



# Hydrographic Relationships and Nutrient Dynamics in Coastal Waters of Pulau Tuan, Aceh Besar, Indonesia

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## Abstract

This study aimed to examine the relationship between temperature, salinity, and water mass circulation, determine the trophic status of the waters based on chlorophyll-a concentrations, and analyze nitrate and phosphate levels using spectrophotometry. Water sampling was conducted during both high and low tides. Chlorophyll-a concentrations during high tide were 0.00217 mg/L (T1A01) and 0.005673 mg/L (T3A01), while during low tide, the values were 0.005045 mg/L (T1A01) and 0.002907 mg/L (T3A01). Nitrate concentrations at high tide were 730 µg/L (T1A01) and 875 µg/L (T3A01), increasing to 840 µg/L and 862 µg/L during low tide. Phosphate levels were 58.53 µg/L (T1A01) and 61.35 µg/L (T3A01) during high tide, and 65.75 µg/L and 68.85 µg/L during low tide, respectively. The results indicate temporal and spatial variations in nutrient concentrations and primary productivity indicators, reflecting the dynamic characteristics of coastal waters.

**Keywords:** Chlorophyll-a, Spectrophotometry, Nitrate, Phosphate, Water Rirculation.

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## 1 Introduction

Aquatic ecosystems play a crucial role in maintaining the balance of life on Earth, harboring a diverse array of organisms ranging from microscopic life forms to larger species. Among these organisms, plankton, a term encompassing various microscopic life forms, plays an essential role in aquatic productivity and the overall health of marine environments. Plankton consists of two primary categories as (a) phytoplankton, which are plant-like organisms capable of photosynthesis, and (b) zooplankton, which are microscopic animals that drift in the water column and feed on phytoplankton and other organic matter [1,2]. As primary producers in aquatic food webs, phytoplankton are fundamental to the generation of dissolved oxygen, while zooplankton act as secondary consumers and serve as an important food source for the larval stages of many aquatic organisms [3].

Chlorophyll, derived from the Greek words chloros (green) and phyllon (leaf), is a pigment found in phytoplankton that captures sunlight for photosynthesis, enabling the production of glucose and the release of oxygen as a byproduct. The chemical formula of chlorophyll is  $C_{55}H_{72}O_5N_4Mg$  with magnesium serving as the central atom [4]. Chlorophyll-a, in particular, is a key indicator of primary productivity in marine environments, as its concentration closely correlates with various oceanographic and physicochemical parameters,

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53 including light intensity and nutrient availability,  
54 especially nitrates and phosphates [5,6]. Variations  
55 in these parameters directly influence phytoplankton  
56 productivity and, consequently, shape the ecological  
57 dynamics of marine ecosystems [7].

58 Nitrate ( $\text{NO}_3^-$ ) is a stable nitrogen compound  
59 essential for protein synthesis in both plant and  
60 animal life. Although nitrates are necessary for  
61 growth, elevated concentrations can stimulate  
62 excessive algal blooms, potentially leading to hypoxic  
63 conditions in water bodies and causing severe  
64 impacts on aquatic organisms, including fish [8].  
65 Under natural conditions, nitrate concentrations  
66 in aquatic systems are typically low; however,  
67 agricultural activities involving fertilizer application  
68 can substantially increase these levels, contributing to  
69 nutrient pollution [9]. Similarly, phosphates are vital  
70 nutrients that regulate the growth and development of  
71 aquatic organisms, with their availability influenced  
72 by complex biogeochemical interactions within  
73 the ecosystem [10]. The relationship between  
74 phytoplankton abundance and nutrient concentrations  
75 underscores the delicate balance required to maintain  
76 healthy aquatic ecosystems, as these nutrients can  
77 sustain productivity or disrupt ecological stability  
78 when present in excessive amounts [9,11].

79 Therefore, understanding the dynamics of plankton  
80 and the roles of chlorophyll, nitrates, and phosphates  
81 is essential to elucidate nutrient interactions in aquatic  
82 ecosystems. Continued research on these processes  
83 will enhance our understanding of aquatic chemistry  
84 and support sustainable management strategies that  
85 aim to preserve the health of marine environments  
86 [12,13].

