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A comparative investigation of physicochemical and biological variables of Aerial & Port Blair Bays, Andaman Islands with focus on the anthropogenic influence

B K Sahu*[a,b], P Goswami[a], M Begum[a,c], D K Jha[a,d], N V Vinithkumar[a] & G Dharani[d]

[a]Atal Centre for Ocean Science & Technology for Islands, National Institute of Ocean Technology, Ministry of Earth Sciences, Government of India, Port Blair – 744 103, India

[b]CSIR-National Institute of Oceanography, Dona Paula, Goa – 403 004, India

[c]Department of Civil Engineering, SRM Institute of Science and Technology, Chennai – 603 203, India

[d]Ocean Science and Technology for Islands, National Institute of Ocean Technology, Ministry of Earth Sciences, Government of India, Chennai – 600 100, India

*[E-mail: birajkumar@gmail.com]

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Major anthropogenic activities surround the Port Blair Bay, while Aerial Bay remains as a pristine environment. A field study was carried out during the south-west monsoon season (July – August, 2011) in the two bays to compare the physico-chemical parameters and their effect on phytoplankton community structure. Among the physico-chemical parameters, water temperature ($p < 0.01$, n = 18), DO ($p < 0.01$, n = 18) and TP ($p < 0.05$, n = 18) showed significant variation between the Bays. Salinity and Redfield ratio (N:P) was lower in Aerial Bay as compared to Port Blair Bay; while the Si:N ratio was higher in the Aerial Bay. The average chlorophyll-*a* concentration as well as species richness was found to be higher in the Port Blair Bay as compared to the Aerial Bay. The highest phytoplankton density and centric diatom abundance were observed in Port Blair Bay. In Aerial Bay, the centric diatoms like *Dactyliosolen fragilissimus* (44.5 %) and *Guinardia flaccida* (7.1 %) dominated, while in the Port Blair Bay, the centric diatom *Skeletonema costatum* (25.0 %) and a pennate diatom *Nitzschia closterium* (24.3 %) dominated the phytoplankton. The phytoplankton community was influenced by the nutrients from the tidal mud flats and rain-fed rivulets in the Aerial Bay; while, in the Port Blair Bay, the phytoplankton abundance was influenced by nutrients from land runoff, inundated areas and anthropogenic sources.

[**Keywords**: Biomass, Chlorophyll-*a*, Physicochemical parameters, Phytoplankton, Oceanic island, Zooplankton]

Introduction

Among aquatic biota, plankton are generally highly sensitive and their population dynamics can be seriously affected by the environmental perturbation[1]. The study of plankton diversity in most of the aquatic environments is an issue directly related to assessment of system diversity and consequently the ecosystem function[2-4]. Although functional diversity may determine ecosystem functioning, the species diversity has an essential role in ecosystem stability[5].

Andaman & Nicobar (A&N) Islands are known for their rich biodiversity, and most of their coral islands are unique ecosystems providing food and shelter to diverse marine life[6-7]. Such least disturbed reef areas of the Indo-Pacific support several new and endemic species[6]. These islands consist of a chain of islands and extended up to a distance of 1120 km between Burma and Sumatra in the eastern part of Bay of Bengal. The coastal areas are mostly bordered by rich mangrove vegetation and fringing coral reefs. The coast is relatively wavy with many bays and creeks supporting rocky, sandy and muddy beaches.

The sea level in Aerial Bay has receded from the previous level due to the land uplift (+0.6 m) during the 26th December 2004, M 9.1 mega earthquake followed by tsunami while the sea level advanced in Port Blair Bay due to land subsidence (-0.95 m)[8-9]. Low lying areas have been exposed in most of the Aerial Bay region which affected the existing mangrove and coral reef environments. In Port Blair, a portion of land got inundated in the tsunami, and some areas of coastal land submerged due to land subsidence. A considerable area of mangrove forest has degraded due to continuous submergence, and a major portion of the previous intertidal areas have been lost[10]. Thus, the earthquake and the subsequent tsunami event has caused major changes in both the Bays. It has affected the physicochemical parameters for short term[11]. Major anthropogenic activities took place in the Port Blair Bay; whereas the Aerial Bay is still a pristine environment. Here, the physico-chemical parameters and plankton diversity of both the bays is compared to understand the influence of anthropogenic activities on the pelagic environment of the bay.

