Spatial analysis of plankton distribution in Northern Waters of Aceh: an indicator of marine environmental quality

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Abstract. Plankton, especially phytoplankton, serves as the essential building block of the marine food chain. As a result, the presence of plankton in a body of water is frequently utilized as a measure of water quality and primary productivity. This study aims to determine plankton's spatial patterns in Northern Aceh's waters as a bioindicator of water quality. The spatial distribution of plankton was analyzed through water sampling at several points in the sea in the Northern Waters of Aceh (NWA). Plankton analysis included abundance, diversity, and community composition. Concurrently, an analysis of environmental parameters, including temperature, salinity, pH, and dissolved oxygen, was conducted. Information on plankton abundance and environmental parameters was then linked to identify their spatial relationships. Furthermore, to understand the spatial distribution of plankton, plankton abundance was correlated with spectral bands from satellite imagery. The study results indicate spatial variation in plankton abundance in NWA due to the physicochemical parameters of the seawater. Analysis reveals that Cyanobacteria, Bacillariophyta (diatoms), Chlorophyta, Arthropoda, and Rotifera are present in NWA, with Bacillariophyta being the most dominant. The dominance of Bacillariophyta (diatoms) over Cyanobacteria, combined with the absence of *Pseudo-nitzschia spp.,* highlights the good ecological health and fertility of NWA.

1 Introduction

Phytoplankton serves as the fundamental basis of the oceanic food web and plays a vital role in maintaining the equilibrium of aquatic ecosystems. [1, 2]. The presence of plankton in

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water can be an indicator of water quality and primary productivity. Plankton, especially phytoplankton, contributes greatly to oxygen production and the global carbon cycle through photosynthesis [1, 3]. Therefore, monitoring the distribution of plankton provides an overview of the health of the aquatic environment [4, 5]. Plankton is a bioindicators of water quality because their spatial distribution and population density are influenced by key environmental variables, including temperature, salinity, pH, and dissolved oxygen concentration [6]. Alterations in the types and quantities of plankton can signal changes in the physical and chemical conditions of water. These changes may result from human activities and climate change. [5–7]. Spatial analysis of plankton can reveal distribution patterns related to water quality parameters so that it can be used to detect sources of pollution, eutrophication, and other impacts due to anthropogenic activities [3, 4]. NWA is one of Indonesia's important fishing areas, with a high level of biodiversity [8–11]. Therefore, Therefore, it is important to study the capacity of this aquatic environment also plankton distribution to support biodiversity and sustain fisheries productivity while assessing its resilience to environmental pressures and human-induced impacts [12].

Numerous studies have been carried on NWA. Research by [13], [8], and [11] focused on oceanographic parameters and the relationship between physical water parameters and fishing grounds in NWA. [14] explored the impact of dissolved compounds on the water quality in Banda Aceh. Studies related to the spatial distribution of plankton have been conducted in other regions. [15] have predicted marine plankton species by examining the physical and chemical qualities of the water.

[16] examined the substantial impact of surface plankton on the composition and activity of deep ocean prokaryotes, particularly in the Indian Ocean. [17] examined the structure of phytoplankton communities in both degraded and undegraded coral reef areas in the Western Indian Ocean, finding that microphytoplankton density, diversity, and photo-physiological performance were greater in healthier areas. [18] studied phytoplankton's spatial and temporal dynamics in Beibu Gulf, China, revealing information on species and community structures. [19] were the first to investigate mesozooplankton biodiversity in the epipelagic zone of the Northeast Indian Ocean off the coast of Myanmar, which adjoins NWA. [20] examined the spatial variability of plankton metabolic balance during the spring intermonsoon in the tropical Indian Ocean and discovered that nutrient availability is a significant factor influencing metabolic rates, with the Gross Primary Production (GPP) threshold closely matching the global average. [21] explored surface phytoplankton communities and their influencing factors in the Strait of Malacca and the Sunda Shelf, noting positive correlations between total phytoplankton and chlorophyll-a (chl-a) levels, as well as negative correlations with salinity. Cold seawater favored higher diatom abundance, while warmer conditions supported dinoflagellates and cyanobacteria. So far, information on NWA marine plankton needs to be improved, especially regarding its distribution and relationship to the NWA aquatic environment.

The research assesses the quality of NWA through the distribution and abundance of plankton and the condition of the seawater (temperature, salinity, pH, and Dissolved oxygen). It also examines the connection between phytoplankton and ocean color by spatial analysis, laying the groundwork for predictions about future water quality.

2 Research method

2.1 Field observation

NWA is located next to the Andaman Sea, the Strait of Malacca, and the Indian Ocean. However, this study focuses on areas dominated by marine operational activities in NWA,

namely at several points along the coast of Banda Aceh and the small islands of Aceh (Nasi Island and Batee Island).

Field data collection was conducted at 12 stations in NWA in July 2024, as illustrated in Figure 1. In situ measurements of physical and chemical parameters—including temperature, salinity, brightness, pH, and Total Dissolved Solids (TDS)—were taken using a portable water quality meter. Additionally, Dissolved Oxygen (DO) levels and plankton parameters were analyzed in the laboratory.

Plankton sampling was conducted using the Bucket Sampling method, which entailed filtering 100 liters of surface seawater with a 25 µm plankton net. The water samples were then put into labeled dark bottles. For plankton identification purposes, several bottles were added with 0.15 ml of 4% Lugol preservative solution. Next, the samples were stored in a cool box to be identified in the laboratory.

