

Figure 6. Simulated spatial distribution of surface thermal plume under four hydrodynamic conditions during the 1–15 May 2025 simulation period: (a) highest high water level, (b) lowest low water level, (c) slack water, and (d) neap. The results indicate that the joint influence of tidal currents and wind forcing tends to elongate the thermal plume along the coastline, but the high temperature is limited to the vicinity of the outfall and rapidly dissipates offshore.

The spatial distribution of the plume area (**Table 2**) indicates that the 30–30.5 °C temperature range was predominant in all hydrodynamic conditions, with an area of 62.26 Km² at high tide, 62.23 km² at low tide, 62.21 Km² at slack water and increasing to 66.06 Km² at neap tide. The wide dominance of this temperature interval suggests that most of the ambient water had been sufficiently diluted and was close to ambient conditions. In contrast, the area of higher temperature classes was greatly reduced. The category of 30.5–31 °C covered only 1.67–4.08 km², whereas the range of 31–31.5 °C covered about 0.79–2.71 Km². Temperature zones above 31.5 °C were relatively small, almost always <1 Km², and the maximum extent of the 34–34.5 °C class was only 0.14 Km². The results indicate that the zones that received the greatest thermal impact were primarily those in the vicinity of the outfall and that only small temperature increases occurred in waters distant from the discharge source.

Table 2. Surface area coverage (Km^2) of thermal plume classified into temperature intervals. Four hydrodynamics phases. In the affected area, the lowest temperature class (30–30.5 °C) is predominant under all conditions, with a maximum of 66.06 Km^2 during neap tide, while high temperature zones (>31.5 °C) are very localised (<1 Km^2 near the discharge source).

Temperature Range (°C)	Area (Km^2)			
	High Tide	*Low Tide*	*Slack Water*	*Neap Tide*
30–30.5	62.26	62.23	62.21	66.06
30.5–31	4.06	3.88	4.08	1.67
31–31.5	1.77	2.71	2.51	0.79
31.5–32	0.81	0.15	0.14	0.24
32–32.5	0.03	0.03	0.02	0.06
32.5–33	0.02	0.02	0.02	0.05
33–33.5	0.02	0.01	0.02	0.04
33.5–34	0.02	0.01	0.02	0.03
34–34.5	0.08	0.03	0.06	0.14

Differences between hydrodynamic phases were more pronounced in the intermediate temperature ranges. The 31–31.5 °C class increased to 2.71 Km^2 during low tide, which was higher than the area recorded during high tide conditions. This pattern indicates that lower seawater volume during low tide reduced the dilution capacity around the discharge zone. In contrast, at neap tide the intermediate and higher temperature classes were smaller and the 30–30.5 °C range had the largest area. For the weaker current condition, the heat seemed to be more widely spread, but less intense, rather than a large region of high temperature. Overall, the thermal plume in the study area was characterised by a relatively narrow hotspot surrounding the outfall and a wider zone of low-intensity warming. Supporting data from Marine Copernicus SST at the nearest grid point also showed relatively stable surface temperatures during 1–15 May 2025, ranging from approximately 30.00 to 30.35 °C. This provides support for the choice of 30 °C for the ambient seawater temperature for the simulation and indicates that the background thermal condition modeled was regionally representative.

3.3. Water Quality Characteristics

Water-quality conditions were reviewed to describe the physicochemical environment that might influence thermal plume behaviour and plankton reaction. The parameters studied were temperature, salinity, pH, Dissolved Oxygen (DO), BOD_5, Total Suspended Solids (TSS) and concentrations of nutrients such as ammonia, nitrate and orthophosphate. Furthermore, the spatial differences between the four monitoring stations were further assessed to describe the environmental conditions in the Lombok Strait coastal waters (**Table 3**).

Table 3. Spatial variation of physicochemical parameters of water quality at the four monitoring stations around the power plant outfall. Station TP3 shows elevated levels of suspended solids and nutrients. Dissolved oxygen and pH are relatively stable across all stations, indicating overall resilience of the local marine environment to operational inputs.