Information on plankton diversity in the coastal area of Andaman & Nicobar Islands is meagre. Earlier studies on plankton in the Andaman Islands are mostly confined to offshore areas in the Bay of Bengal and Andaman Sea[12-17]. Very few studies are carried out in the eastern coastal area of the Andaman Islands[18]. The present study compares the physico-chemical parameters, phytoplankton community structure and zooplankton biomass between Aerial Bay (North Andaman Island) and Port Blair Bay (South Andaman Island).

Materials and Methods

Study area

Aerial Bay (AB) in the North Andaman Island, extends from northwest to southeast direction and opens to the Andaman Sea (Fig. 1). The depth of the bay ranges from 0.5 to 30 m. Aerial Bay covers an area of about 55 km^{2}(Ref. 19), having a small harbor. It

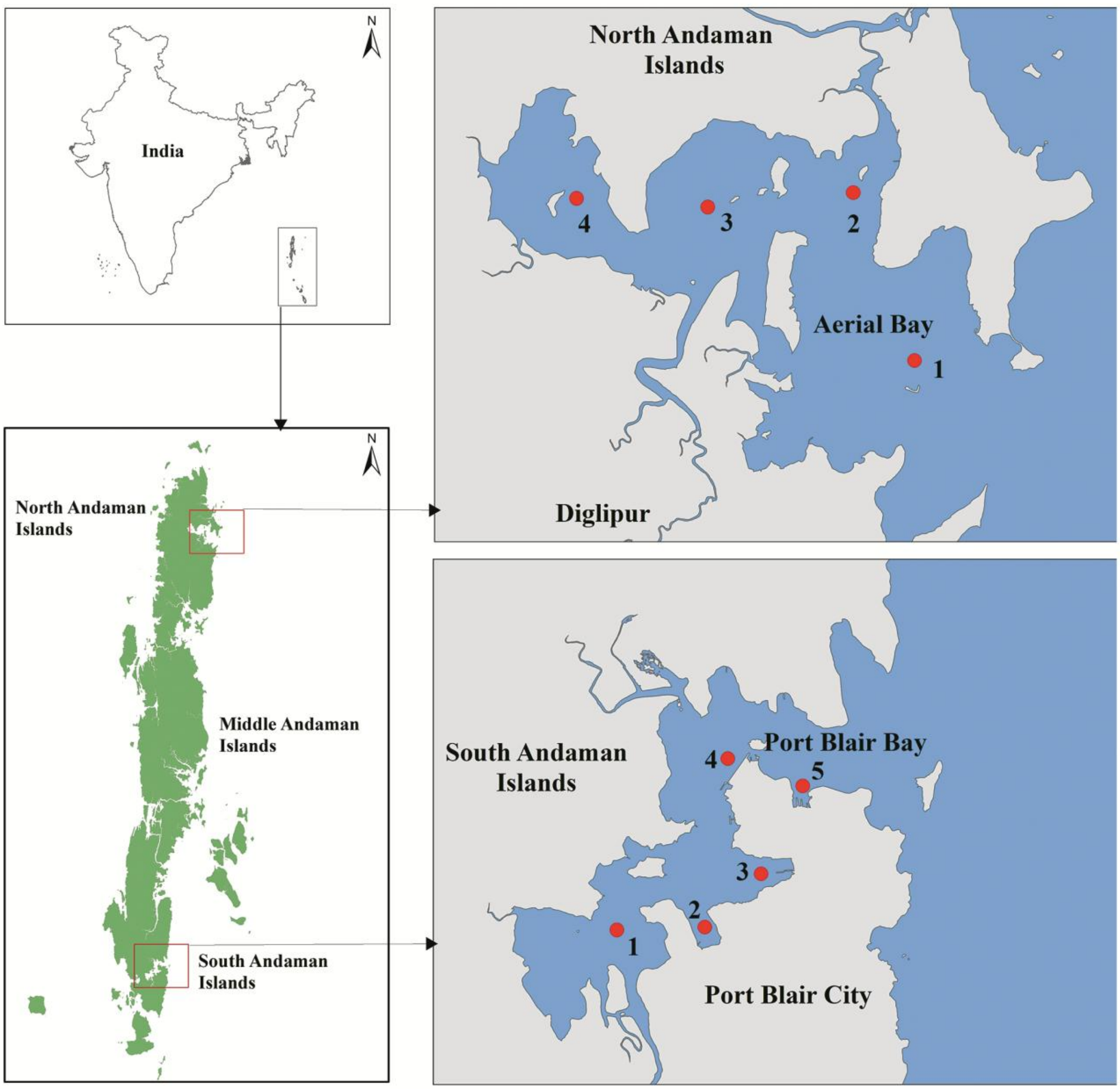

Fig. 1 — Map showing sampling stations (1-4) in Aerial Bay, North Andaman and sampling stations (1-5) in Port Blair Bay [1: Flat Bay, 2: Minnie Bay, 3: Junglighat Bay, 4: Haddo Harbour, 5: Phoenix Bay], South Andaman Island

has various smaller bays, bordered mainly by mangrove vegetation and villages. It is divided into three sections, namely: outer (Aerial & Atlanta Bay), middle (Minerva Bay) and inner (Blair Bay). The Aerial Bay receives a continuous influx of freshwater from the Kalpong River and many associated streams. The dominant mangrove species encircling the bay are *Rhizophora apiculata*, *R. mucronata* and *Avicennia marina*[10]. The lush growth of *Rhizophora* species dominates the muddy environment.

The Port Blair Bay (PBB) situated in the South Andaman Island, extends in a northeast to southwest direction and opens to the Andaman Sea (Fig. 1). The depth of the bay ranges from 3 to 25 m, whereas in the open sea near the mouth, the depth is around 55 m. The bay has patches of mangrove plants. It is the center of major anthropic activities in Port Blair city, which congregates a major portion of the total A&N Islands' population. The population of North Andaman Island is 42,541 and of South Andaman Island is 2,38,142 as per Census of 2011.

The climate of the A&N Islands is usually tropical, with heavy gales, cyclones, and hot and humid conditions. The yearly temperature fluctuates between 18 °C and 36 °C, with a slight increase from north to south. Rainfall is intense and occurs from May to December, averaging about 3100 mm/year. Most rainfall occurs from late May to early October (southwest monsoon), while a weak spell of northeast monsoon brings rain during November – December[20] (IMD, India).