## 87 2 Methodology

### 88 2.1 Study Area and Sampling Design

89 This study was conducted in the coastal  
90 conservation zone of Pulau Tuan, Ujung Pancu,  
91 Peukan Bada District, Aceh Besar, Indonesia  
92 ( $5^\circ 33' - 5^\circ 35' \text{ N}$ ,  $95^\circ 14' - 95^\circ 16' \text{ E}$ ) (Figure 1). The  
93 site was selected due to its ecological significance  
94 and relatively undisturbed environmental condition,  
95 providing a representative setting for assessing natural  
96 variability in coastal water quality and associated  
97 biological parameters. Sampling was carried out  
98 at four stations (T1–T4) arranged linearly along  
99 the coastline to capture spatial heterogeneity in  
100 hydrological and biological characteristics. Each  
101 station comprised three sub-stations (A–C) positioned

horizontally at 100 m intervals to ensure adequate  
spatial coverage.

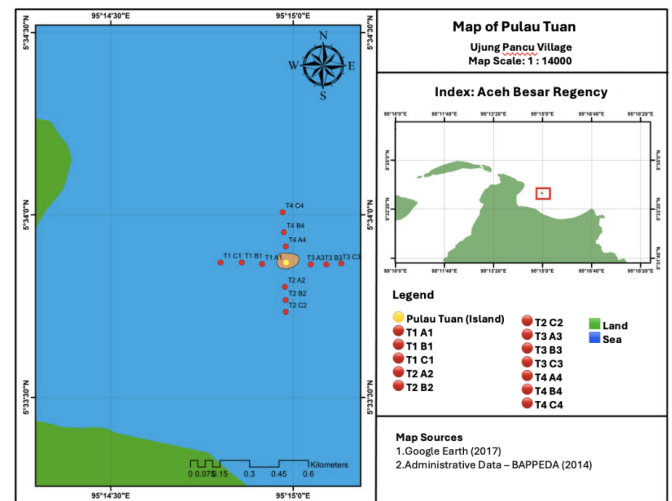


Figure 1. Study area.

104 On the other hand, field sampling was conducted  
105 under high- and low-tide conditions to evaluate  
106 the influence of tidal dynamics on physicochemical  
107 properties and biological communities. At each  
108 sub-station, vertical profiling was performed,  
109 and water samples were collected from three  
110 depth strata (surface, mid-water, and bottom)  
111 using a pre-cleaned water sampler. In total, 24  
112 experimental units (4 stations  $\times$  3 sub-stations  $\times$  2  
113 tidal conditions) were established. Replicate samples  
114 were collected to enhance analytical precision and  
115 ensure reproducibility of laboratory measurements.

### 116 2.2 Plankton Sampling and Identification

117 At each sub-station, 5 L of seawater were collected and  
118 filtered through a plankton net with a mesh size of  
119 20–50  $\mu\text{m}$ . The sampling procedure was repeated ten  
120 times per sub-station to ensure representative coverage  
121 of plankton communities throughout the water  
122 column. The concentrated plankton samples were  
123 subsequently transferred into 100 mL polyethylene  
124 bottles for laboratory analysis. In the laboratory, a  
125 drop of each sample was placed on a clean glass  
126 slide, covered with a coverslip, and examined under a  
127 compound light microscope at magnifications of 100 $\times$   
128 to 400 $\times$ . Observations were performed in triplicate  
129 to minimize random error and enhance identification  
130 accuracy. Plankton taxa were identified using standard  
131 marine plankton taxonomic references [20]. Plankton  
132 abundance was quantified using standard volumetric  
133 methods and expressed as individuals per liter  
134 ( $\text{ind L}^{-1}$ ) to determine population density and relative



135 species dominance.

### 136 2.3 Chlorophyll-a Analysis

137 For chlorophyll-a analysis, 500 mL seawater samples  
 138 were collected from three depth strata—surface,  
 139 mid-water column, and near-bottom, using Niskin  
 140 bottles or equivalent pre-cleaned containers. The  
 141 samples were immediately filtered through Whatman  
 142 GF/C glass fiber filters using a vacuum filtration  
 143 system. The filters were wrapped in aluminum  
 144 foil to prevent photodegradation and stored at 4  
 145 °C in darkness for 24 h prior to pigment extraction.  
 146 Chlorophyll-a was extracted using 90% acetone, and  
 147 the absorbance of the extracts was measured with a  
 148 UV-Visible spectrophotometer at wavelengths of 665  
 149 nm, 645 nm, and 630 nm, with turbidity correction  
 150 at 750 nm. Chlorophyll-a concentration ( $\text{mg L}^{-1}$ )  
 151 was calculated according to the equation described  
 152 in [10]. This method provides a reliable estimate of  
 153 phytoplankton biomass and serves as an indicator of  
 154 primary productivity within the water column.