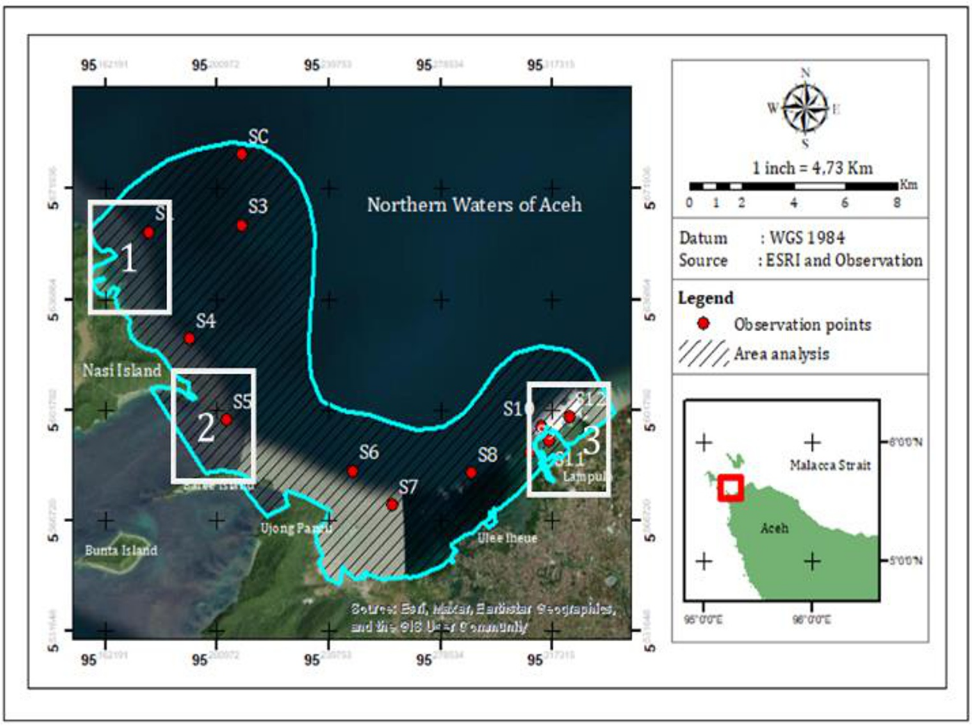


Fig.1. Research locations in NWA: Nasi Island Waters (box 1), Batee Island Waters (box 2), and Lampulo or Banda Aceh Waters (box 3).

2.2 Laboratory analysis

DO measurement using the SNI 06-2425-1991 method. Meanwhile, plankton identification was carried out by microscopic observation [22]. A total of 3 ml of homogenized water samples were dropped into the Sedgewick Rafter Chamber and observed under a microscope. The type of microscope used was the Optical B310 binocular with 4x and 10x magnification and zig-zag observation. Furthermore, individual plankton, particularly phytoplankton, were analyzed to determine their abundance (abundance index), diversity (Shannon-Wiener index), uniformity (Pielou index), and dominance (Simpson index). While diversity and uniformity are both measures of biodiversity, they serve distinct purposes in assessing the ecological balance and distribution of species within the ecosystem [12].

2.3 Remote-sensing data

Band 2 (490 nm) and Band 3 (560 nm) of Sentinel-2 (ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED")) are designed to detect various photosynthetic pigments in water (blue-green), including chlorophyll a, which is a major indicator of phytoplankton biomass. The resolution of these Sentinel-2 bands data reaches 10 meters, making it very useful when combined with field measurements. Band 2 and 3 data are compared with phytoplankton abundance information to obtain empirical equations for phytoplankton prediction.

2.4 Spatial analysis

Phytoplankton and water quality parameters from 12 stations were further interpolated using the Kriging method. The Kriging interpolation method is a geostatistical approach utilized to estimate values at unmeasured sites by relying on data collected from other measured locations. This study used a simple calculation method, namely by considering local variations in the data and using the nearest measurement point to produce spatial estimates [24]. To facilitate the analysis, we define three main locations in NWA, namely Nasi Island Waters (box 1), Batee Island Waters (box 2), and Lampulo or Banda Aceh Waters (box 3) (see Fig. 1).

3 Results and discussion

3.1 Plankton species

Based on identification, 5 plankton phyla were found in NWA: Phylum Cyanobacteria, Chlorophyta, Bacillariophyta (Diatom), Arthropoda and Rotifera (Fig. 2). Phylum Bacillariophyta (Diatom) is dominant in NWA. Diatoms play an important role in the global marine and atmospheric ecosystems in global primary production. Diatom communities can change significantly in response to environmental stress, making them effective bioindicators for monitoring the health of aquatic ecosystems [26].

Previous studies have shown that diatom diversity negatively correlates with aquatic nutrients, especially phosphate content [26, 29]. Diatoms are usually more competitive in oligotrophic (low nutrient) conditions, where they can utilize other nutrients more efficiently than other phytoplankton species. Conversely, when phosphate content increases (for example, due to pollution from agricultural runoff or industrial waste), other types of algae that are more tolerant of eutrophic conditions, such as cyanobacteria, can dominate the aquatic ecosystem. Cyanobacteria were only found at station 1, around the waters of Nasi Island. In contrast to diatoms, the presence of Cyanobacteria indicates that the waters are polluted. Cyanobacteria thrive in eutrophic zones, the detriment of sensitive phytoplankton species such as diatoms. Cyanobacteria are highly tolerant and can grow in freshwater, estuaries or seawater. However, the presence of cyanobacteria is quite small in NWA compared to other phytoplankton and zooplankton species. The presence of Cyanobacteria in the waters around Nasi Island may be because this area serves as its natural habitat or could be a momentary incident. Such incidents can result from the dynamics of ocean currents, weather changes, or fluctuations in the supply of natural nutrients in the NWA, particularly in the waters around Nasi Island. This is especially true since anthropogenic activities in the area are minimal and have little impact. However, long-term plankton information and further studies are still needed to confirm this finding. In general, the plankton species found are phytoplankton and zooplankton species that can be found in the

sea and estuaries, such as *Gyrosigma fasciola, Rhizosolenia sp.,* and *Chaetoceros sp*. Some types are freshwater and estuary plankton, such as *Aulacoseira granulata* and *Navicula sp* [27–29].