Parameter	Unit	TP1	TP2	TP3	TP4
Temperature	°C	31.6	30.2	30.6	30.1
Salinity	‰	30.1	30.2	30.1	30.1
pH	-	7.62	8.12	8.27	8.22
Dissolved Oxygen (DO)	mg/L	5	4	5	4
Biochemical Oxygen Demand (BOD_5)	mg/L	3	4	3	6
Total Suspended Solids (TSS)	mg/L	5	2.5	6	2.5
Ammonia Total	mg/L	0.05	0.02	0.2	0.05
Orthophosphate (P)	mg/L	0.02	0.01	0.04	0.01
Nitrate (N)	mg/L	0.1	0.02	0.38	0.02

Overall, there were minor spatial differences in the measured water-quality parameters, although an environmental gradient associated with the outfall area was still apparent. The station nearest to the discharge outlet (TP3) showed the highest temperature (30.6 °C), nitrate (0.38 mg/L), total ammonia (0.20 mg/L), orthophosphate (0.04 mg/L), and TSS (6 mg/L). Temperature and dissolved oxygen (DO) are particularly relevant to thermal discharge because increasing temperature reduces oxygen solubility and can affect oxygen availability for aquatic organisms (Boyd, 2019). Temperature can also modify nutrient cycling and phytoplankton physiological processes, although the magnitude and direction of these responses vary among species and depend on local environmental conditions (Claquin et al., 2008; Hyun et al., 2014). The relatively high nutrient concentrations at TP3, together with its relatively warm conditions, therefore indicate that thermal exposure occurred concurrently with changes in other environmental factors that may influence plankton communities. However, the relatively stable salinity, pH, and DO concentrations among stations suggest that the thermal discharge did not produce substantial deterioration of overall water quality during the observation period. Similar observations were made by Nashaat et al. (2019) who stated that the ecological impact of thermal discharge is usually most pronounced in areas closest to the discharge source.

3.4. Plankton Community Structure

The plankton community composition found in the study area generally reflected relatively stable ecological conditions. Total plankton abundance, reported as the combined abundance of phytoplankton and zooplankton, ranged from 819 to 1,890 ind. L^{-1} across the four monitoring stations (**Table 4**). The highest abundance was recorded at Station TP4, whereas TP1 and TP2 showed the lowest values. Although total abundance varied spatially, this pattern was not consistently associated with changes in community diversity or dominance, suggesting that variations in abundance alone did not necessarily reflect differences in community structure. These values indicate moderate species diversity, fairly even distribution of individuals among taxa and lack of strong dominance by a single species. The results showed that in general, the plankton communities in the coastal waters of Lombok have not yet suffered serious ecological disturbance. Similar results were reported by Majdi et al. (2020) who showed that moderate temperature increases could impact the structure of the aquatic community without necessarily leading to major declines in diversity.

Table 4. Total plankton abundance (combined phytoplankton and zooplankton), Shannon diversity (H'), evenness (E), and Simpson dominance (D) at the four monitoring stations. Abundance values were reported by the accredited laboratory as total plankton individuals per liter (ind. L^{-1}).

Ecological Index	Station			
	1	2	3	4
Total Plankton Abundance (ind/L)	819	819	1260	1890
Diversity (H’)	1.99	1.93	2.21	2.07
Evenness (E)	0.96	0.93	0.96	0.86
Dominance (D)	0.15	0.17	0.12	0.17

TP3 had some interesting characteristics among all observation stations. This station was closest to the outfall and showed highest nutrient concentrations, but also had highest diversity value (H’ = 2.21), high evenness (E = 0.96) and lowest dominance index (D = 0.12). Although TP3 did not have the highest total plankton abundance, its relatively high diversity and evenness indicate a more balanced community composition, suggesting that environmental conditions in the initial mixing zone remained suitable for the coexistence of multiple plankton taxa. These observations suggest that the levels of thermal exposure and nutrient enrichment at TP3 had not yet been associated with an apparent reduction in community balance during the sampling period. Unlike the results found by Nashaat et al. (2019) where phytoplankton diversity decreased in the proximity of heated discharge zones, the Lombok coastal system seems to have enough mixing capacity to support fairly stable plankton assemblages (Paerl et al., 2011).

Table 5. Checklist of phytoplankton and zooplankton taxa observed in the monitoring stations of the study area. Diatoms (Bacillariophyceae) dominate the community with *Chaetoceros* sp. present at all stations. The occurrence of *Coscinodiscus* sp. and *Trichodesmium clevei* at Station TP3 indicates a more productive assemblage associated with nutrient enriched conditions close to the outfall.