$$\text{Chl-a} = 11.85(A_{665} - A_{750}) - 1.54(A_{645} - A_{750}) + 0.08(A_{630} - A_{750}) \quad (1)$$

### 155 2.4 Nitrate and Phosphate Determination

156 The same seawater samples collected for chlorophyll-a  
 157 analysis were also used for the determination of  
 158 nitrate ( $\text{NO}_3^-$ ) and phosphate ( $\text{PO}_4^{3-}$ ) concentrations.  
 159 Samples were stored in acid-washed polyethylene  
 160 bottles, maintained under cool and dark conditions,  
 161 and transported promptly to the Faculty of Agriculture  
 162 Laboratory, Universitas Syiah Kuala, for analysis.  
 163 Nutrient analyses were conducted in accordance with  
 164 the Standard Methods for the Examination of Water  
 165 and Wastewater [20]. Nitrate concentrations were  
 166 determined using the cadmium reduction method,  
 167 whereas phosphate concentrations were measured  
 168 using the ascorbic acid method. Absorbance was  
 169 measured using a UV-Visible spectrophotometer at  
 170 880 nm. Nutrient concentrations were expressed as  
 171  $\mu\text{g L}^{-1}$ .

## 172 3 Results

### 173 3.1 Plankton Abundance

174 Plankton sampling conducted under both high- and  
 175 low-tide conditions across the four sampling stations  
 176 (T1–T4) revealed measurable variations in species  
 177 composition and abundance. A total of six species  
 178 were identified during low tide, whereas seven species

179 were recorded during high tide, indicating a slight  
 180 increase in species richness under high-tide conditions.  
 181 Species distribution varied among stations; however,  
 182 *Pseudo-nitzschia subfraudulenta* consistently exhibited  
 183 the highest abundance under both tidal regimes.  
 184 The maximum abundance was recorded during low  
 185 tide, reaching  $896.439 \text{ ind L}^{-1}$ , suggesting favorable  
 186 environmental conditions for its proliferation during  
 187 reduced tidal mixing. The persistence of this species  
 188 across all stations indicates its strong ecological  
 189 adaptability within the study area. Overall, tidal  
 190 dynamics appeared to influence both species richness  
 191 and community structure, with high tide contributing  
 192 to slightly increased diversity, possibly due to  
 193 enhanced water exchange and nutrient redistribution.  
 194 In contrast, the higher dominance observed during low  
 195 tide may reflect localized retention effects and reduced  
 196 hydrodynamic dispersion.

**Table 1.** Plankton abundance during low and high tide conditions.

No	Species	Low Tide ( $\text{ind L}^{-1}$ )	High Tide ( $\text{ind L}^{-1}$ )
1	<i>Pseudo-nitzschia subfraudulenta</i>	896.439	424.629
2	<i>Rhizosolenia curvata</i>	660.534	47.812
3	<i>Dactyliosolen blavyanus</i>	141.543	–
4	<i>Toxarium undulatum</i>	–	141.543
5	<i>Rhizosolenia antennata</i>	–	141.543
6	<i>Rhizosolenia sima</i>	–	94.362
7	<i>Hemialus hauckii</i>	47.183	47.181
8	<i>Navicula distans</i>	47.189	–
9	<i>Branchionus calyciflorus amphiceros</i>	47.181	–
<b>Total Identified Species</b>		<b>6</b>	<b>7</b>

