

Phytoplankton Composition Indicators for the Assessment of Eutrophication at Patong Beach, Phuket

Audomlak Khongsang, Raymond James Ritchie* and Suhailar Sma-Air

ABSTRACT

Recurrent phytoplankton blooms at Patong Beach, Phuket, Thailand, a major international tourist destination, pose a potential threat to coastal ecosystems, public health, and the local tourism economy. This study monitored phytoplankton community structure, cell abundance, diversity indices, and chlorophyll *a* (Chl *a*) at five stations spanning a drainage canal and adjacent beach waters from December 2022 to September 2023. Bloom events were observed at the southern end of the beach in February and April. In February, the estuarine station was dominated by the colonial diatom *Chaetoceros socialis* (up to 99% of total abundance; 695,750 cells·L⁻¹), while the beach stations showed a strong contribution from the dinoflagellate *Peridinium quinquecorne*. In April, *C. socialis* dominated all marine stations, coinciding with sharp reductions in species diversity and Chl *a* concentrations approaching 100 µg·L⁻¹. Blooms were not observed in the drainage canal during the study period, despite its strong land-based influence, suggesting that physical retention conditions in the bay, together with nutrient inputs, may be important in promoting bloom formation near the beach. Shannon–Wiener diversity (*H'*) and Margalef richness (*d*) were the most sensitive indices for detecting bloom-related community change and are recommended for routine monitoring. These findings provide a useful framework for bloom detection and risk assessment at Patong Beach and comparable tropical tourist destinations, while also highlighting the need for future studies integrating nutrient dynamics, sediment cyst surveys, and hydrodynamic observations.

Keywords: Bioindicator, Diatom, Phytoplankton, Plankton bloom, Red tide, Seasonality

INTRODUCTION

Red tide phenomena, phytoplankton blooms that occasionally occur in coastal regions worldwide, have become more frequent and intense in recent decades, raising global concerns about the impacts of land-based pollution on marine ecosystems, public health, and coastal economies reliant on tourism and fisheries. In the Phuket area, particularly at Patong Beach, a world-renowned tourist destination, red tides have been observed annually in March or April, coinciding with the end of the regional monsoon season (Wong, 1998). These blooms are often associated with eutrophication,

driven by elevated concentrations of nitrogen and phosphorus in coastal waters. Such nutrient enrichment is largely caused by anthropogenic activities, including the use of chemical fertilizers in agriculture and the discharge of treated and untreated wastewater from urban runoff, households, and industries.

Plankton bloom phenomena have been frequently reported on the west coast of Phuket, including Patong Beach, Kata Beach, and Kata Noi Beach. A change in the color of sea water is often seen after heavy rain events between January and April, which is summer or dry season of Phuket

Island. Phuket has a maritime monsoonal climate, and the dry season often has several heavy rainfall events, so the dry season in this coastal region is not as arid as it is further inland. During this period, temperature and sunlight conditions are suitable for phytoplankton growth and increased abundance in estuaries and seawater. Sea currents and wind patterns during the dry season favour the accumulation of phytoplankton in sheltered bays such as Patong Beach (Bahulayan and Unnikrishnan, 1992; Isa *et al.*, 2020). Hence, the relationship between nutrient levels and algal blooms may not always follow a simple cause-and-effect model: instead, the presence of suitable environmental conditions is also necessary. In addition, when nutrients are introduced from land through rainwater runoff, they may allow phytoplankton to grow quickly in a short time, particularly species such as *Chaetoceros socialis*, which can remain dormant in sediments and germinate quickly when conditions become favorable. Phytoplankton genera reported to cause blooms along the coast of Phuket Island between 2016–2017 included the often toxic dinoflagellates *Alexandrium* and *Gymnodinium* (Charoenvattanaporn, 2017). *Peridinium aciculiferum* is also known to produce toxins (Rengefors and Legrand, 2001). In addition, dinoflagellate genera are of concern due to their potential to cause diarrhetic shellfish poisoning (DSP). Furthermore, diatoms such as *Belleriochea* and *Chaetoceros socialis* have also been identified in bloom events (Charoenvattanaporn, 2017).

Phytoplankton are important producers in the food chain of various water bodies by converting inorganic substances into organic substances through the process of photosynthesis. Major nutrients required for phytoplankton growth include fixed nitrogen (ammonia, nitrite, nitrates, and organic N-compounds) and phosphorus. Silicate can be a rate-limiting nutrient for diatoms (Tsunogai and Watanabe, 1983). If the water body has high levels of inorganic substances such as nitrates and phosphates, phytoplankton may multiply exponentially when the water source has sufficient light and water currents and wind patterns do not encourage plankton dispersal (Bahulayan and Unnikrishnan, 1992; Isa *et al.*, 2020). Therefore,

the abundance of phytoplankton may be used to indicate the amount of inorganic substances in water sources. In addition, some phytoplankton species can be used as bioindicators of water quality. Dinoflagellate blooms may be of concern because of dinotoxins: furthermore, new dinotoxins are regularly identified, limiting the value of database files of known toxins.

This research project is part of a broader study series investigating eutrophication-related processes in Phuket Province. In the present study, we aimed to evaluate whether phytoplankton community composition, abundance, chlorophyll *a*, and selected ecological indices could be used as practical indicators of bloom development and eutrophication-related risk in the Patong Beach area. The information obtained from the study can be used to form a conceptual model for the eutrophication process in the Patong Beach area. This will help relevant agencies to understand the pattern of bloom occurrence during the year and to find ways to prevent and manage it in the future and to make appropriate health concern alerts. Because this study focused primarily on phytoplankton indicators and general water quality variables, the interpretation of bloom drivers is discussed in relation to published nutrient and circulation studies from the area. Plankton blooms, even non-toxic blooms, have a serious impact on the beach tourism industry (Wong, 1998).

MATERIALS AND METHODS

Study sites

Patong Beach is located on the west coast of Phuket Island. There are two distinct seasons in this area. The rainy season occurs between May and October, and the dry season occurs between December and April. The dry season is not as arid as areas farther inland because the area has a maritime-modified monsoon climate. The Andaman Sea currents and wind directions change from offshore during the wet season to more continental patterns during the dry season (Bahulayan and Unnikrishnan, 1992; Isa *et al.*, 2020).

This study established five sampling stations (Figure 1). Station 1 (St.1: $7^{\circ}53'09.9''\text{N}$ $98^{\circ}17'50.1''\text{E}$) was situated near the effluent pipe of the wastewater treatment plant of the Patong City Municipality wastewater treatment plant, and Station 2 (St.2: $7^{\circ}52'59.4''\text{N}$ $98^{\circ}17'36.2''\text{E}$) was located at Klong Pak Bang Bridge over the drainage canal. Station 3 (St.3: $7^{\circ}53'07.2''\text{N}$ $98^{\circ}17'13.6''\text{E}$) was located at the south end of Patong Beach, at the outlet of the drainage canal (Figures 1 and 5), while Station 4 (St.4: $7^{\circ}53'28.3''\text{N}$ $98^{\circ}17'35.2''\text{E}$) was located offshore in front of the beach, and Station 5 (St.5: $7^{\circ}54'02.5''\text{N}$ $98^{\circ}17'46.7''\text{E}$) was located on the northern side of the beach. Station 1 reflected inputs from urban runoff and treated wastewater; Station 2 represented polluted tidal brackish/freshwater conditions; Station 3 represented an estuarine tidal environment; and Stations 4 and 5 were beach locations.

Collection and investigation of phytoplankton samples

The phytoplankton samples were collected every two months from December 2022 (dry season) to September 2023 (wet season). Twenty-liter

water samples were collected from the surface at low tide between 1:00 p.m. and 5:00 p.m. and filtered through a plankton net with a $20\ \mu\text{m}$ mesh size. For identification purposes, the filtered sample was poured into a 250 mL bottle, preserved with 4% formaldehyde solution, and stored in the laboratory for microscopic analysis. The temperature, salinity, dissolved oxygen (DO), and pH of the surface water were measured using multiparameter probes (HORIBA model LAQUA act DO210 and EUTECH PC 450). Environmental data could not be measured in June due to a temporary failure of the multiparameter probes.