Plankton	Station			
	1	2	3	4
PHYTOPLANKTON				
Bacillariophyceae				
Bacillaria sp.				+
Chaetoceros sp.	+	+	+	+
Coscinodiscus sp.		+	+	+
Lauderia sp.	+			
Melosira borreri	+		+	+
Pleurosigma sp.		+	+	
Rhabdonema arcuatum				+
Rhizosolenia bergonii			+	+
Cyanophyceae				
Trichodesmium clevei			+	
Dinophyceae				
Dinophysis caudata	+_			
Protoperidinium depressum		+		
Protoperidinium sp.		+	+	+
ZOOPLANKTON				
Crustacea				
Acartia clausii	+	+	+	+
Acartia omorii	+		+	+
Eurytemora affinis			+	
Eurytemora caspica	+	+		
Eurytemora pacifica				+
Protozoa				
Tintinnopsis aperta				+
Amphileptidae				
Litonotus sp.	+	+		

Taxonomically, Bacillariophyceae was the dominant group in the plankton community. *Chaetoceros* sp. was recorded at all sampling stations (**Table 5**). The genus is generally acknowledged as an opportunistic diatom that quickly reacts to nutrient availability in coastal environments (Cloern, 2001). TP3 showed the presence of several other taxa such as *Coscinodiscus* sp., *Rhizosolenia bergonii* and *Trichodesmium clevei*, suggesting relatively productive environmental conditions related to local nutrient input. However, the composition observed did not lead to bloom formation. The presence of *Trichodesmium* probably correlates to the warm and stable features of tropical waters (Breitbarth et al., 2007). The sporadic presence of *Dinophysis caudata* indicates that the conditions conducive to the proliferation of harmful dinoflagellates were still weak (Reguera et al., 2014). In general, the plankton composition at TP3 still indicated relatively stable ecological conditions without obvious signs of advanced eutrophication. However, observations from the downstream Jangkok River, which discharges into coastal waters adjacent to the study area, showed that higher pollution pressure resulted in the absence of zooplankton and greater variation in community structure (Safnowandi, 2024). Although the Jangkok River was not included as one of the monitoring stations (TP1–TP4), these findings provide supporting evidence that increased anthropogenic inputs may alter plankton community composition in nearby coastal environments.

3.5. Relationship Between Environmental Parameters and the Plankton Community

Spearman correlation analysis was performed to evaluate the relationships between environmental parameters and plankton community indices. **Table 6** shows the overall correlation matrix and **Table 7** highlights the statistically significant relationships ($p = 0.05$).

Table 6. Spearman rank correlation matrix between physicochemical variables and plankton ecological metrics in the coastal ecosystem. Plankton abundance represents the total abundance of phytoplankton and zooplankton combined, expressed as individuals per liter (ind. L^{-1}), based on the accredited laboratory analytical report.

Variables	Temp	Salt	pH	DO	BOD_5	TSS	A	P	N	Total Abundance	H	E	D
Temp	1	-0.26	-0.40	0.89	-0.95	0.74	0.32	0.74	0.74	-0.63	0.00	0.95	-0.74
Salt	-0.26	1	-0.26	-0.58	0.27	-0.54	-0.82	-0.54	-0.54	-0.54	-0.77	-0.27	0.54
pH	-0.40	-0.26	1	0.00	0.11	0.32	0.63	0.32	0.32	0.74	0.80	-0.11	-0.32
DO	0.89	-0.58	0.00	1	-0.94	0.94	0.71	0.94	0.94	-0.24	0.45	0.94	-0.94
BOD_5	-0.95	0.27	0.11	-0.94	1	-0.89	-0.50	-0.89	-0.89	0.50	-0.21	-1.00	0.89
TSS	0.74	-0.54	0.32	0.94	-0.89	1	0.83	1.00	1.00	-0.06	0.63	0.89	-1.00
A	0.32	-0.82	0.63	0.71	-0.50	0.83	1	0.83	0.83	0.50	0.95	0.50	-0.83
P	0.74	-0.54	0.32	0.94	-0.89	1.00	0.83	1	1.00	-0.06	0.63	0.89	-1.00
N	0.74	-0.54	0.32	0.94	-0.89	1.00	0.83	1.00	1	-0.06	0.63	0.89	-1.00
Total Abundance	-0.63	-0.54	0.74	-0.24	0.50	-0.06	0.50	-0.06	-0.06	1	0.74	-0.50	0.06
H	0.00	-0.77	0.80	0.45	-0.21	0.63	0.95	0.63	0.63	0.74	1	0.21	-0.63
E	0.95	-0.27	-0.11	0.94	-1.00	0.89	0.50	0.89	0.89	-0.50	0.21	1	-0.89
D	-0.74	0.54	-0.32	-0.94	0.89	-1.00	-0.83	-1.00	-1.00	0.06	-0.63	-0.89	1

Table 7. Spearman correlation coefficients ($\alpha = 0.05$) between major environmental parameters and biological indices. Because the analysis was based on four observation stations, the reported relationships should be interpreted as exploratory ecological patterns rather than evidence of causal relationships.