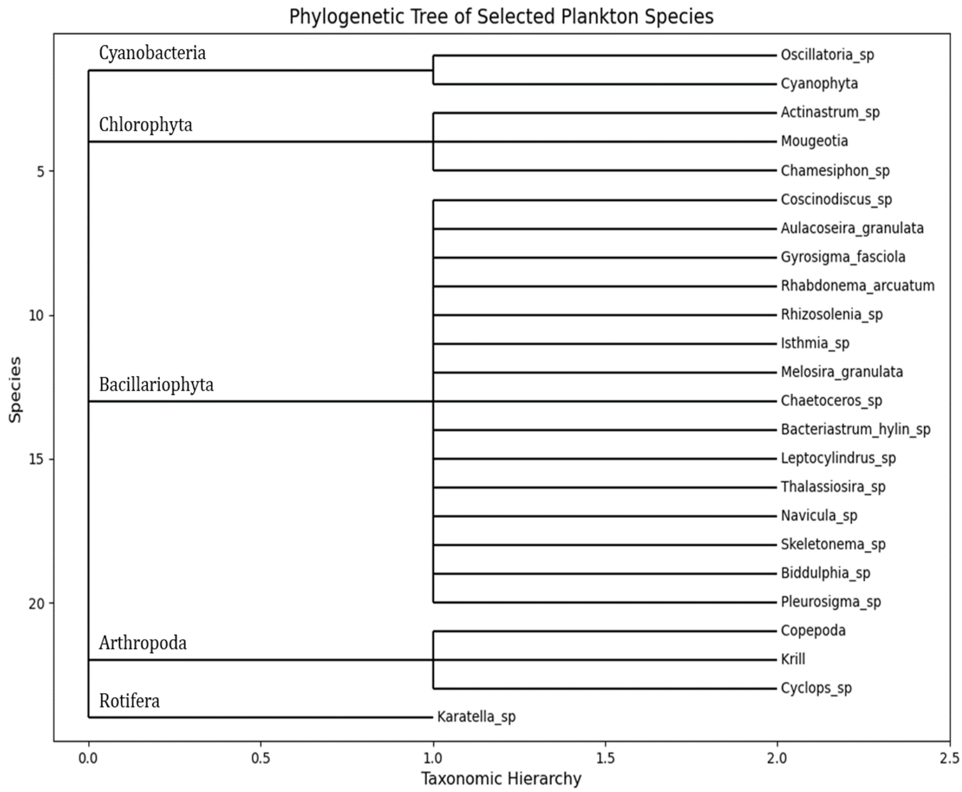
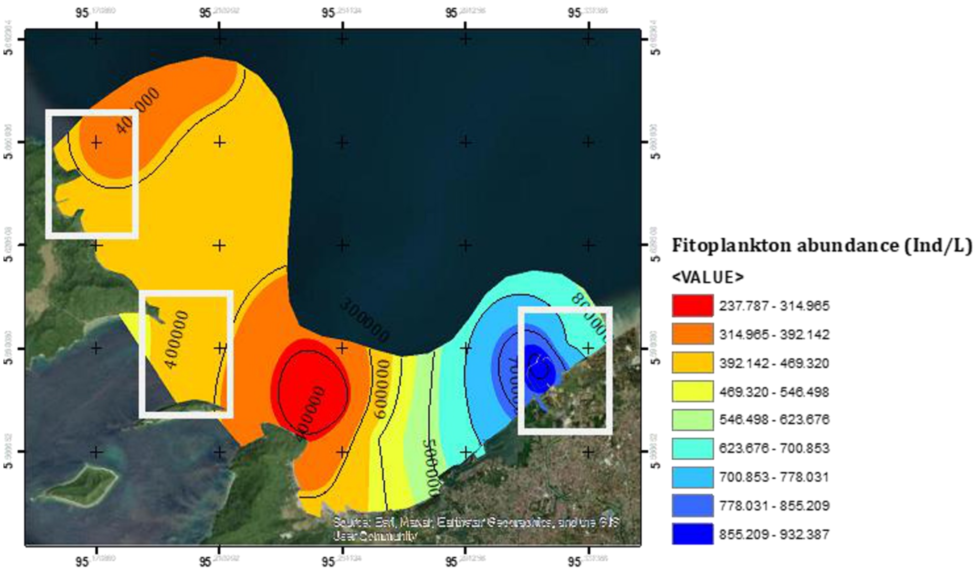


Fig. 2. Plankton species obtained in NWA.

3.2 Spatial distribution of plankton index

Phytoplankton abundance along the NWA coastline varies spatially Figure 3(a). In NWA, Banda Aceh (Lampulo) Waters have the highest phytoplankton abundance. This is due to the high anthropogenic activity in Banda Aceh (Lampulo, box 3) Waters compared to other water bodies in the NWA. Banda Aceh (Lampulo) Waters is the area where the main river flows, which provides freshwater runoff (rich in nutrients) to the sea. In addition, Banda Aceh Waters are the area of Banda Aceh and Aceh Besar fishing port activities. Thus, anthropogenic and freshwater runoff increase nutrient concentrations, supporting several phytoplankton species' growth. Based on the analysis of phytoplankton diversity (Figure 3(b)), Banda Aceh Waters also has a high level of diversity (reaching 1.23). This indicates that the water conditions support the growth of various phytoplankton species. Quite high phytoplankton diversity was also found in Batee Island Waters, which is a strait connecting Aceh Waters with the Indian Ocean. In Batee Island Waters, hydro-oceanic factors such as ocean currents can influence phytoplankton abundance, diversity, uniformity, and dominance. In general, the uniformity index (Fig. 3c) is the opposite of diversity (Figure 3(b)). The level of uniformity in Batee Island Waters is high (reaching 0.958), which indicates that the types of phytoplankton are relatively homogeneous.

On the other hand, in Banda Aceh Waters, the types of phytoplankton are more varied. Although the uniformity is high, the phytoplankton species in Banda Aceh Waters are balanced or have a small dominance (0.29) (Fig. 3d). The phytoplankton dominance that tends to be higher than Banda Aceh Waters is Pulau Nasi Waters.



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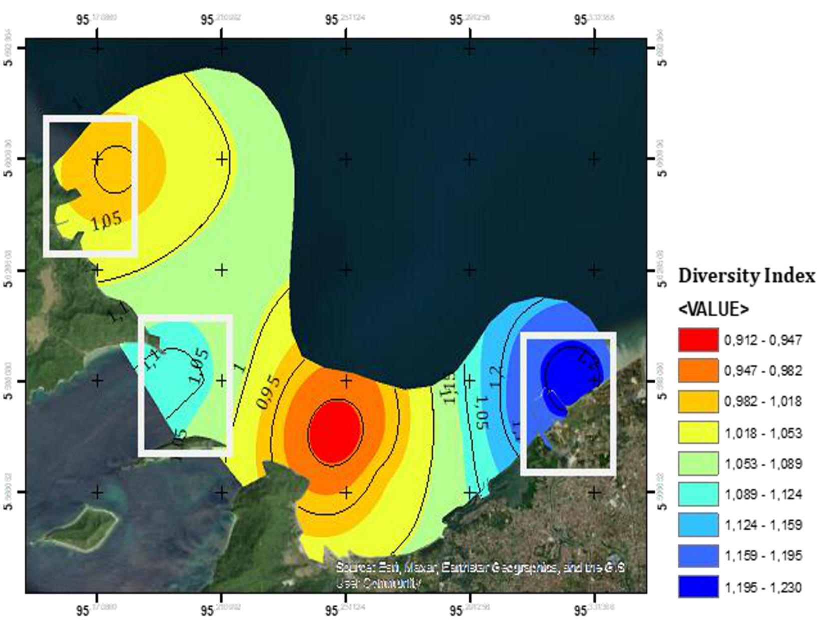