Phytoplankton species composition was analysed in the laboratory under a light microscope; at least five drops of each sample were examined at different magnifications ($\times 100$ and $\times 400$). Appropriate texts and protocols were used for identification (Wongrat, 2001; Wongrat and Boonyapiwat, 2003; Zar, 2014). Before phytoplankton density was analysed, the sample bottles were gently shaken to ensure even distribution. A 1 mL aliquot of each sample was pipetted into a Sedgwick-Rafter counting cell, and the phytoplankton were counted in triplicate. The average phytoplankton density

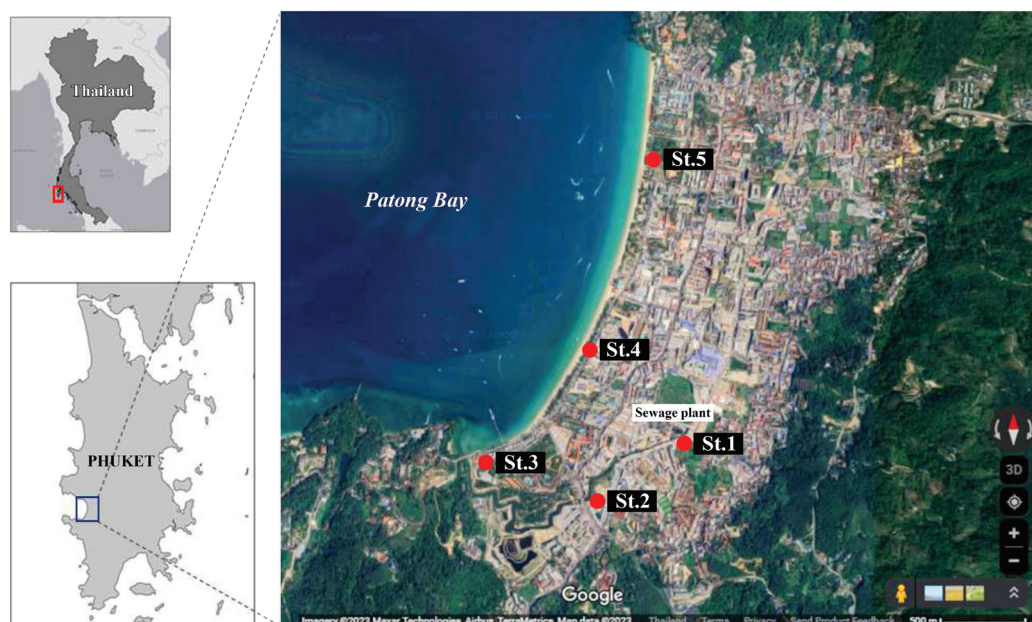


Figure 1. Locations of the five sampling stations in the Patong Beach area, Phuket Province, Thailand.

was then calculated according to the method of Wongrat and Boonyapiwat (2003) using the following formula:

$$C = NV_2 / V_1 \quad \text{Equation 1}$$

where C is the abundance of phytoplankton (number of individuals per liter), N is the number of individuals of the same taxon per mL, V_1 is the volume of water sampled (L), and V_2 is the volume of filtered water collected in the bottle (mL).

Measurements of diversity

Various indices can be used to assess the state of algal bloom development under field conditions (Pielou, 1966; Palmer, 1969; Junqueira and Campos, 1998). The Shannon–Wiener diversity index (H') (Shannon, 1948) was used to calculate the diversity of the phytoplankton community. High values of H' indicate high species diversity, whereas low values indicate lower diversity. This index was calculated as:

$$H' = -\sum_{i=1}^S P_i \ln P_i \quad \text{Equation 2}$$

where, P_i is the proportion of the entire community represented by species i and S is the total number of taxa.

Simpson's Diversity Index (D) (Simpson, 1949) was used as an alternative measure of diversity. The index ranges from 0 to 1. A value close to 1 indicates high diversity, whereas a value close to 0 indicates low diversity. A value of zero indicates that the community contains only one species, and therefore has no diversity. This index was calculated as:

$$D = 1 - \sum_{i=1}^S \left(\frac{n_i}{N} \right)^2 \quad \text{Equation 3}$$

where D is the Simpson's Diversity Index, n_i is the number of individuals belonging to species i and N is the total number of individuals in the observed sample, as described by Simpson (1949).

Measurement of species richness

Margalef's index was used as a measure of species richness (Margalef, 1958):

$$d = \frac{S - 1}{\ln N} \quad \text{Equation 4}$$

where d is Margalef's species richness index, s is the total number of species and N is the total number of individuals.

Measurement of evenness

Pielou's evenness index (J') (Pielou, 1966) was used to calculate the evenness of species distribution, indicating whether individuals were distributed equally or unevenly among taxa at the sampling sites. The evenness index differs from the diversity indices described above (Equations 2 and 3):

$$J' = \frac{H'}{\ln S} \quad \text{Equation 5}$$

where, J' is the Pielou's evenness index, H' is the Shannon diversity index and s is the total number of taxa.

Chlorophyll protocol

Water samples of varying volumes (100, 250, 500, or 1,000 mL) were collected in triplicate from all five stations, with the selected volume depending on sample clarity. Samples were filtered through 0.45 μm membrane filters (MF-Millipore, MCE Membrane, 47 mm; Merck Millipore, Tullagreen, Cork, Ireland). Chlorophyll was extracted using 3 mL of DMSO (dimethyl sulphoxide), which is a more efficient extractant than 90% acetone (Ritchie *et al.*, 2021; 2022). Chlorophyll a concentrations were calculated from the DMSO extracts and expressed $\mu\text{g}\cdot\text{L}^{-1}$ of the original water sample. Extracts were stored frozen at -20°C prior to analysis. Chlorophyll concentrations in the DMSO extracts were measured spectroscopically using a Shimadzu UV-1601 UV–visible spectrophotometer (UVProbe

2.21 software; Shimadzu Corporation, Kyoto, Japan) with a bandwidth of 1 nm. The DMSO algorithms described by Ritchie *et al.* (2021; 2022) were applied, with the absorbance at 840 nm used as the blank reference.

RESULTS

Environmental parameters

The physicochemical characteristics at all five stations are summarised in Table 1. No data were collected in June 2023 due to equipment failure. At the drainage canal stations (St.1 and St.2),

salinity was consistently low (0–4‰), confirming their freshwater and tidal freshwater characteristics, respectively. The beach stations (St.4 and St.5) were fully marine (30–32‰), while St.3 was estuarine, with salinity ranging from 2‰ to 29‰ depending on tidal and rainfall conditions (Figure 1).

Water temperature, pH, and dissolved oxygen (DO) differed significantly among stations and sampling periods (one-way ANOVA with Tukey's HSD post hoc test; Zar, 2014; Table 1). Temperature ranged from 27.73 °C (St.1, December 2022) to 36.20 °C (St.1, February 2023); Station 1 was consistently the coolest, while no significant differences were found among Stations 2–5 during

Table 1. Environmental parameters measured at five sampling stations in the Patong Beach area from December 2022 to September 2023. Values are presented as mean $\pm$ SD; different superscript letters indicate significant differences among stations within the same sampling period ($p < 0.05$). No data were available for June 2023 because of equipment failure.