Sampling and analysis

Sampling was carried out at four locations (1 to 4) in Aerial Bay (AB) and five at locations in Port Blair Bay (PBB) (1 to 5) (Fig. 1). Samples were collected in low and high tides during July 2011 in AB and August 2011 in PBB. Atmospheric Temperature (AT), Water Temperature (WT) and pH were recorded onboard during sampling. Transparency was measured by lowering a Secchi disc. Sub-surface water samples were collected using a GO-FLO water sampler. Water samples were fixed instantly with Winkler's A and Winkler's B for Dissolved Oxygen (DO); and Biochemical Oxygen Demand (BOD) samples were fixed after three days of incubation at room temperature. DO and BOD were analyzed by Winkler's titration method and salinity by argentometric titration method. Nutrients like nitrite, nitrate, ammonium, Inorganic Phosphate (IP), silicate, Total Nitrogen (TN) and Total Phosphorus (TP) were analyzed following the standard methods of Grasshoff *et al.*[21]. Phytoplankton samples (5L) were collected in plastic cans and fixed with Lugol's iodine solution and formaldehyde (4 %). The fixed samples were brought to the laboratory and reduced from 5L to 10 – 15 mL following the sedimentation technique. Phytoplankton identification and counting were carried out by observing an aliquot of the sample under a microscope (Nikon Eclipse E600) and by using the standard taxonomic literature[22-24]. Phytoplankton abundance (Cells/L) was calculated as "(counts in one ml X reduced volume of sample in ml)/5". Zooplankton samples were collected by using a zooplankton net (150 µm mesh size, 0.5 m diameter and 1.8 m length) fitted with a flowmeter (HydroBios) and preserved in 5 % formalin. Zooplankton biomass (ml/m^3) was analysed by volume displacement method and by the formula "displaced volume in ml/volume of water filtered in m^3". In the laboratory, an aliquot of the sample was observed under a stereomicroscope for identification and counting purposes. Zooplankton abundance (Nos./m^3) was calculated by the formula "[counts in 5 ml sample X (total sample volume in ml/5)]/volume of water filtered in m^3". Standard literature was followed for identification[25]. Chlorophyll-*a* and phaeophytin pigments were analyzed following the Spectrophotometric method[26].