### 197 3.2 Chlorophyll-a Concentration

198 Chlorophyll-a concentrations were determined at two  
 199 representative sampling stations (T1A01 and T3A01)  
 200 under both high- and low-tide conditions using  
 201 spectrophotometric analysis at wavelengths of 630,  
 202 645, and 665 nm, with turbidity correction applied at  
 203 750 nm. The measured chlorophyll-a concentrations  
 204 ranged from 0.00217 to  $0.005673 \text{ mg L}^{-1}$  across  
 205 the sampling sites. Spatial variation was observed  
 206 between stations, with higher chlorophyll-a levels  
 207 generally recorded at T3A01 compared to T1A01.  
 208 The maximum concentration ( $0.005673 \text{ mg L}^{-1}$ )  
 209 was detected at T3A01 during high tide, indicating  
 210 enhanced phytoplankton biomass under increased  
 211 tidal exchange. In contrast, lower concentrations  
 212 were observed at T1A01, suggesting comparatively  
 213 reduced phytoplankton productivity or differences in  
 214 local hydrodynamic conditions. Temporal differences  
 215 between tidal phases were also evident, with  
 216 chlorophyll-a concentrations tending to increase  
 217 during high tide. This pattern may reflect improved  
 218 nutrient replenishment and mixing processes

219 associated with tidal inflow, which can stimulate  
 220 phytoplankton growth. Overall, the recorded  
 221 concentrations indicate relatively low to moderate  
 222 phytoplankton biomass within the study area,  
 223 consistent with coastal waters influenced by natural  
 224 tidal dynamics rather than anthropogenic nutrient  
 225 enrichment.

**Table 2.** Chlorophyll-a concentration under different tidal conditions.

Tidal Condition	Station	Chlorophyll-a ( $\text{mg L}^{-1}$ )
High Tide	T1A01	0.002176
High Tide	T3A01	0.005673
Low Tide	T1A01	0.005045
Low Tide	T3A01	0.002907

### 226 3.3 Nitrate and Phosphate Concentrations

227 Nutrient analysis was conducted on a total of 24  
 228 water samples, comprising 12 samples collected during  
 229 high tide and 12 during low tide across stations  
 230 T1–T4. Detectable concentrations of both nitrate  
 231 and phosphate were observed under all sampling  
 232 conditions, indicating consistent nutrient availability  
 233 within the study area. Nitrate concentrations ranged  
 234 from 710 to 875  $\mu\text{g L}^{-1}$  during high tide and from 753  
 235 to 862  $\mu\text{g L}^{-1}$  during low tide. Although the overall  
 236 ranges between tidal conditions were comparable,  
 237 slightly elevated maximum values were recorded  
 238 during high tide, suggesting enhanced nutrient influx  
 239 or mixing associated with tidal exchange. The  
 240 relatively narrow variation between tidal phases  
 241 indicates that nitrate distribution in the area may be  
 242 influenced by both tidal advection and local retention  
 243 processes.

**Table 3.** Maximum and minimum nitrate and phosphate concentrations under different tidal conditions at Station T3A01.

Tidal Condition	Station	Max Nitrate ( $\mu\text{g L}^{-1}$ )	Min Nitrate ( $\mu\text{g L}^{-1}$ )	Max Phosphate ( $\mu\text{g L}^{-1}$ )	Min Phosphate ( $\mu\text{g L}^{-1}$ )
High Tide	T3A01	875	710	61.35	58.15
Low Tide	T3A01	862	753	68.85	65.32

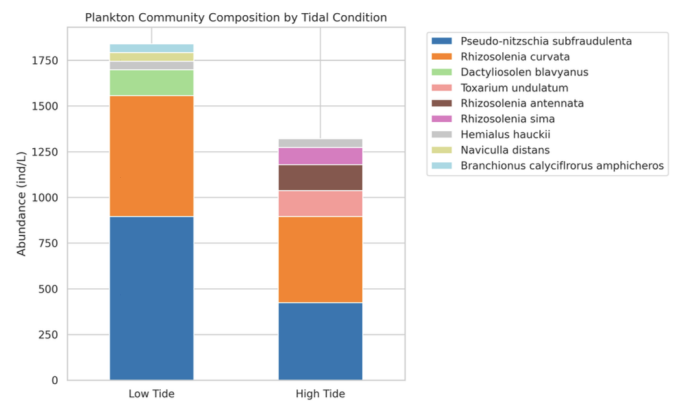
244 Phosphate concentrations were consistently elevated  
 245 across all stations and tidal conditions, ranging from  
 246 58.15 to 68.85  $\mu\text{g L}^{-1}$ . The uniformly high phosphate  
 247 levels suggest substantial nutrient loading in the  
 248 coastal system. Such concentrations may reflect natural  
 249 nutrient inputs from surrounding waters, sediment  
 250 resuspension, or land-based runoff. The persistence  
 251 of elevated phosphate concentrations under both  
 252 tidal regimes indicates that tidal fluctuation alone  
 253 does not significantly reduce nutrient accumulation  
 254 within the system. Overall, the observed nitrate and

phosphate levels indicate moderate to high nutrient  
 availability, which may support phytoplankton growth  
 and influence primary productivity patterns in the  
 study area.