Parameter	Drainage canal			Beach	
	St.1	St.2	St.3	St.4	St.5
December 2022 (Dry)					
Salinity (‰)	0	0	2	30	30
Water temperature (°C)	27.73 $\pm$ 0.12 ^a	29.43 $\pm$ 0.60 ^b	30.5 $\pm$ 1.47 ^{bc}	31.1 $\pm$ 0.95 ^{bc}	31.37 $\pm$ 0.21 ^c
pH	7.14 $\pm$ 0.02 ^a	7.14 $\pm$ 0.01 ^a	7.16 $\pm$ 0.02 ^a	8.11 $\pm$ 0.09 ^b	7.92 $\pm$ 0.03 ^b
Dissolved oxygen (mg·L ⁻¹)	2.45 $\pm$ 0.03 ^a	2.78 $\pm$ 0.02 ^a	2.12 $\pm$ 0.04 ^a	4.16 $\pm$ 0.11 ^b	4.53 $\pm$ 0.02 ^b
February 2023 (Dry)					
Salinity (‰)	0	1	29	31	32
Water temperature (°C)	36.20 $\pm$ 0.96 ^a	36.03 $\pm$ 1.84 ^a	35.13 $\pm$ 0.70 ^a	35.2 $\pm$ 0.89 ^a	36.17 $\pm$ 0.76 ^a
pH	7.27 $\pm$ 0.02 ^a	7.52 $\pm$ 0.03 ^a	8.34 $\pm$ 0.01 ^b	8.13 $\pm$ 0.03 ^b	8.17 $\pm$ 0.02 ^b
Dissolved oxygen (mg·L ⁻¹)	3.45 $\pm$ 0.03 ^a	1.37 $\pm$ 0.02 ^b	4.47 $\pm$ 0.04 ^a	4.45 $\pm$ 0.07 ^a	4.63 $\pm$ 0.02 ^a
April 2023 (End of dry)					
Salinity (‰)	2	4	15	30	31
Water temperature (°C)	32.27 $\pm$ 0.15 ^a	33.3 $\pm$ 0.46 ^a	33.93 $\pm$ 0.75 ^a	35.5 $\pm$ 0.52 ^b	35.97 $\pm$ 0.06 ^b
pH	7.41 $\pm$ 0.02 ^a	7.66 $\pm$ 0.02 ^a	7.91 $\pm$ 0.02 ^b	9.07 $\pm$ 0.02 ^c	8.49 $\pm$ 0.03 ^c
Dissolved oxygen (mg·L ⁻¹)	2.54 $\pm$ 0.02 ^a	2.42 $\pm$ 0.02 ^a	3.33 $\pm$ 0.05 ^b	5.25 $\pm$ 0.03 ^c	4.67 $\pm$ 0.02 ^c
June 2023 (Wet)					
No data (equipment failure)					
September 2023 (Wet)					
Salinity (‰)	0	0	10	30	30
Water temperature (°C)	29.13 $\pm$ 0.03 ^a	29.63 $\pm$ 0.35 ^a	30.10 $\pm$ 0.56 ^a	30.00 $\pm$ 0.17 ^a	29.90 $\pm$ 0.30 ^a
pH	7.23 $\pm$ 0.01 ^a	7.51 $\pm$ 0.05 ^a	7.90 $\pm$ 0.08 ^b	8.17 $\pm$ 0.03 ^b	8.10 $\pm$ 0.08 ^b
Dissolved oxygen (mg·L ⁻¹)	3.15 $\pm$ 0.01 ^a	3.04 $\pm$ 0.07 ^a	4.12 $\pm$ 0.02 ^b	4.51 $\pm$ 0.16 ^b	5.05 $\pm$ 0.15 ^b

Note: Mean $\pm$ SD within the same rows followed by different lowercase superscript letters are significantly different (one-way ANOVA followed by Tukey's HSD, $p < 0.05$).

most sampling periods ($F_{19,59} = 43.49$, $p = 7.5 \times 10^{-21}$). Surface water pH was lowest at the freshwater canal stations (7.14–7.51) and highest at St.4 during the April bloom (9.07 ± 0.02), where the elevated pH reflected intense photosynthetic activity ($F_{19,59} = 523$, $p = 6.3 \times 10^{-42}$). DO was severely depleted at Stations 1 and 2 (reaching a minimum of $1.37 \text{ mg} \cdot \text{L}^{-1}$ at St.2 in February), while the beach stations (St.4 and St.5) were near air saturation ($\sim 6.0 \text{ mg} \cdot \text{L}^{-1}$; Garcia and Gordon, 1992) throughout the study ($F_{19,55} = 2310$, $p = 7.9 \times 10^{-55}$).

Phytoplankton composition, abundance, and distribution

A total of 48 phytoplankton species were identified at the canal stations (St.1 and St.2; Appendix), comprising Cyanophyceae (12 species), Chlorophyceae (15), Euglenophyceae (10), Bacillariophyceae (10) and Dinophyceae (1). The estuarine and marine stations (St.3–5) supported a more diverse assemblage of 77 species, dominated by diatoms (49 species) and dinoflagellates (8 species). Species richness at

St.1 was consistently the lowest among all stations (7–14 species per sampling period), while St.4 and St.5 generally had the highest richness, peaking at St.5 in April (28 species; Figure 2). One-way ANOVA confirmed significant variation in species richness across stations and periods ($F_{24,305} = 40.36$, $p < 0.001$; Tukey's HSD MSD = 5.85 species; Zar, 2014).

Phytoplankton abundance showed a similar temporal pattern (Figure 3), with the dominant signal being bloom events in February and April at Stations 3 and 4. Following log₁₀ transformation (required by the extreme range of the data), one-way ANOVA was significant ($F_{24,74} = 9.887$, $p < 0.001$; MSR = 0.1886; overall mean = $7,536 \pm 194 \text{ cells} \cdot \text{L}^{-1}$). Of 300 possible pairwise comparisons, only six were statistically significant (Tukey's HSD, MSD = 1.383 log₁₀ units; Zar, 2014), all involving bloom stations (Table 2). Peak abundances were $695,750 \text{ cells} \cdot \text{L}^{-1}$ at St.3 in February and $688,316 \text{ cells} \cdot \text{L}^{-1}$ at St.4 in April. Station 1 maintained consistently low density throughout ($1,379$ – $7,875 \text{ cells} \cdot \text{L}^{-1}$; Figure 3).

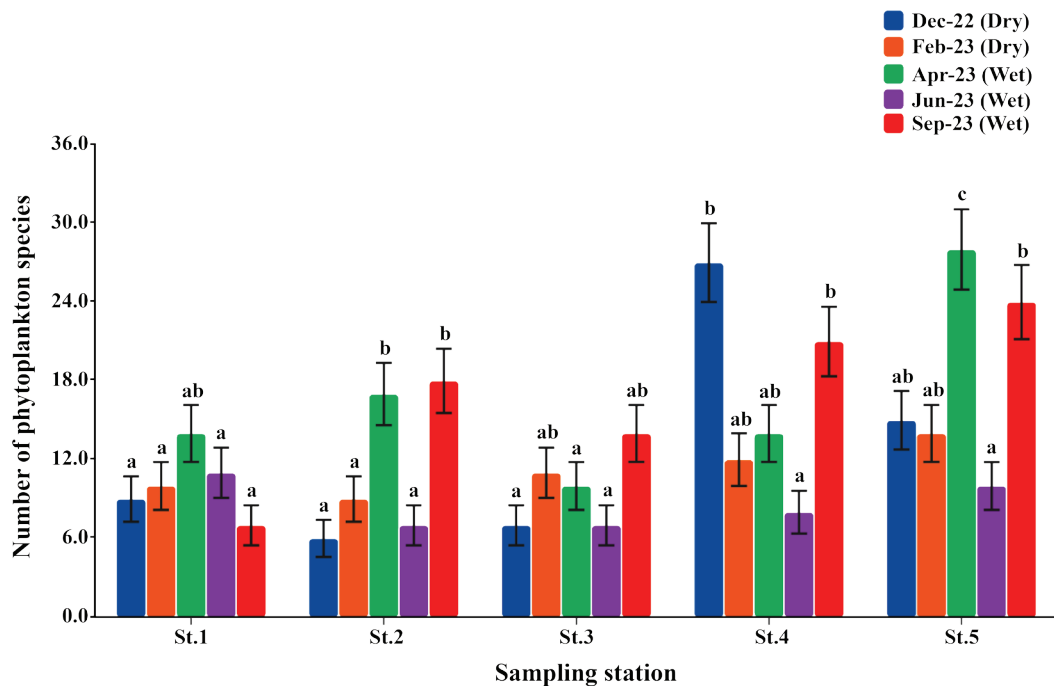


Figure 2. Bimonthly variation in phytoplankton species richness at five sampling stations in the Patong Beach from December 2022 to September 2023. Error bars represent $\pm \text{SE}$ ($n = 3$). Different lowercase letters above the bars indicate significant differences among stations within each sampling period (Tukey's HSD, MSD = 5.85 species, $p < 0.05$).