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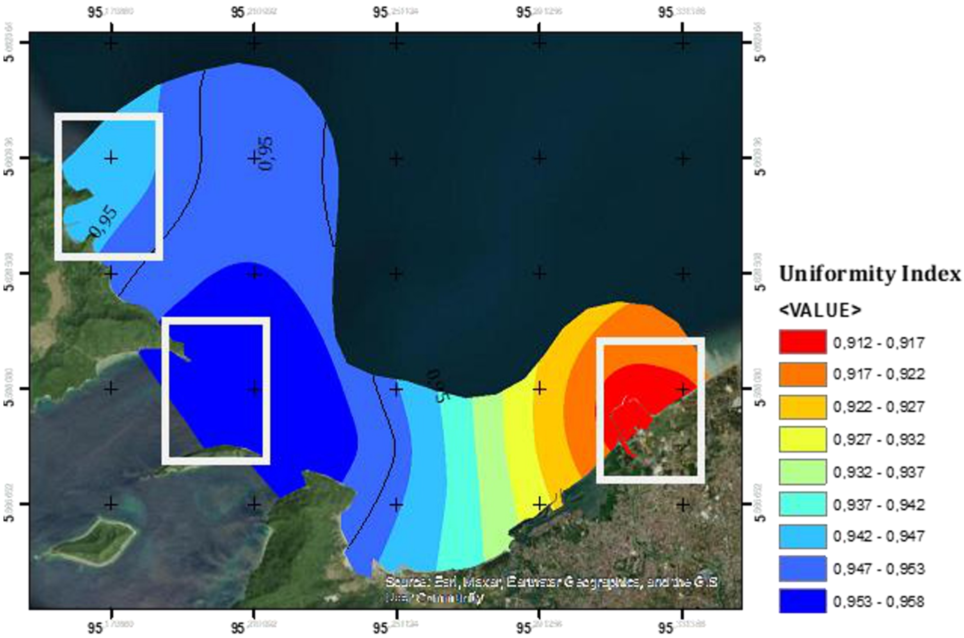

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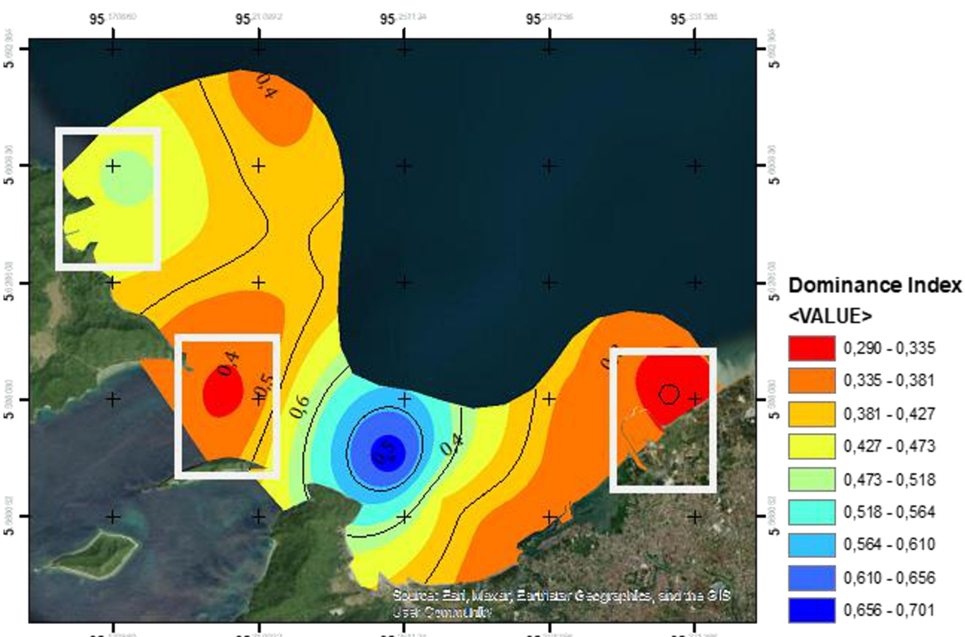


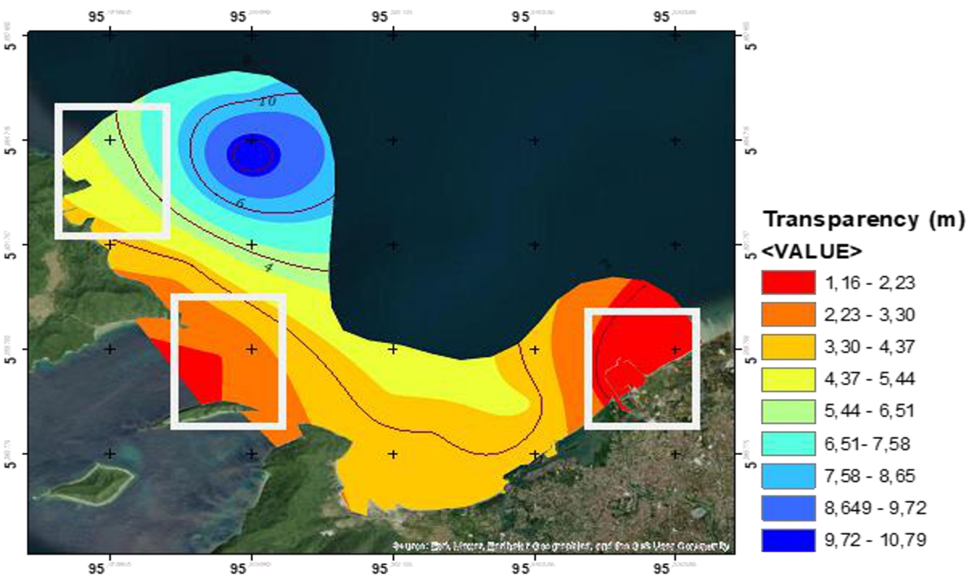
(d)

Fig. 3. (a) Distribution of Abundance, (b) Diversity, (c) Uniformity, and (d) Dominance of Phytoplankton (see Figure 1 for their definition).