## 259 4 Discussion

### 260 4.1 Variation of Plankton Abundances

261 The marked variation in plankton abundance between  
 262 high- and low-tide conditions demonstrates the  
 263 strong coupling between tidal hydrodynamics and  
 264 biological processes in shallow coastal systems. The  
 265 dominance of *Pseudo-nitzschia subfraudulenta* under  
 266 both tidal states, particularly during low tide (896.439  
 267  $\text{ind L}^{-1}$ )—indicates a clear ecological advantage under  
 268 reduced hydrodynamic disturbance. Such dominance  
 269 may be attributed to species-specific physiological  
 270 traits, including efficient nutrient uptake kinetics, rapid  
 271 growth rates, and tolerance to fluctuating salinity and  
 272 light conditions (Figure 2).



**Figure 2.** Plankton Abundances

273 Tidal oscillations play a central role in regulating  
 274 vertical mixing, sediment resuspension, nutrient  
 275 redistribution, and light penetration. During low  
 276 tide, reduced water depth and weaker mixing  
 277 likely promote the retention and concentration of  
 278 plankton within the photic layer, thereby enhancing  
 279 photosynthetic potential. Conversely, high tide  
 280 may introduce offshore water masses and increase  
 281 vertical exchange, potentially diluting resident  
 282 plankton populations or altering nutrient ratios  
 283 [14]. The observed decline in total plankton  
 284 abundance during high tide is therefore consistent  
 285 with physical dilution effects and hydrodynamic  
 286 dispersion. Interestingly, although species richness  
 287 was slightly higher during high tide (seven species)  
 288 compared to low tide (six species), this increase  
 289 did not translate into greater biomass. This finding  
 290 underscores the well-established ecological principle



291 that biodiversity and productivity are not necessarily  
 292 positively correlated, particularly in transitional or  
 293 hydrodynamically variable environments [15]. In  
 294 such systems, dominance by a few opportunistic taxa  
 295 may contribute more substantially to total biomass  
 296 than overall species richness.

297 **4.2 Limitations of Chlorophyll-a as a Productivity**  
 298 **Indicator**

299 Chlorophyll-a concentrations recorded in this  
 300 study were relatively low (0.002176–0.005673  
 301 mg L<sup>-1</sup>), falling within the oligotrophic range (<0.01  
 302 mg L<sup>-1</sup>). This observation appears inconsistent  
 303 with the relatively elevated nitrate and phosphate  
 304 concentrations and thus warrants further ecological  
 305 interpretation (Figure 3).

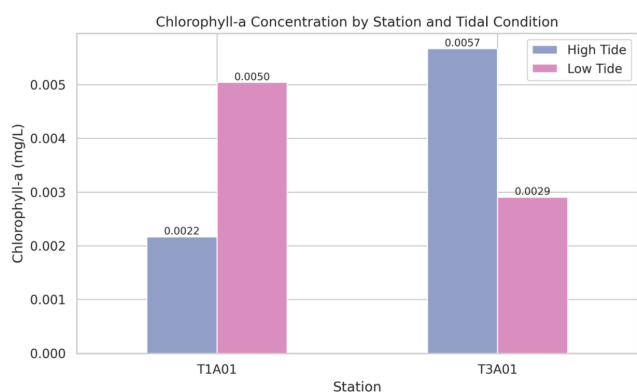


Figure 3. Chlorophyll-a concentrations across all samples.