Statistical analysis

Univariate measures [Shannon-Wiener diversity index (H′), Margalef's species richness (d) and Pielou's evenness (J′), Simpson dominance (D)] were analyzed using PRIMER-E (version 6.1.7). Canonical Correspondence Analysis (CCA) was performed using CANOCO 4.5 to find out the relationship between phytoplankton species and physico-chemical parameters. To study the changes in phytoplankton composition in both the bays a non-metric Multidimensional Scaling (nMDS) based on Bray-Curtis similarities was applied to the data using PRIMER V6 software[27]. A square-root transformation was applied to the species data before analysis.

Results and Discussion

Physico-chemical parameters

In AB, the Water Temperature (WT) varied from 29.1 to 30.1 °C (avg. 29.5±0.5 °C) in high tide and from 29.0 to 31.2 °C (avg. 30.0±1.1 °C) in low tide (Fig. 2, Table S1). Secchi disc depth ranged from 0.9 m

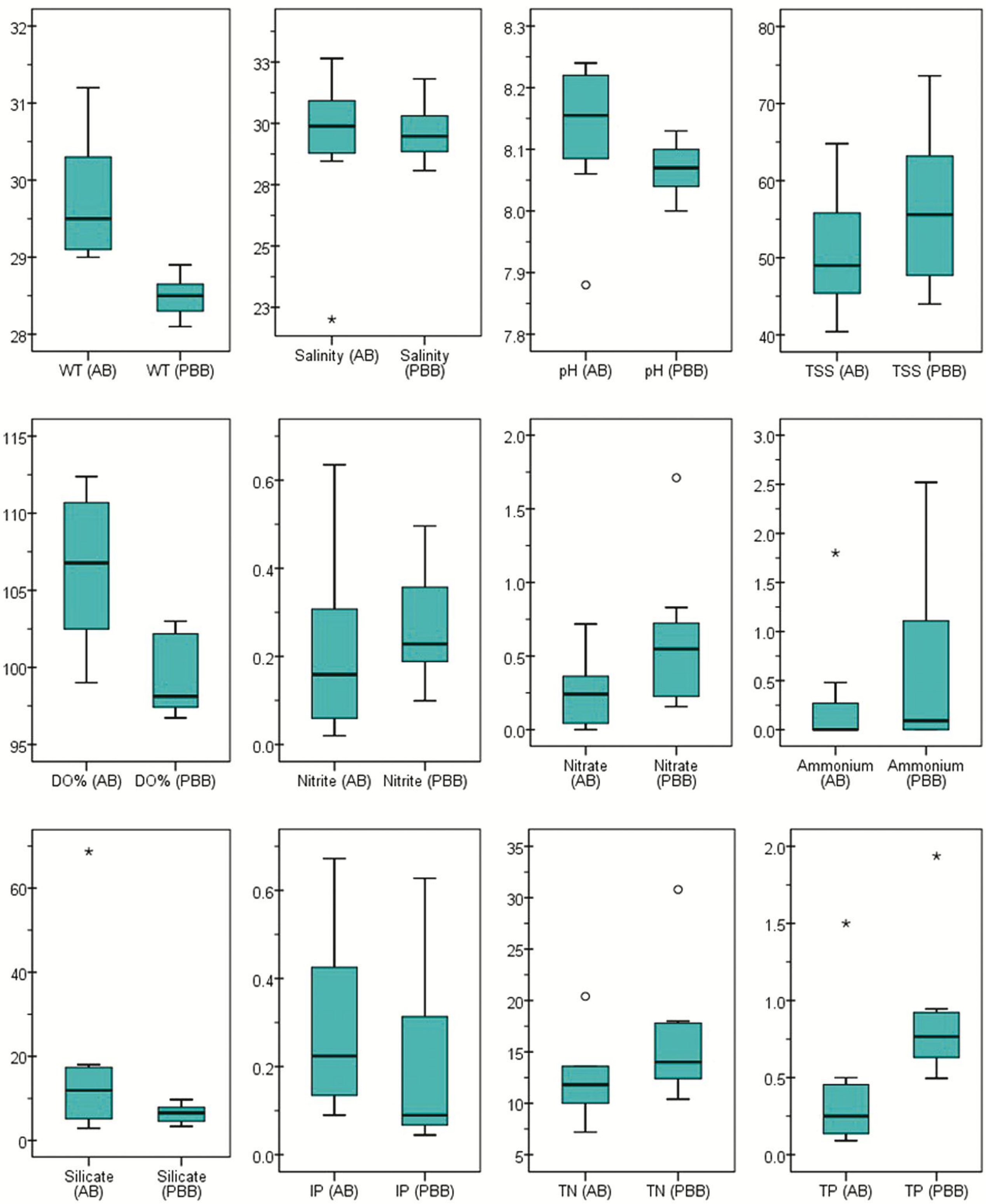

Fig. 2 — Boxplot showing variation of physico-chemical parameters in Aerial Bay (AB), and Port Blair Bay (PBB) [In each box plot, the central point represents the median, the box gives the interval between the 25 % and 75 % percentiles, and the whisker indicates the range. o, * : extreme high/low values]

to 9.8 m (avg. 3.9±4.0 m) in high tide and 0.4 to 6.3 m (avg. 2.3±2.7 m) in low tide. Transparency was found to decrease from the outer to the inner bay and was deeper during high tide than in low tide.

Salinity values ranged from 29.11 to 32.65 PSU (avg. 30.87±1.48 PSU) in high tide and 22.01 to 30.62 PSU (avg. 27.59±3.83 PSU) in low tide (Fig. 2, Table S1). The minimum salinity of 22.01 PSU was found in the inner bay at station 4 (AB), which is the innermost area of the bay and is influenced by the inflow of freshwater through rivulets and channels. In an earlier report, the lowest salinity of 18.51 PSU was recorded during the monsoon in the bay, which was due to the influx of freshwater from the Kalpong River[28]. pH ranged from 7.88 to 8.24, and was in decreasing order towards the inner bay. These variations in pH are may be due to the influx of freshwater enriched with organic matter in the inner bay surrounded by mangroves and also due to the muddy substratum in intertidal