No	Variable 1	Variable 2	Spearman r	p-value
1	Temperature	E	0.95	0.05
2	Temperature	BOD_5	-0.95	0.05
3	BOD_5	E	-1.00	0.00
4	Ammonia	H	0.95	0.05

Correlation analysis showed that variation in plankton community structure could not be explained by temperature alone. The correlation matrix showed a negative association between temperature and total plankton abundance ($r = -0.63$), although separate phytoplankton abundance data were not available to determine whether higher temperature directly reduced phytoplankton abundance. Temperature was not significantly associated with the Shannon–Wiener diversity index (H') ($r = 0.00$; $p > 0.05$), but showed a strong positive correlation with evenness (E) ($r = 0.95$; $p = 0.05$) and a strong negative correlation with BOD_5 ($r = -0.95$; $p = 0.05$). Ammonia was also positively correlated with diversity (H') ($r = 0.95$; $p = 0.05$). These patterns suggest that plankton community variation may be related to the combined effects of temperature, organic matter, and nutrient availability rather than temperature alone. Previous studies have similarly reported that plankton responses to temperature are influenced by interactions among multiple environmental variables, including nutrient availability, hydrodynamic processes, and local environmental conditions (Reynolds, 2009; Boyce et al., 2010; Magurran, 2021). Likewise, the observed relationships between temperature, BOD_5, and evenness may indicate concurrent ecological variation rather than direct cause-and-effect relationships. Although higher organic loading can influence community stability through decomposition and oxygen consumption (Boyd, 2019; Smith and Schindler, 2009), the present dataset is insufficient to demonstrate that these processes were directly driven by thermal inputs. Given the limited sample size (n = 4), the observed correlations should therefore be interpreted as exploratory ecological patterns rather than causal relationships.

Correspondence Analysis (**Table 8**) showed that the two main dimensions explained 79.40% of the total variation in community composition, with contributions of 52.51% for F1 and 26.88% for F2. This indicates that the species-station association pattern can be well explained in a two-dimensional space. TP1 was located on the positive side of F1 and was associated with *Eurytemora caspica* and *Dinophysis caudata*, whereas TP3 was located on the negative side of F1 and was associated with diatoms such as *Chaetoceros* sp., *Rhizosolenia bergonii*, and *Melosira borreri*. TP2 occupied a transitional position with associations to *Pleurosigma* sp. and *Protoperidinium* sp. (**Figure 7**). These associations suggest differences in species composition among stations; however, because the analysis was based on only four observation stations, the ordination should be interpreted as an exploratory description of community patterns rather than definitive evidence of environmental gradients or ecological zonation. The observed grouping may reflect the combined influence of multiple environmental factors, including thermal conditions, nutrient availability, and local hydrodynamic processes, which cannot be distinguished independently by Correspondence Analysis alone.

Table 8. Eigenvalues, explained variance, and cumulative inertia from the two-dimensional Correspondence Analysis of plankton community composition. The first two axes (F1 and F2) explained 79.40% of the total inertia, indicating that the ordination adequately summarizes the variation in species composition among observation stations.

	F1	F2	F3
Eigenvalue	0.476	0.244	0.187
Inertia (%)	52.513	26.883	20.603
Cumulative %	52.513	79.397	100.000