306 Although chlorophyll-a is widely used as a proxy for  
 307 phytoplankton biomass, several limitations constrain  
 308 its reliability as a sole productivity indicator [16].  
 309 First, chlorophyll content per cell is highly variable  
 310 and influenced by species composition, physiological  
 311 condition, nutrient availability, and light regime.  
 312 Diatom taxa such as *Pseudo-nitzschia* may exhibit  
 313 relatively low chlorophyll content per unit biomass  
 314 under certain environmental conditions, particularly  
 315 when acclimated to fluctuating light or nutrient  
 316 regimes. Second, shallow coastal systems are often  
 317 subject to sediment resuspension and increased  
 318 turbidity during tidal transitions, which can reduce  
 319 light availability and induce photophysiological stress.  
 320 Under such conditions, phytoplankton may adjust  
 321 pigment composition or reduce chlorophyll synthesis  
 322 despite sufficient nutrient supply [17]. Consequently,  
 323 chlorophyll-a measurements may underestimate  
 324 actual carbon fixation or cell abundance in turbid  
 325 coastal environments.

326 Furthermore, top-down controls may also contribute

to the observed discrepancy. Grazing pressure from  
 microzooplankton or mesozooplankton—parameters  
 not quantified in this study—can substantially reduce  
 phytoplankton standing stock despite continuous  
 nutrient inputs [18]. This trophic regulation  
 may partially explain the apparent decoupling  
 between nutrient availability and chlorophyll-based  
 biomass estimates. Collectively, these findings  
 highlight that chlorophyll-a alone may not fully  
 capture ecosystem productivity in dynamic coastal  
 systems. Future investigations should integrate  
 nutrient stoichiometry (e.g., N:P ratios), grazing  
 assessments, and physiological measurements such  
 as maximum quantum yield (Fv/Fm) to obtain a  
 more comprehensive understanding of phytoplankton  
 productivity under tidal influence.

343 **4.3 Nutrient Enrichment, Potential Eutrophication,**  
 344 **and Management Implications**

345 The persistent presence of elevated nitrate  
 346 (710–875 μg L<sup>-1</sup>) and phosphate (58.15–68.85  
 347 μg L<sup>-1</sup>) concentrations across both tidal phases  
 348 indicates a nutrient-enriched coastal system. These  
 349 concentrations likely reflect a combination of natural  
 350 sedimentary nutrient fluxes and diffuse anthropogenic  
 351 inputs, including surface runoff and agricultural  
 352 leaching [19]. Notably, phosphate concentrations  
 353 exceeding 0.051 mg L<sup>-1</sup> (51 μg L<sup>-1</sup>) are commonly  
 354 associated with eutrophic conditions. All recorded  
 355 phosphate values in this study surpassed this  
 356 threshold, with several approaching 70 μg L<sup>-1</sup>,  
 357 suggesting that the waters surrounding Pulau Tuan  
 358 are chemically fertile despite the relatively low  
 359 chlorophyll-a concentrations observed (Figure 4).

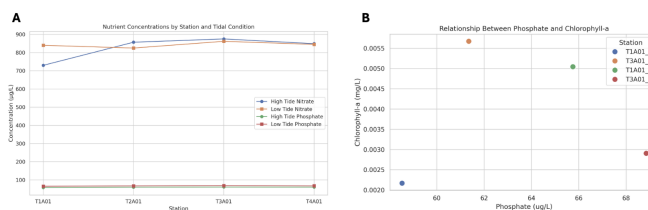


Figure 4. Nutrient Enrichment based on (a) Nutrient concentration and (b) Phosphate and chlorophyll-a relationship.

360 The apparent decoupling between high nutrient  
 361 availability and low phytoplankton biomass suggests  
 362 that biological productivity in the system is regulated  
 363 by additional constraints beyond macronutrient  
 364 supply. Potential mechanisms include internal  
 365 nutrient cycling processes (e.g., redox-driven  
 366 sediment release and benthic uptake), stoichiometric

367 imbalances in N:P ratios, and biological limitations  
368 such as micronutrient deficiency. In shallow,  
369 tidally influenced coastal systems, hydrodynamic  
370 variability can also suppress biomass accumulation by  
371 enhancing dispersion and limiting stable stratification,  
372 thereby preventing sustained phytoplankton  
373 blooms. Of particular ecological concern is the  
374 dominance of *Pseudo-nitzschia*, a genus that includes  
375 toxin-producing species capable of synthesizing  
376 domoic acid. Although toxin production was not  
377 evaluated in this study, the consistent dominance  
378 of potentially harmful taxa may represent an early  
379 ecological warning signal [20]. In nutrient-enriched  
380 environments, relatively minor environmental shifts,  
381 such as prolonged stratification, reduced flushing,  
382 or increased temperature, can rapidly convert latent  
383 nutrient accumulation into active bloom development,  
384 including harmful algal blooms (HABs).