Table 2. Station–period pairs showing significant differences in phytoplankton abundance based on Tukey’s HSD following one-way ANOVA ($F_{24,74} = 9.887$, $p < 0.001$; $MSR = 0.1886$; $MSD = 1.383 \log_{10}$ units; Zar, 2014). Of the 300 possible pairwise comparisons, 294 were not significant. Significant differences were primarily associated with bloom-related station–period combinations, particularly St.3 in February 2023 and St.4 in April 2023.

	Group A (higher abundance)	n A (cells·L ⁻¹)	Group B (lower abundance)	n B (cells·L ⁻¹)	$\Delta \log_{10}$ (A–B)	Ratio (A/B)	p-value
1	Feb-23, St.3	695,750	Apr-23, St.2	34,000	+1.311	20×	< 0.05
2	Apr-23, St.4	688,316	Sep-23, St.5	13,850	+1.696	50×	< 0.05
3	Apr-23, St.3	69,825	Dec-22, St.5	2,875	+1.385	24×	< 0.05
4	Feb-23, St.4	46,664	Jun-23, St.5	1,594	+1.466	29×	< 0.05
5	Apr-23, St.5	37,875	Jun-23, St.4	1,425	+1.425	27×	< 0.05
6	Apr-23, St.2	34,000	Dec-22, St.1	1,379	+1.392	25×	< 0.05

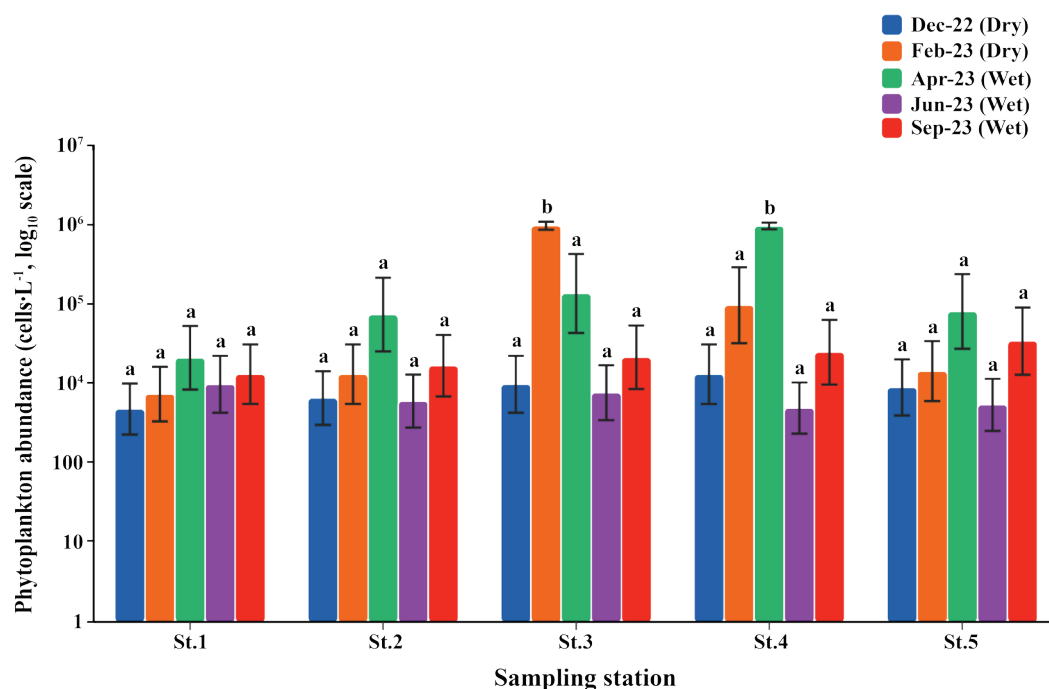


Figure 3. Bimonthly variation in phytoplankton abundance (cells·L⁻¹) at five stations at Patong Beach from December 2022 to September 2023. Values are shown on a log₁₀ scale. Error bars represent $\pm SE$ ($n = 3$). Different lowercase letters above bars indicate significant differences among station–period means based on Tukey’s HSD following one-way ANOVA ($MSD = 1.383 \log_{10}$ units, $p < 0.05$).

Dominant species during bloom events

At St.3 in February, *Chaetoceros socialis* (a marine, chain-forming diatom) comprised 99% of the total phytoplankton abundance (693,125 cells·L⁻¹). In contrast, at the beach stations (St.4 and St.5) in February, the dinoflagellate *Peridinium quinquecorne* was predominant (67% and 53%

respectively). These contrasting dominance patterns indicate that the February bloom was spatially heterogeneous across the estuarine-to-marine gradient. The occurrence of *P. quinquecorne* is notable because some dinoflagellate taxa are associated with harmful algal bloom events and shellfish-related health risks, although toxin production was not assessed in the present study.