3.3 Distribution of environmental marine quality

Water quality parameters have been spatially mapped and classified based on the interpolation results from in situ data. Figures 4a-f display the distribution of these

parameters in the NWA region. The transparency around Nasi Island is notably higher than that around Banda Aceh Waters (Lampulo) (Fig. 4a). Similarly, the sea surface temperature (SST) in Banda Aceh Waters is relatively higher than in the surrounding Nasi Island and Batee Island (Fig. 4b). Total dissolved solids (TDS) concentrations are also higher in Banda Aceh Waters than in Nasi Island and Batee Island (Figure 4c). It is attributed to the fact that Banda Aceh Waters, particularly Lampulo, is a significant fishing transportation area and serves as the main estuary in NWA. Freshwater runoff and land pollution can flow from the Lampulo Waters into the sea. It is further evidenced by the lower salinity levels in Banda Aceh Waters, especially in Lampulo, compared to other regions (Figure 4d). However, the pH levels in Banda Aceh Waters are not significantly lower than those of Batee Island (Fig. 4e). Due to the combination of low brightness, high temperatures, and elevated salinity, the dissolved oxygen (DO) concentration in Banda Aceh Waters is lower than in the waters surrounding Batee Island and Nasi Island (Fig. 4f). It indicates that the water quality in Banda Aceh, particularly in Lampulo, is inferior to that of the Aceh Islands (Nasi Island and Batee Island).



(a)

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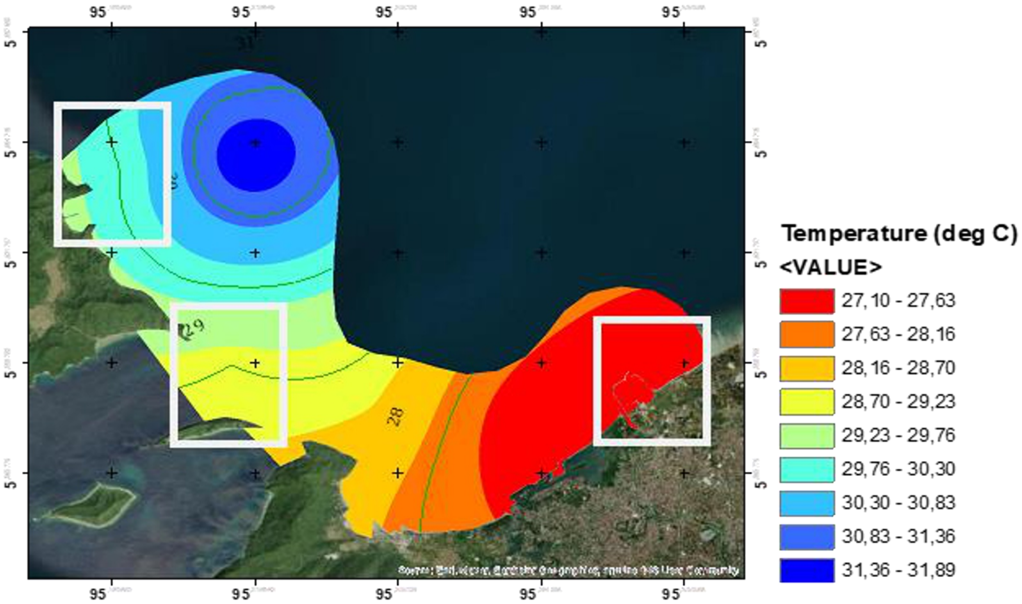

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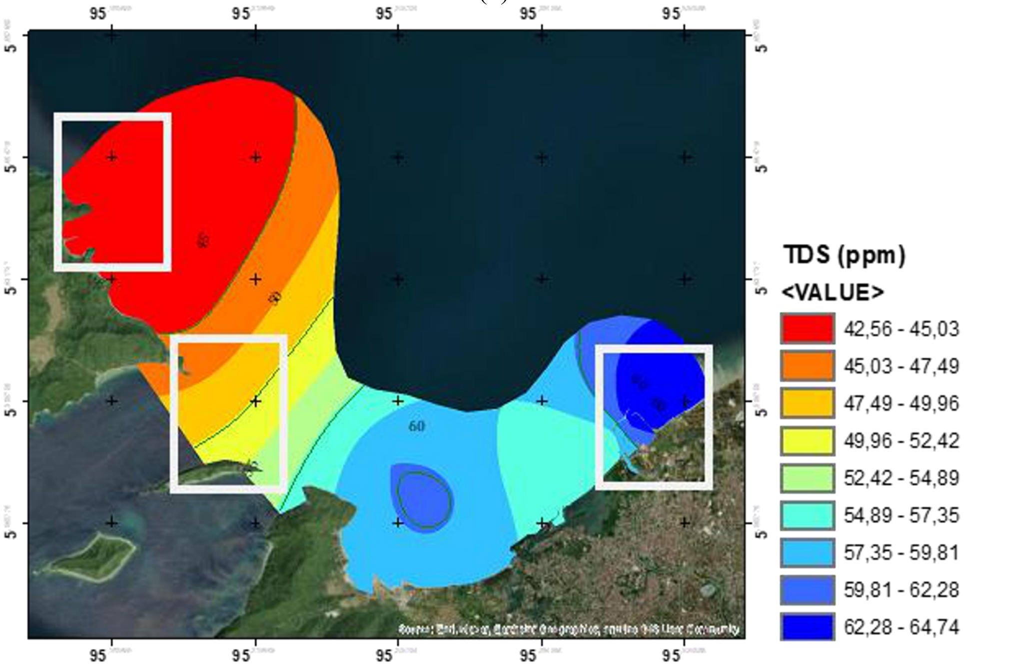