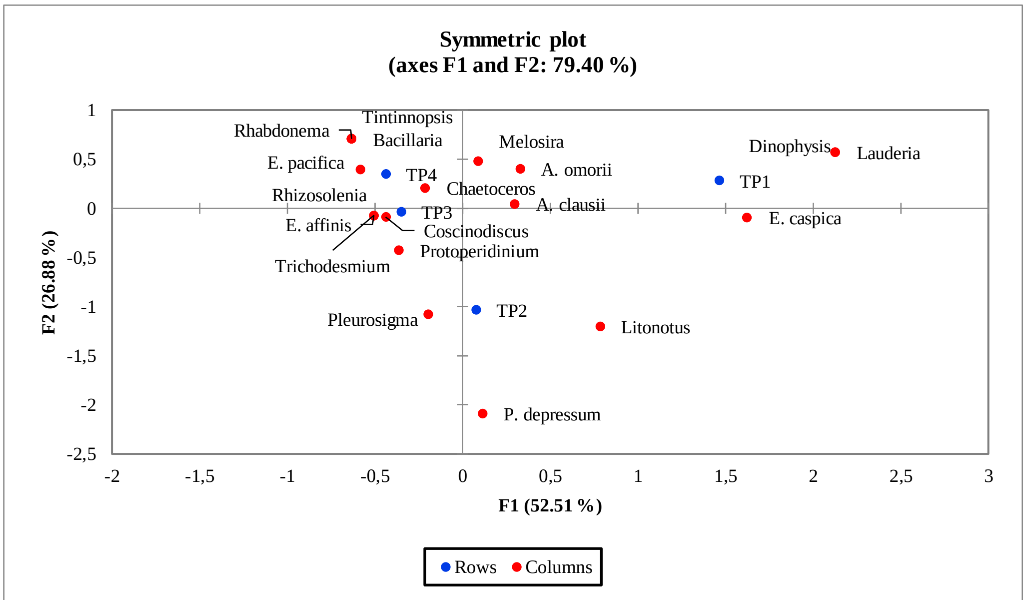

Figure 7. Bi-plot of Two-dimensional Correspondence Analysis of relationships between sampling stations and plankton taxa. The first two factorial axes explained 79.40 % of the total variance and showed differences in species associations among the observation stations. Station TP3 was strongly correlated with opportunistic diatoms such as *Chaetoceros* sp. and *Coscinodiscus* sp., which may be associated with relatively higher nutrient concentrations observed at TP3.

The pattern of separation seen in Correspondence Analysis agrees with previous studies of coastal thermal effluent systems. Research by Hu et al. (2023) found distinct plankton communities in thermal-influenced coastal waters at the inlet and outlet, while Beng et al. (2025) reported that long-term exposure to heated conditions could alter the composition of plankton assemblages versus non-impacted areas. Similar observations were also described by

Nashaat et al. (2019), who reported that ecological pressure tends to increase around discharge locations. However, the distribution of stations and taxa in the CA diagram must be considered as an ecological association rather than direct evidence of cause-and-effect relationships. TP3 was associated with opportunistic diatoms such as *Chaetoceros* sp. and *Coscinodiscus* sp., which may reflect their tolerance to the relatively warm and nutrient-enriched conditions at this station. Laboratory studies have shown that marine microalgae exhibit species-specific responses to elevated temperature (Claquin et al., 2008; Hyun et al., 2014), indicating that higher temperature does not necessarily produce the same response across taxa. Therefore, the association of *Chaetoceros* sp. and *Coscinodiscus* sp. with TP3 should not be interpreted as evidence that these taxa were negatively affected by temperature; rather, their occurrence may indicate tolerance to the prevailing environmental conditions. Other taxa may show weaker associations with TP3 because their distribution can be influenced by differences in thermal tolerance, nutrient availability, and hydrodynamic conditions. The results of the correlation and CA analyses suggest that the structure of the plankton community in the Lombok coastal waters is influenced by the complex interactions of temperature, nutrients, suspended solids, and hydrodynamic conditions, rather than temperature as the sole controlling factor. This lends support to the hypothesis that biological responses to thermal stress are closely related to surrounding physicochemical conditions (Choi et al., 2012; Feng et al., 2015; Ren et al., 2022; Patova et al., 2023). Thermal gradients caused by plume discharge have also been shown to affect long-term changes in zooplankton community structure (Jiang and Wang, 2020; Tao et al., 2026), highlighting the role of local thermal conditions in controlling plankton dynamics.

4. Conclusions

The thermal plume in the Lombok coastal waters was mainly controlled by tidal movement, surface current, and wind conditions, resulting in a relatively narrow hot spot around the outfall and a wider area of low-intensity warming. The modelled plume was dominated by the 30–30.5 °C temperature range under different hydrodynamic conditions, covering approximately 62.21–66.06 km². Despite the presence of thermal discharge, the plankton community remained relatively stable, with diversity values of 1.93–2.21, evenness of 0.86–0.96, and dominance indices of 0.12–0.17. Temperature alone was not significantly correlated with plankton diversity, while the observed community patterns were associated with the combined influence of temperature, nutrient availability, and local hydrodynamic processes. These findings indicate that thermal plume dispersion in the Lombok coastal waters is strongly governed by hydrodynamic conditions, while the observed spatial variation in plankton community structure cannot be attributed to temperature alone.

Conflicts of Interest

The author declares that there is no conflict of interest in this research.

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During the preparation of this manuscript, the authors used artificial intelligence (AI) tools for translating the manuscript from Indonesian into English. All translated content was checked, revised and edited by the authors, who take full responsibility for the accuracy and final content of the manuscript.

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