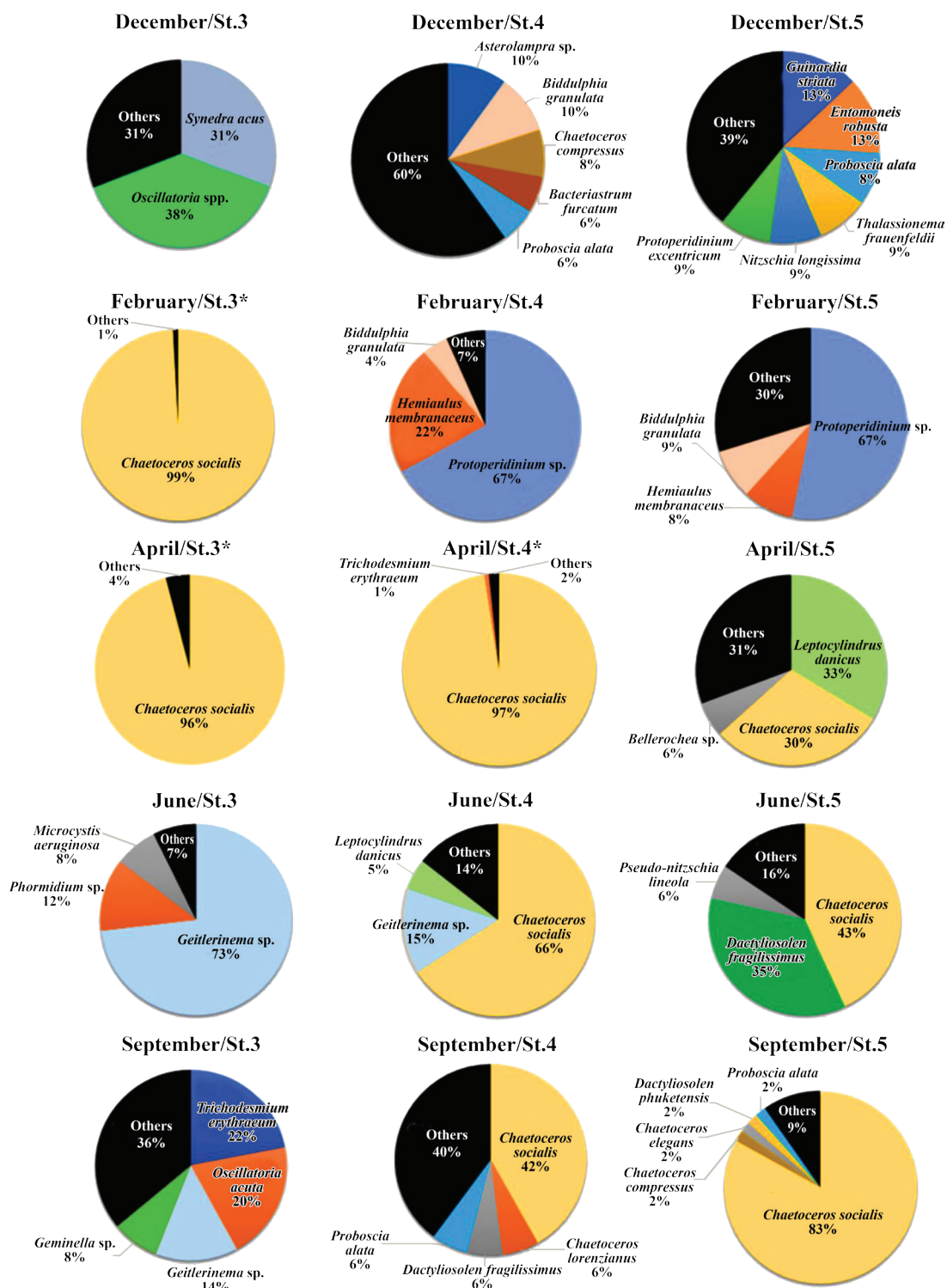


Figure 4. Proportional species composition at Stations 3, 4 and 5 at Patong Beach across the December 2022, February 2023, April 2023, June 2023, and September 2023 sampling periods. Percentages indicate the relative abundance of dominant taxa within each station and period.

In April, *C. socialis* dominated all three marine stations, comprising 96% of the total phytoplankton abundance at St.3 (69,825 cells·L⁻¹), 98% at St.4 (688,316 cells·L⁻¹) and approximately 50% at St.5, where it co-occurred with *Leptocylindrus danicus* in similar proportions. The April bloom at Stations 3–5 caused the sea to turn yellowish-brown (Figure 5). Species proportions within each station are summarised in Figure 4; all dominant species at bloom stations were significantly different from one another (Tukey's HSD, $p < 0.05$), except for *Leptocylindrus* and *Chaetoceros* at St.5 in April, which occurred in similar proportions. Light micrographs of representative species are shown in Figure 6.

Phytoplankton diversity indices

Species identification was based on Wongrat (2001) and Wongrat and Boonyapiwat (2003) as taxonomic authorities. The Shannon–Wiener diversity index (H') and Simpson's diversity index (D) were highest at St.4 in December 2022 ($H' = 3.127$; $D = 0.948$) and St.5 ($H' = 2.608$; $D = 0.919$), reflecting the calm, low-turbulence conditions of the dry season that favour diverse buoyant assemblages (Zhou *et al.*, 2015). Both indices were sharply depressed during bloom events. At St.3 in February, H' fell to 0.033 and D to 0.008, indicating near-monospecific dominance by *C. socialis*. A similarly severe decline was recorded at St.4 in

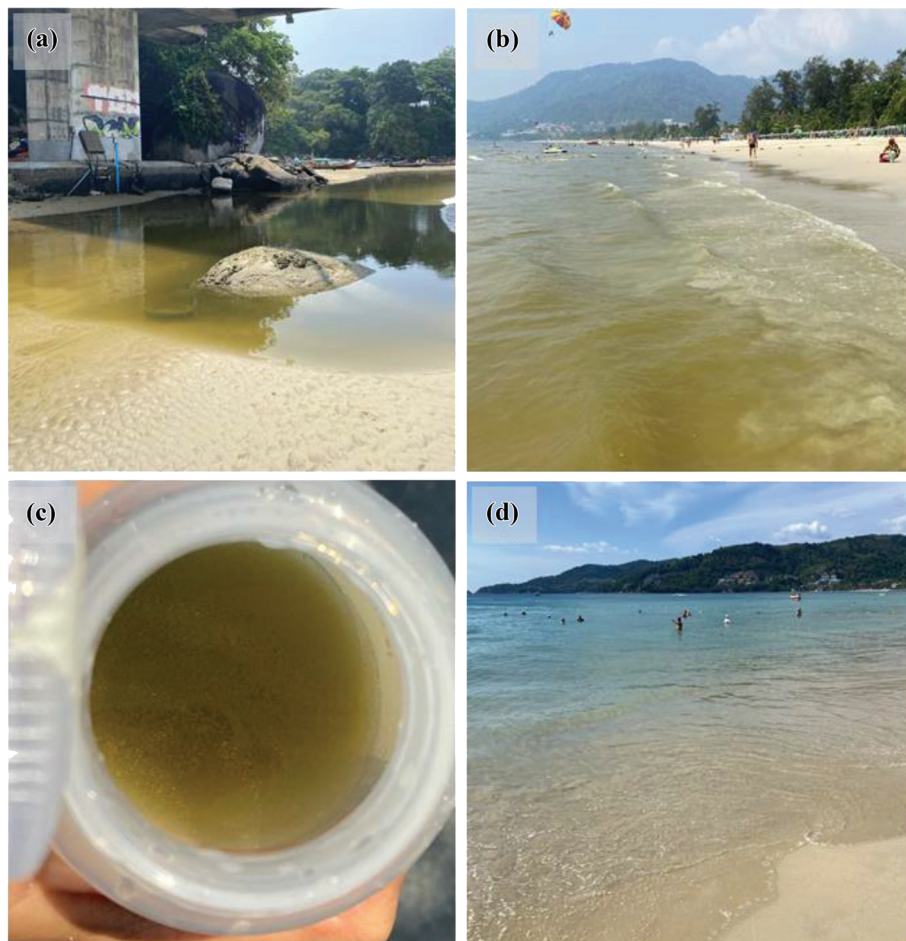


Figure 5. Plankton bloom event at Patong Beach in April 2023, dominated by *Chaetoceros socialis*: a) Station 3, b) Station 4, c) yellowish-brown seawater discolouration, and d) Station 5.