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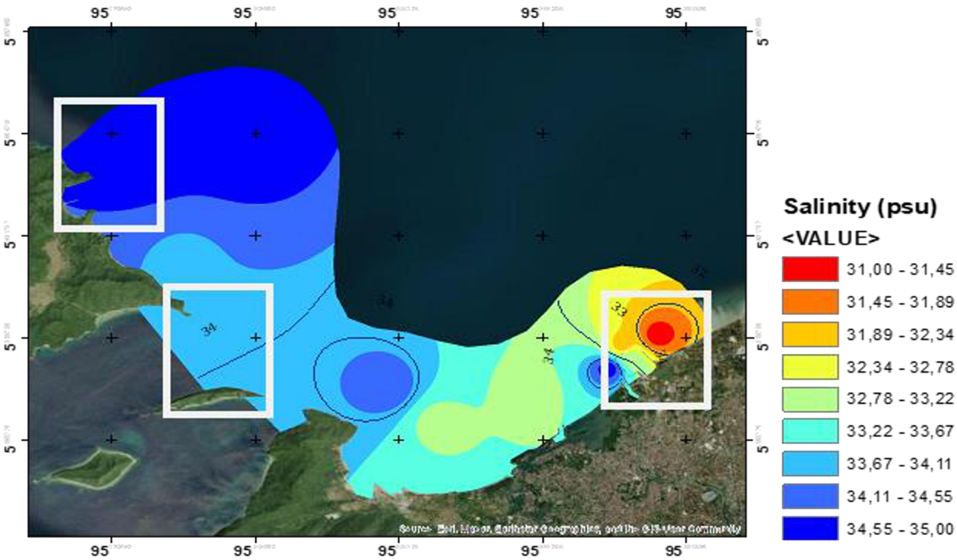
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31,45 - 31,89
31,89 - 32,34
32,34 - 32,78
32,78 - 33,22
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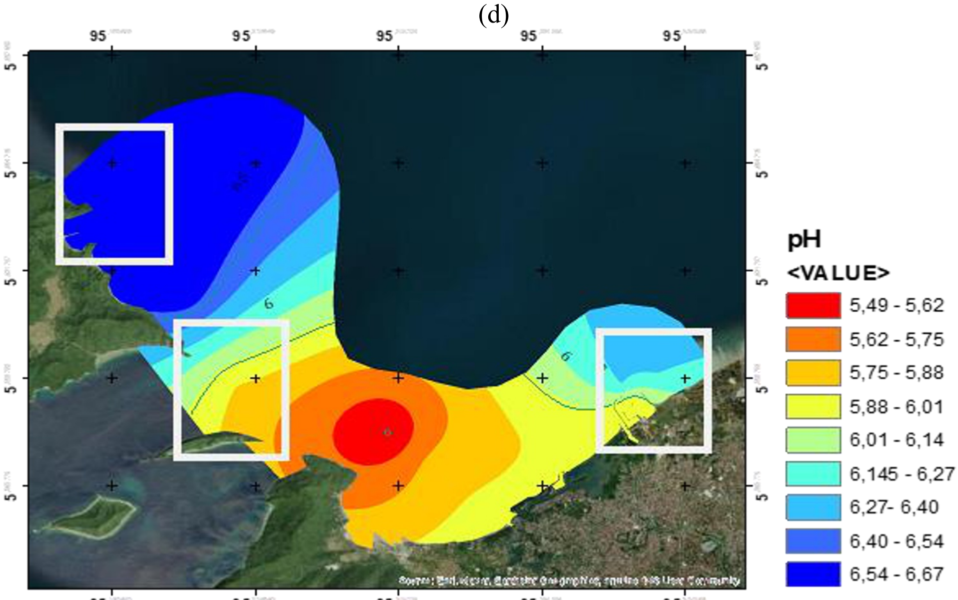
33,67 - 34,11
34,11 - 34,55
34,55 - 35,00

(d)


pH
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5,62 - 5,75
5,75 - 5,88
5,88 - 6,01
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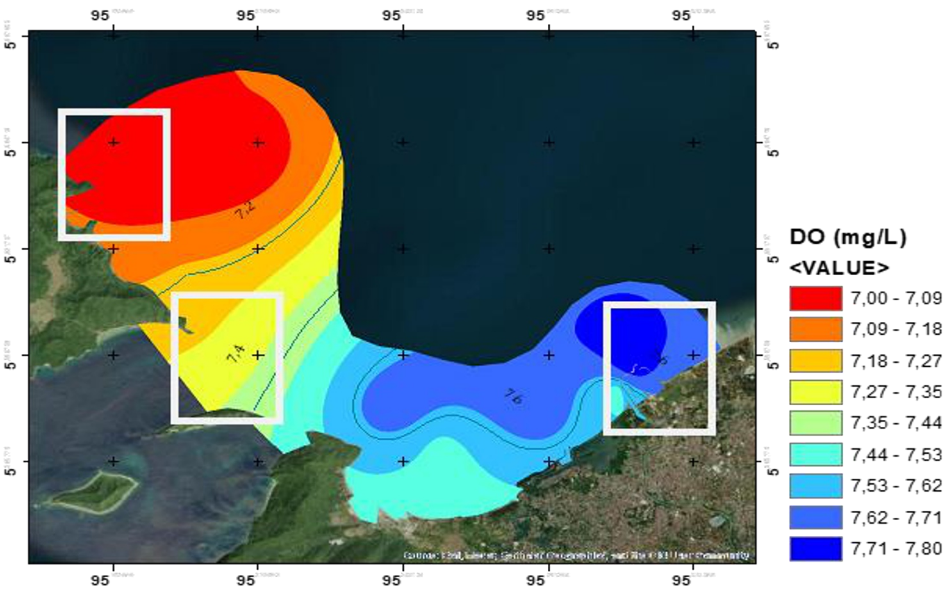
6,27- 6,40
6,40 - 6,54
6,54 - 6,67

(e)



(f)

Fig. 4. (a-f). Spatial distribution of water quality parameters in NWA. White boxes represent the areas analyzed and compared (see Fig. 1 for their definition).

3.4 Relationship between plankton and water quality parameters

Based on the Pearson correlation analysis in Fig. 5, sea surface temperature (SST) strongly correlates with several water quality parameters, including phytoplankton abundance. In particular, SST is positively correlated with brightness, pH, and salinity. In contrast, SST shows a significant negative correlation with total dissolved solids (TDS) and dissolved oxygen (DO) concentration, while it has a moderate negative correlation with phytoplankton abundance. Increased brightness aligns with the deeper penetration of light, which leads to an increasing of sea temperatures. As sea temperatures rise, the concentration of dissolved hydrogen ions also increases, which lowers the pH value.

Furthermore, warmer temperatures can increase respiration rates, leading to decreased DO concentrations or lower levels in general (correlation between DO and pH is -0.71). Higher temperatures also reflect and uniformity of phytoplankton populations. This is because only a few species may survive the changes and increased sea temperature. While higher temperatures can lead to a decline in phytoplankton abundance, they may simultaneously increase uniformity among phytoplankton species.

Seawater clarity is positively correlated with salinity and temperature, indicating that saltier and warmer seawater or from the ocean tends to be clearer. This is because the suspended particles in ocean waters are fewer and less concentrated than in coastal areas. In contrast, clarity showed a negative correlation with phytoplankton abundance, implying that high phytoplankton concentrations can reduce water clarity due to their light-absorbing properties. In addition, clarity had a weak negative correlation with dissolved oxygen (DO). Although phytoplankton produce DO through photosynthesis, the decomposition of these organisms can lead to decreased oxygen levels in the water. TDS was positively correlated with DO, indicating that ions present in seawater can increase DO concentrations. However, TDS showed a negative correlation with salinity, indicating that TDS may originate from freshwater runoff entering the ocean. Phytoplankton (abundace and diversity) exhibited a

moderate negative correlation with salinity, indicating that the influx of freshwater may enhance plankton abundance and diversity in marine ecosystems.