385 Collectively, the data characterize the coastal  
386 waters of Pulau Tuan as a chemically fertile yet  
387 biologically moderated system. This condition may  
388 represent a transitional ecological state, in which  
389 tidal mixing currently buffers against excessive  
390 biomass accumulation but allows progressive nutrient  
391 storage. Under future climate-related stressors, such  
392 as intensified rainfall, altered runoff regimes, sea-level  
393 rise, or enhanced thermal stratification, this latent  
394 nutrient pool could increase the risk of episodic  
395 eutrophication events. Based on a management  
396 perspective, the sensitivity of nutrient dynamics and  
397 plankton structure to tidal variability underscores  
398 the need for temporally stratified monitoring  
399 programs rather than single-point assessments.  
400 Incorporating tidal-phase sampling, HAB surveillance,  
401 and integrated bioindicator measurements (e.g.,  
402 chlorophyll-a, community composition, and nutrient  
403 stoichiometry) would provide a more robust  
404 framework for detecting early signs of ecosystem  
405 imbalance. Such integrated monitoring is essential for  
406 guiding adaptive nutrient management strategies and  
407 safeguarding coastal ecosystem resilience in the face  
408 of increasing anthropogenic and climatic pressures.

## 409 5 Conclusion

410 This study provides an integrated assessment of  
411 the physicochemical and biological characteristics of  
412 the coastal waters surrounding Pulau Tuan, Ujung  
413 Pancu. The results demonstrate clear spatial and  
414 tidal variability in plankton abundance, chlorophyll-a  
415 concentration, and nutrient dynamics. Plankton  
416 analysis identified *Pseudo-nitzschia subfraudulenta* as

the dominant taxon under both high- and low-tide 417  
conditions, with peak abundance occurring during 418  
low tide. This pattern underscores the significant 419  
role of tidal hydrodynamics in shaping plankton 420  
distribution through mechanisms such as vertical 421  
mixing, nutrient redistribution, and light availability. 422  
The higher abundance observed during low tide 423  
suggests enhanced retention and concentration within 424  
the photic zone under reduced mixing intensity. 425

Despite relatively elevated nitrate and phosphate 426  
concentrations, exceeding thresholds commonly 427  
associated with eutrophic systems, chlorophyll-a 428  
concentrations remained consistently low ( $<0.006$  429  
 $\text{mg L}^{-1}$ ), falling within oligotrophic ranges. This 430  
decoupling between nutrient availability and 431  
phytoplankton biomass indicates that additional 432  
regulatory mechanisms, including light limitation, 433  
grazing pressure, or species-specific pigment 434  
variability, may constrain primary productivity. The 435  
system therefore appears chemically enriched but 436  
biologically moderated. 437

Collectively, the findings suggest that the coastal 438  
waters of Pulau Tuan represent a dynamically 439  
regulated ecosystem that is nutrient-fertile yet not 440  
currently exhibiting overt eutrophication symptoms. 441  
However, the persistent dominance of potentially 442  
harmful taxa and sustained nutrient accumulation 443  
highlight the ecological sensitivity of the area. Under 444  
altered hydrodynamic or climatic conditions, the 445  
system may become increasingly vulnerable to 446  
episodic bloom events. Continuous, temporally 447  
resolved monitoring incorporating additional 448  
parameters, such as turbidity, dissolved oxygen, 449  
nutrient stoichiometry, and zooplankton grazing, will 450  
be essential for improving ecosystem assessments and 451  
for anticipating potential risks, including harmful 452  
algal blooms (HABs) and progressive nutrient 453  
enrichment. 454

## 455 Data Availability Statement

Data will be made available on request. 456

## 457 Author Contributions

M.I., K.K., L.L., K.A., and S.S. contributed to the 458  
conceptualization of the study. M.I. performed the 459  
methodology, formal analysis, investigation, data 460  
curation, visualization, and preparation of the original 461  
draft. Validation was conducted by K.K., P.H.P.S., R.W., 462  
and S.S. All authors have read and approved the final 463  
version of the manuscript. 464



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## Conflicts of Interest

The authors declare no conflicts of interest.

## Ethical Approval and Consent to Participate

Not applicable.

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