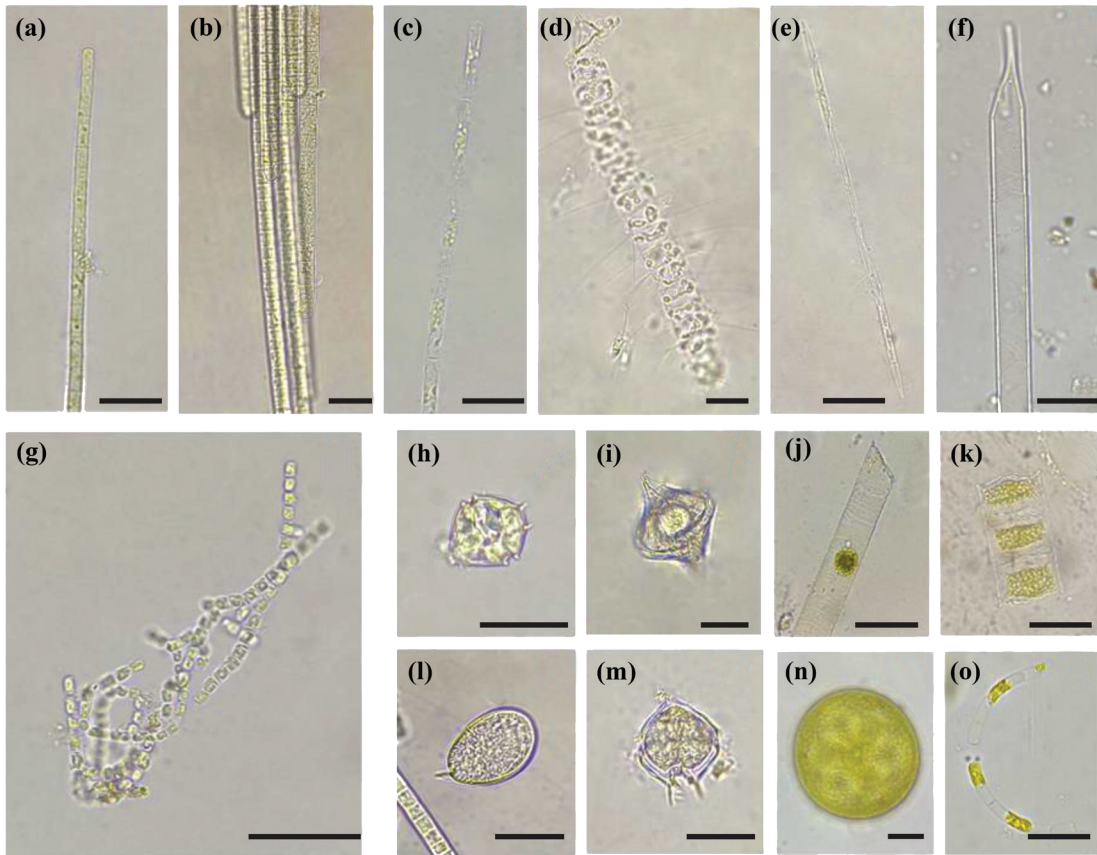


Figure 6. Light micrographs of a. *Oscillaria* sp. (species uncertain); b. *Trichodesmium erythraeum*; c. *Leptocylindrus danicus*; d. *Chaetoceros compressus*; e. *Pseudo-nitzschia* sp. (species uncertain); f. *Proboscia alata*; g. *Chaetoceros socialis*; h. *Peridinium quinquecorne*; i. *Protoperidinium divergens*; j. *Rhizosolenia striata*; k. *Bellerophoea* sp.; l. *Prorocentrum compressum*; m. *Protoperidinium* sp.; n. *Coscinodiscus radiatus*; o. *Guinardia striata*, Scale bar = 20 μ m.

April ($H' = 0.149$; $D = 0.044$). One-way ANOVA confirmed significant temporal variation in both H' and D at St.3 and 4 ($p < 0.02$; Table 3), but not at the canal stations (St.1 and 2).

Pielou's evenness (J') showed a similar pattern of bloom-driven depression, reaching 0.014 at St.3 in February and 0.057 at St.4 in April, but temporal variation was statistically significant only at those two stations. Margalef's richness (d) peaked at St.4 in December 2022 ($d = 3.230$; 27 taxa) and reached its minimum at St.3 in February ($d = 0.743$; 11 taxa); significant temporal variation

was detected at St.4 and 5 ($p < 0.05$; Table 3), but not at St.3 or the canal stations.

Analysis of diversity indices

H' and D were strongly correlated ($r = 0.952$, $p < 0.001$) and both were strongly correlated with J' ($H' \& J'$: $r = 0.908$; $D \& J'$: $r = 0.967$; both $p < 0.001$), indicating that these three indices largely reflect the same community property: the degree of dominance by one or a few species. The Margalef richness index (d) showed weaker correlations with H' ($r = 0.664$, $p < 0.001$) and D ($r = 0.454$, $p =$

0.022), whereas J' and d were not significantly correlated ($r = 0.325$, $p = 0.113$), confirming that d independently captures species richness rather than the evenness of distribution.

At the canal stations (St.1 and 2), none of the four indices showed significant temporal

variation, consistent with the stable freshwater environment under strong land-based influence, which maintained a low-diversity community throughout the year (Table 1). In contrast, H' , D , and d varied significantly at the estuarine and beach stations (St.3–5), with the largest changes driven by the *C. socialis* bloom events in February and

Table 3. Phytoplankton diversity indices at five sampling stations in the Patong Beach area from December 2022 to September 2023. H' = Shannon–Wiener index; D = Simpson's index; J' = Pielou's evenness; d = Margalef's richness. The number of taxa used to calculate the indices is shown as 'n'. Sampling periods are grouped by season.

Index	Drainage canal			Beach	
	St.1	St.2	St.3	St.4	St.5
December 2022 (Dry)					
Taxa (n)	9	6	7	27	15
Diversity (H')	1.832	1.203	1.780	3.127	2.608
Diversity (D)	0.777	0.555	0.805	0.948	0.919
Evenness (J')	0.834	0.671	0.915	0.949	0.963
Richness (d)	1.107	0.717	0.895	3.230	1.758
February 2023 (Dry)					
Taxa (n)	10	9	11	12	14
Diversity (H')	1.607	1.461	0.033	1.056	1.802
Diversity (D)	0.694	0.646	0.008	0.501	0.693
Evenness (J')	0.698	0.665	0.014	0.425	0.683
Richness (d)	0.931	0.831	0.743	1.023	1.498
April 2023 (End of Dry)					
Taxa (n)	14	17	10	14	28
Diversity (H')	1.889	1.559	0.239	0.149	2.164
Diversity (D)	0.733	0.723	0.080	0.044	0.789
Evenness (J')	0.716	0.550	0.104	0.057	0.649
Richness (d)	1.452	1.533	0.807	0.967	2.561
June 2023 (Wet)					
Taxa (n)	11	7	7	8	10
Diversity (H')	1.657	1.227	0.965	1.207	1.485
Diversity (D)	0.699	0.556	0.443	0.538	0.682
Evenness (J')	0.691	0.630	0.496	0.580	0.645
Richness (d)	1.203	0.784	0.787	0.964	1.221
September 2023 (Wet)					
Taxa (n)	7	18	14	21	24
Diversity (H')	1.533	2.307	2.298	2.297	0.944
Diversity (D)	0.719	0.855	0.870	0.801	0.309
Evenness (J')	0.788	0.798	0.871	0.754	0.297
Richness (d)	0.771	1.982	1.580	2.405	2.412

April (Table 3). Station 5, at the northern end of the beach, showed less extreme variation, reflecting the attenuation of bloom effects at that location. Overall, H' and d emerged as the most informative indices for detecting seasonal changes, while J' was the least sensitive and provided no additional information beyond H' and D .

Chlorophyll concentration

Chlorophyll a concentrations were generally low ($<10 \mu\text{g}\cdot\text{L}^{-1}$) throughout the study, with the notable exception of the *C. socialis* bloom events, during which Chl a reached nearly $100 \mu\text{g}\cdot\text{L}^{-1}$ at St.4 in April (Figure 7). At the canal stations (St.1 and St.2), populations were dominated by cyanobacteria (Chl a only) and green algae (Chl $a+b$), whereas the marine stations were dominated by diatoms

(Chl $a+c_1c_2$) and, during the February bloom, dinoflagellates (Chl $a+c_2$). Chl a was readily measurable at the low concentrations found in DMSO extracts, but accurate quantification of minor chlorophylls was limited by spectroscopic sensitivity. On the basis of the spectroscopic profiles, dinoflagellate and diatom blooms were not readily distinguishable from one another (Chl $a+c_2$ versus Chl $a+c_1c_2$).

One-way ANOVA of Chl a was significant ($F_{24,125} = 252.3$, $p < 0.001$; $\text{MSR} = 8.146$; overall mean = $8.146 \pm 0.233 \text{ SE } \mu\text{g}\cdot\text{L}^{-1}$). Post hoc Tukey's HSD ($\text{MSD} = 6.21 \mu\text{g}\cdot\text{L}^{-1}$; Zar, 2014) identified eight significantly different station-period pairs, all driven by the April bloom at St.4, where Chl a ($94.25 \mu\text{g}\cdot\text{L}^{-1}$) was significantly higher than that in all other station-period combinations except St.5 in April ($20.27 \mu\text{g}\cdot\text{L}^{-1}$).