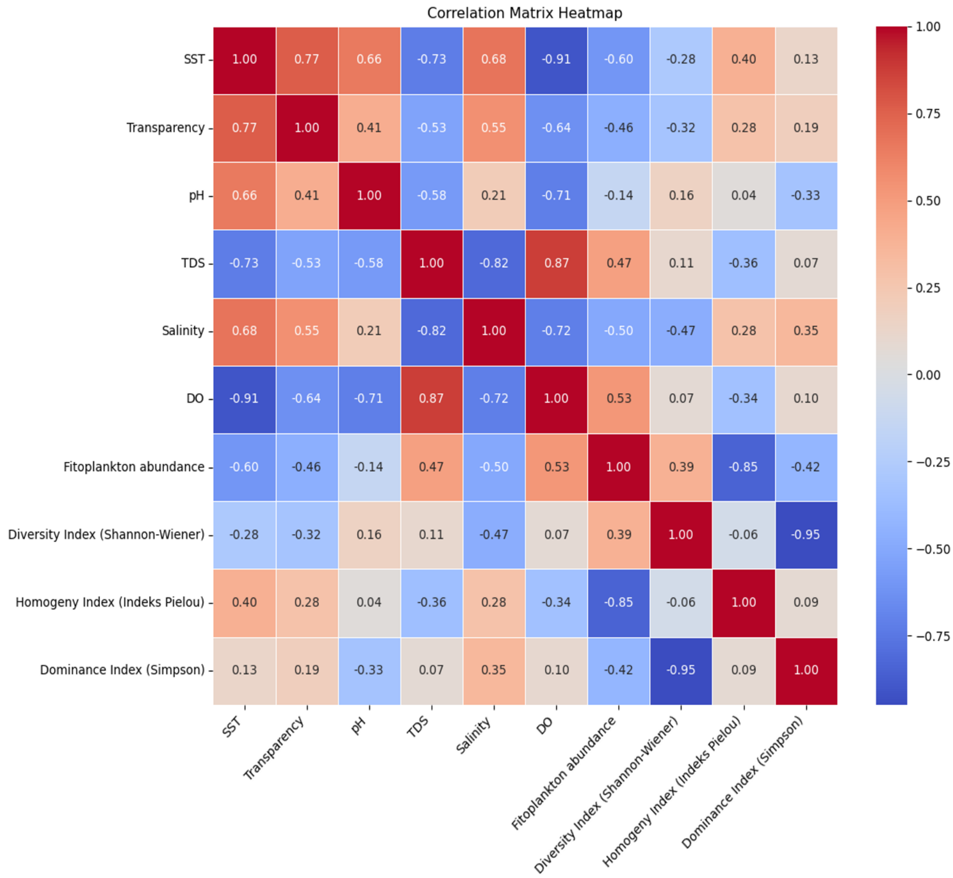


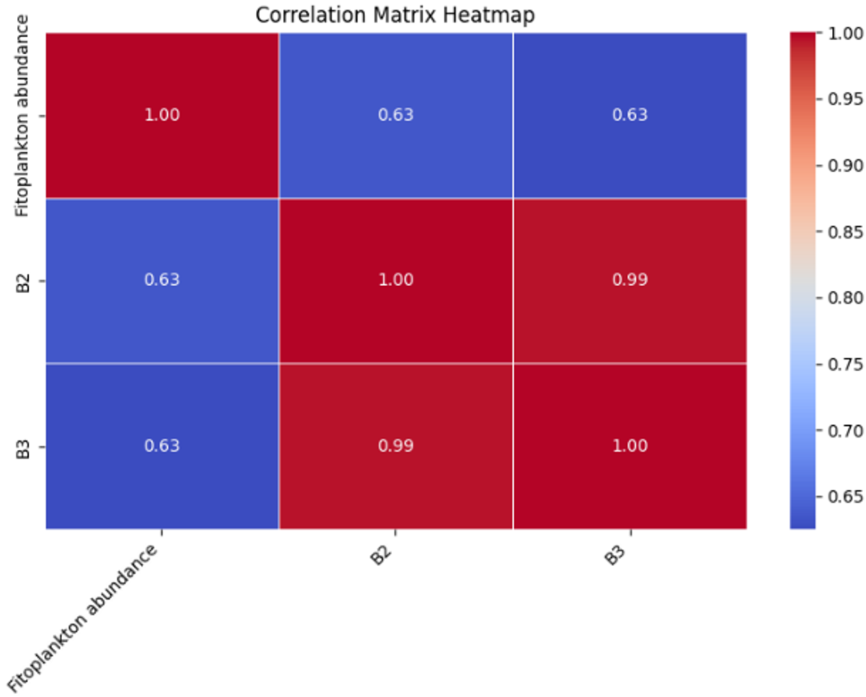
Fig. 5. Pearson correlation of seawater quality parameters in NWA (r> 0.7 or r< -0.7, the correlation value is quite strong).

3.5 The relationship between phytoplankton and ocean color

The relationship between plankton and ocean color is related to the optical properties of water, which are influenced by the presence of phytoplankton and dissolved organic compounds. Phytoplankton are the key players in this relationship with their pigments like chlorophyll-a. These pigments significantly alter the light absorbed and reflected by seawater. Band 2 is important in detecting seawater quality (such as suspended sediment and algae detection in waters). Similarly, Band 3, which includes green wavelengths (560 nm), is important for chlorophyll mapping.

Phytoplankton has a moderate positive correlation to Band 2 and Band 3 (correlation coefficient = 0.63) (Figure 6a). The higher the reflectance value in Bands 2 and 3, the higher the phytoplankton concentration in NWA. Based on the relationship, several linear regression models were constructed, namely the regression between Band 2 and phytoplankton (Figure 6b), Band 3 and phytoplankton (Figure 6c), and the combination of Band 2 and Band 3 against phytoplankton (Figure 6d). The predictability of the linear regression model between Band 2 and phytoplankton is similar to the one between Band 3 against phytoplankton based on the coefficient of determination (R^2) and RMSE. The model's

prediction is similar to the multiple linear regression model of bands 2 and 3 against phytoplankton. In other words, adding Band 3 does not significantly increase model performance.