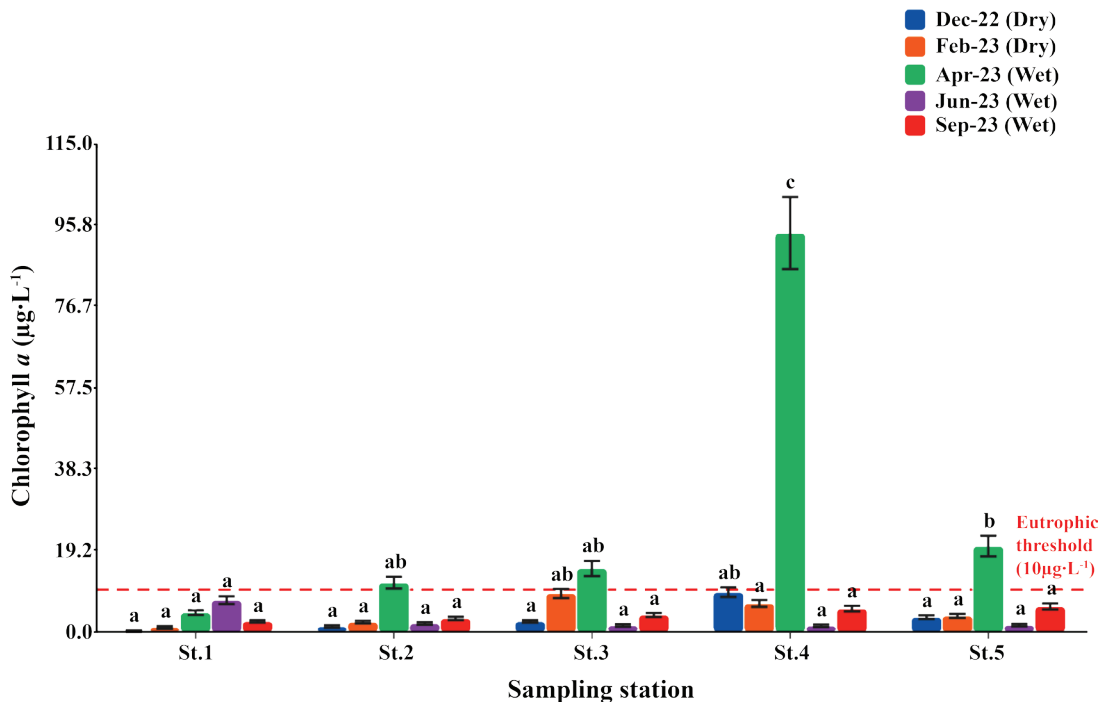


Figure 7. Bimonthly variation in chlorophyll a ($\mu\text{g}\cdot\text{L}^{-1}$) at five stations at Patong Beach from December 2022 to September 2023. Error bars represent $\pm\text{SE}$ ($n = 6$). The dashed line indicates the eutrophic threshold ($10 \mu\text{g}\cdot\text{L}^{-1}$). Different lowercase letters above bars indicate significant differences among station-period means (Tukey's HSD, $p < 0.05$).

DISCUSSION

This study documented two phytoplankton bloom events at Patong Beach in February and April 2023. The bloom events were characterized using a combination of species composition (Figures 2 and 4), cell abundance (Figure 3), diversity indices (Table 3), and chlorophyll *a* (Figure 7), consistent with a multi-parameter monitoring approach advocated by Parker (1987). In February, *Chaetoceros socialis* strongly dominated the estuarine station (St.3), whereas *Peridinium quinquecorne* contributed substantially at the beach stations. In April, *C. socialis* dominated the marine stations more consistently. These observations suggest that bloom structure at Patong Beach may vary across short spatial gradients and between sampling periods, even within the same season.

A notable discrepancy between preserved cell counts and Chl *a* data was apparent at St.3, where cell densities were very high but Chl *a* concentrations remained low. This discrepancy may be explained by the nature of the preserved samples: frustule counts reflect all diatom cells, including intact but potentially non-viable ones, whereas Chl *a* primarily reflects photosynthetically active biomass. Chlorophyll *a* is therefore likely to be a more reliable indicator of bloom biomass, consistent with its use as a standard eutrophication metric.

The sudden appearance of blooms at Patong Beach may be related to rapid population development under favourable environmental conditions and is also consistent with the possible contribution of cyst-based recruitment from sediments. *Chaetoceros socialis* forms benthic resting cysts under conditions of high cell density and nutrient stress (Pelusi *et al.*, 2020), which can remain dormant until conditions become favourable. Jiwarungrueangkul *et al.* (2024) showed that, at Patong Bay, rapid increases in the ratios of dissolved inorganic phosphate (DIP) and dissolved silicate (DSi) to dissolved inorganic nitrogen (DIN) preceded bloom onset by 1–7 days, suggesting that an excess of DIP and DSi relative to nitrogen may act as a proximate trigger (Tsunogai and Watanabe, 1983). Intense rainfall associated with the Andaman Sea

monsoon transition may mobilise large numbers of cysts from canal and estuarine sediments, introducing them into the coastal water column, where they may germinate rapidly in nutrient-enriched runoff. However, because the present study did not directly quantify sediment cyst abundance, nutrient concentrations, or hydrodynamic transport, these mechanisms should be regarded as plausible explanations rather than direct demonstrations.

A striking finding of this study is that phytoplankton blooms were not observed within the drainage canal (St.1 and 2), despite strong land-based influence and wastewater input throughout the study period. This suggests that nutrient enrichment alone may not be sufficient to produce a bloom; physical conditions that retain and concentrate plankton may also be necessary. During the dry season, onshore winds and the convergent circulation within Patong Bay may help to accumulate buoyant phytoplankton at the southern end of the beach near the canal outlet (St.3), creating the spatial conditions favourable for bloom development (Bahulayan and Unnikrishnan, 1992; Isa *et al.*, 2020). The canal, by contrast, is a high-flow, turbid channel that neither retains phytoplankton nor provides sufficient light penetration for bloom-scale growth. These findings are important for management: controlling nutrient inputs from the canal, while necessary, may not by itself eliminate bloom risk as long as the physical retention conditions at the southern end of the beach persist.

Chaetoceros socialis is a cosmopolitan, buoyant, centric diatom found from tropical to polar waters (Hasle and Syvertsen, 1997; Booth *et al.*, 2002; Kraberg *et al.*, 2010), but is sensitive to salinities below approximately 24‰ (Shevchenko *et al.*, 2008). This may explain its virtual absence from the tidal freshwater section of the drainage canal (St.2) while it was abundant at the estuarine canal mouth (St.3) and the beach stations (St.4 and St.5). Blooms occurred during the dry season at Patong Beach (February–April), broadly resembling the spring bloom timing recorded in temperate northern European and Arctic waters (Donnelly, 2006; Kraberg *et al.*, 2010) and reflecting the common role of stratification and nutrient pulses in triggering bloom onset across latitudes.

The physiology of tropical strains of *C. socialis* remains poorly documented, and this represents a priority for future research at sites such as Patong Beach.

The diversity analysis confirmed that H' and Margalef richness (d) were the most sensitive indices for detecting bloom-driven community changes at the marine stations, whereas Pielou's evenness (J') provided little additional interpretive value beyond H' and D and showed significant variation only at the two bloom stations. The strong correlation among H' , D , and J' ($r \geq 0.91$) indicates that these indices largely measure the same property, namely the degree of species dominance, and that calculating all three may be redundant in routine monitoring programmes. We therefore recommend H' as the primary diversity metric for future monitoring at Patong Beach, supplemented by d to capture changes in total species richness that are not reflected in H' alone. These indices should, however, be interpreted alongside taxonomic composition and chlorophyll a , rather than used in isolation. The near-zero H' and D values recorded at St.3 and 4 during bloom events ($H' = 0.033$ and 0.149 , respectively) may be useful quantitative indicators of bloom conditions, complementing visual observations of water discolouration.

Although *C. socialis* blooms are primarily a nuisance affecting the aesthetics and tourism value of Patong Beach (Wong, 1998), the occurrence of *Peridinium quinquecorne* at the beach stations in February deserves continued attention. Some dinoflagellate taxa are associated with harmful algal bloom events and shellfish-related toxins, although toxin production was not evaluated in the present study and should not be inferred directly from species occurrence alone. A further complication is that dinoflagellate blooms (Chl $a+c_2$) are spectrally indistinguishable from diatom blooms (Chl $a+c_2$) by routine spectrophotometry, meaning that microscopic identification of bloom-forming species remains essential. The resting cysts of both *C. socialis* and *P. quinquecorne* are readily identifiable microscopically in sediment samples (Figures 6; Wongrat, 2001; Wongrat and Boonyapiwat, 2003; Kraberg *et al.*, 2010), and

pre-season sediment monitoring could therefore provide an early warning of impending bloom events before they become visible in the water column. We recommend integrating sediment cyst surveys into the existing water quality monitoring programme for Patong Beach.