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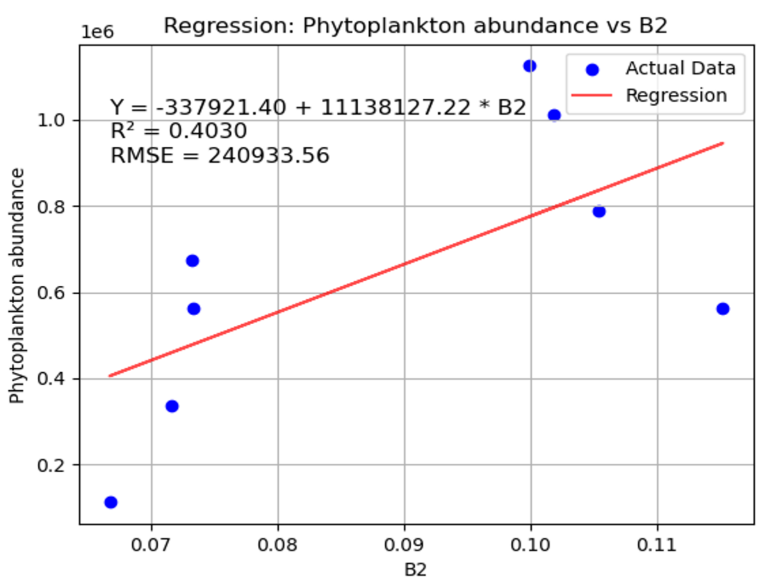

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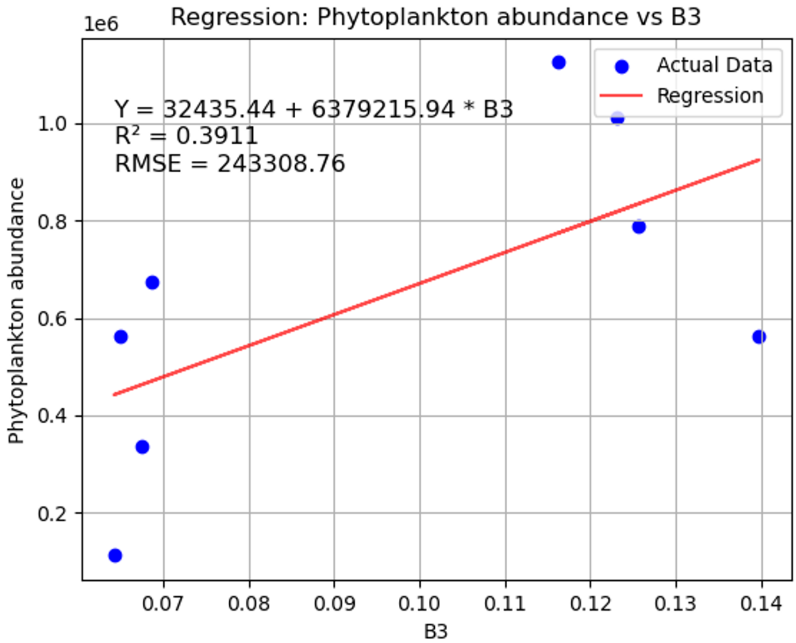

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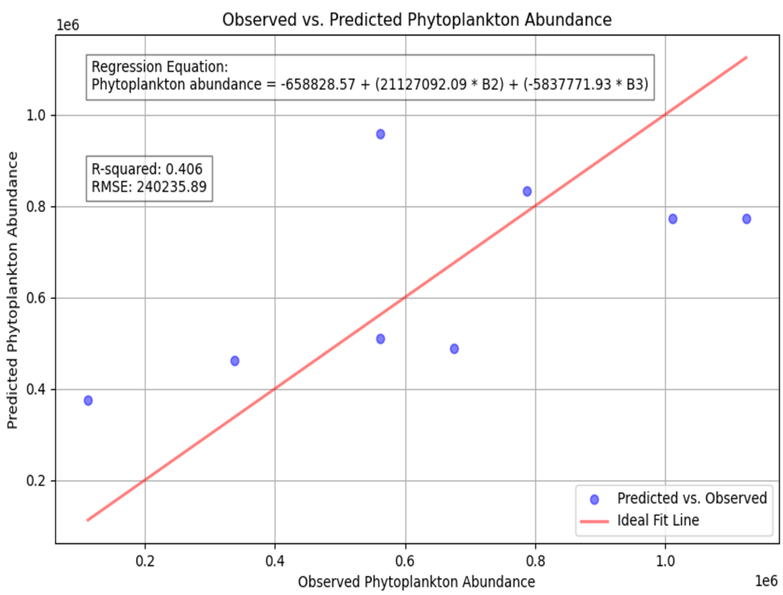

(d)

Fig. 6. (a) Correlation between sentinel-2 bands and phytoplankton abundance, (b) Band 2 vs. phytoplankton abundance regression model, (c) Band 3 vs. phytoplankton abundance regression model, (d) Multiple linear regression of spectral bands 2 and 3 of sentinel 2 on phytoplankton abundance.

4 Conclusion

This study revealed that the abundance of plankton in NWA is influenced by the physical and chemical conditions of the waters, such as temperature, salinity, pH, and dissolved oxygen content. Plankton analysis identified five main phyla: Cyanobacteria, Chlorophyta, Bacillariophyta (diatoms), Arthropoda, and Rotifera, with Bacillariophyta as the most dominant phyla. The dominance of Bacillariophyta indicates healthy and nutrient-rich NWA because diatoms tend to thrive in oligotrophic environments. It makes plankton, especially Bacillariophyta, an effective bioindicator for assessing water quality. However, discovering Cyanobacteria in the Waters of Nasi Island, indicates the potential for local eutrophication. The presence of excessive Cyanobacteria can be an indicator of ecosystem imbalance, leading to eutrophic conditions. The abundance of phytoplankton along the NWA coastline shows spatial variation. Lampulo waters (Banda Aceh) have the highest phytoplankton abundance compared to other areas. This is likely influenced by nutrient input from the River and activities around the fishing port. Human activities are important in influencing variations in phytoplankton abundance in the area so that plankton can be used as a bioindicator. The study also demonstrated the potential of Sentinel-2 remote sensing data for phytoplankton abundance analysis. The moderate correlation between the blue-green spectrum (Band 2 and Band 3) and phytoplankton biomass indicates that monitoring seawater quality can be real-time and efficient through remote sensing. These findings provide a basis for improved monitoring of seawater quality, which is useful for marine resource management.

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