CONCLUSIONS

Phytoplankton bloom events at Patong Beach during this study were seasonal, occurring in February and April at the southern end of the beach (St.3 and St.4). The observations suggest that bloom development in this area is associated not only with land-based inputs but also with local physical conditions that favour phytoplankton retention near the beach. Despite strong land-based influence, no blooms were observed at the drainage canal stations, indicating that bloom formation is not determined by nutrient input alone. Of the diversity indices evaluated, H' and Margalef richness (d) were the most sensitive for detecting seasonal changes; evenness (J') added little information beyond H' and D and is therefore not recommended for routine monitoring. Chlorophyll a was a more reliable indicator of bloom intensity than preserved cell counts, which may overestimate viable cell abundance in diatom and dinoflagellate samples. While *Chaetoceros socialis* blooms are primarily a nuisance affecting beach tourism, the co-occurrence of *Peridinium quinquecorne* warrants continued surveillance. Future studies should integrate nutrient measurements, sediment cyst monitoring, and hydrodynamic observations to better resolve bloom mechanisms at Patong Beach.

LITERATURE CITED

- Bahulayan, N. and A.S. Unnikrishnan. 1992. Simulation of barotropic wind-driven circulation in the upper layers of Bay of Bengal and Andaman Sea during the southwest and northeast monsoon season using observed winds. **Proceedings of the Indian Academy of Science. Earth and Planetary Sciences** 101(1): 47–66.

- Booth, B.C., P. Larouche, S. Bélanger, B. Klein, D. Amiel and Z.P. Mei. 2002. Dynamics of *Chaetoceros socialis* Blooms in the North Water. **Deep Sea Research Part II: Topical Studies in Oceanography** 49(22–23): 5003–5025. DOI: 10.1016/S0967-0645(02)00175-3.
- Charoenvattanaporn, J. 2017. **Eutrophication status and red tide phenomena along the west coast of Phuket island, the Andaman sea**. <https://www.dmcg.go.th/upload/pc/file/file-201709071504757054849.pdf>. Cited 23 Sep 2024.
- Donnelly, K.A.M. 2006. **The importance of morphological/physiological heterogeneity as adaptive strategies in stocks of common Northern/Arctic phytoplankton species with special focus on the common diatom *Chaetoceros socialis***. Master Thesis, University of Tromsø, Tromsø, Norway. 65 pp.
- Garcia, H.E. and L.I. Gordon. 1992. Oxygen solubility in seawater: Better fitting equations. **Limnology and Oceanography** 37(6): 1307–1312.
- Hasle, G.R. and E.E. Syvertsen. 1997. **Marine diatoms**. In: Identifying Marine Phytoplankton (ed. C.R. Tomas), pp. 5–386. Academic Press, San Diego, USA.
- Isa, N.S., M.F. Akhir, I. Khalil, P.K. Kok and N.H. Roseli. 2020. Seasonal characteristics of the sea surface temperature and sea surface currents of the strait of Malacca and Andaman Sea. **Journal of Sustainability Science and Management** 15: 66–77. DOI: 10.46754/jssm.2020.06.007.
- Jiwarungreangkul, T., O. Kongpuen, C. Sangmanee, M. Yucharoen, D. Tipmanee, S. Phongphattarawat, P. Buapet and P. Sompongchaiyakul. 2024. Weekly variations of nutrients and their associations with phytoplankton blooms in the urban coastal waters of Andaman Sea coast: A case study in Patong Bay, Phuket, Thailand. **Marine Pollution Bulletin** 198: 115824. DOI: 10.1016/j.marpolbul.2023.115824.
- Junqueira, V.M. and S.C.M. Campos. 1998. Adaptation of the BMWP method for water quality evaluation to Rio das Velhas watershed (Minas Gerais, Brazil). **Acta Limnologica Brasiliensia** 10: 125–135.
- Kraberg, A., M. Baumann and C.D. Durselen. 2010. **Coastal Phytoplankton: Photo Guide for Northern European Seas**. Verlag Dr. Friedrich Pfeil, Munich, Germany. 204 pp.
- Margalef, R. 1958. Information theory in ecology. **General Systems** 3: 36–71.
- Palmer, C.M. 1969. A composite rating of algae tolerance organic pollution. **Phycology** 5: 78–82.
- Parker, M. 1987. Exceptional plankton blooms. Conclusions of discussions: Convener's report. **Rapports et Procès-verbaux des Réunions Conseil International pour l'Exploration de la Mer** 187: 108–114.
- Pelusi, A., F. Margiotta, A. Passarelli, M.I. Ferrante, M. Ribera d'Alcalà and M. Montresor. 2020. Density-dependent mechanisms regulate spore formation in the diatom *Chaetoceros socialis*. **Limnology and Oceanography Letters** 5(5): 371–378. DOI: 10.1002/lol2.10159.
- Pielou, E.C. 1966. The measurement of diversity in different types of biological collections. **Journal of Theoretical Biology** 13: 131–144. DOI: 10.1016/0022-5193(66)90013-0.
- Rengefors, K. and C. Legrand. 2001. Toxicity in *Peridinium aciculiferum*—an adaptive strategy to outcompete other winter phytoplankton? **Limnology and Oceanography** 46(8): 1990–1997.
- Ritchie, R.J., S. Sma-Air and S. Phongphattarawat. 2021. Using DMSO for chlorophyll spectroscopy. **Applied Phycology** 33: 2047–2055. DOI: 10.1007/s10811-021-02438-8.
- Ritchie, R.J., S. Sma-Air and V. Dummee. 2022. DMSO formula for chlorophyll determination in dinoflagellates (Chl *a+c₂*). **Applied Phycology** 34: 335–341. DOI: 10.1007/s10811-021-02615-9.

- Shannon, C.E. 1948. A mathematical theory of communication. **Bell System Technical Journal** 27: 379–423. DOI: 10.1002/j.1538-7305.1948.tb01338.
- Shevchenko, O.G., T.Y. Orlova and N.A. Aizdaicher. 2008. Development of the diatom *Chaetoceros socialis* f. radians (Schütt) Proschkina-Lavrenko 1963 in laboratory culture. **Russian Journal of Marine Biology** 34: 224–229. DOI: 10.1134/S1063074008040032.
- Simpson, E.H. 1949. Measurement of diversity. **Nature** 163: 688. DOI: 10.1038/163688a0.
- Tsunogai, S. and Y. Watanabe. 1983. Role of dissolved silicate in the occurrence of a phytoplankton bloom. **Journal of the Oceanographical Society of Japan** 39(5): 231–239.
- Wong, P.P. 1998. Coastal tourism development in South East Asia: relevance and lessons for coastal zone management. **Ocean and Coastal Management** 38: 89–109.
- Wongrat, L. 2001. **Phytoplankton**, 2nd ed. Department of Fishery Biology, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand. 851 pp. (in Thai)
- Wongrat, L. and S. Boonyapiwat. 2003. **Manual of Sampling and Analytical Methods of Plankton**. Kasetsart University, Bangkok, Thailand. 270 pp. (In Thai)
- Zar, J.H. 2014. **Biostatistical Analysis**, 5th ed. Pearson New International Edition Pearson, Harlow, England, UK. 761 pp.
- Zhou, J., B. Qin, C. Casenave, X. Han, G. Yang, T. Wu, P. Wu and J. Ma. 2015. Effects of wind wave turbulence on the phytoplankton community composition in large, shallow Lake Taihu. **Environmental Science and Pollution Research International** 22(16): 12737–12746. DOI: 10.1007/s11356-015-4535-2.