and subtidal areas of the inner bay. The freshwater has low pH compared to the seawater and mangrove soil is acidic in nature. DO values varied from 6.42 to 7.06 mg/L (avg. 6.90±0.32 mg/L) in high tide and 6.74 to 7.09 mg/L (avg. 6.84±0.17 mg/L) in low tide (Fig. 2, Table S1). The average DO saturation was above 100 % in both tides. Nutrient concentrations were found in increasing order from the outer to inner bay. This trend was due to increased nutrient input from mangrove vegetation in the inner bay. The average silicate and ammonium concentrations were very high in low tide (silicate: 24.71±29.95 µmol/L, ammonium: 0.57±0.85 µmol/L) compared to high tide (silicate: 10.41±6.47 µmol/L, ammonium: 0.02±0.03 µmol/L) (Fig. 2, Table S1). Another interesting feature observed was that all nutrient concentrations were found higher at station 4 (AB) in the inner bay during low tide. This increased nutrient concentration can be attributed to the tidal flow of water on the muddy substratum as they are rich in nutrients and organic matter and the inflow of suspended matter and nutrients from the freshwater flow.

Coastal bay ecosystems of the Andaman Islands receive nearly year-round allochthonous nutrient and organic matter input due to land runoff from heavy rainfall, providing a favorable environment for phytoplankton growth. As a result, frequent occurrences of phytoplankton bloom have been reported by several researchers[14,29-32]. Chlorophyll-*a* (Chl-*a*) values ranged from 0.99 to 3.08 mg/m^3 (avg. 1.88±0.88 mg/m^3) in high tide and from 1.28 to 6.11 mg/m^3 (avg. 3.07±2.23 mg/m^3) in low tide (Fig. 3, Table S1). Chl-*a* values were found to be higher in the inner bay. In central bay (station 3 [AB]), Chl-*a* value was observed lower; at the same time, nitrate concentration went below detectable level, but phosphate concentration (0.09 to 0.45 µmol/L) was observed in water samples. Hence, nitrate is a limiting factor for phytoplankton growth in this bay, as evident from the Redfield ratio (N:P = 0.6 – 6.5 and Si:N = 9.3 – 60.1) (Table S1). Statistically, there was no significant tidal variation of parameters in AB.

In PBB, the water temperature ranged from 28.8 to 29.6 °C (avg. 29.1±0.3 °C) in high tide and from

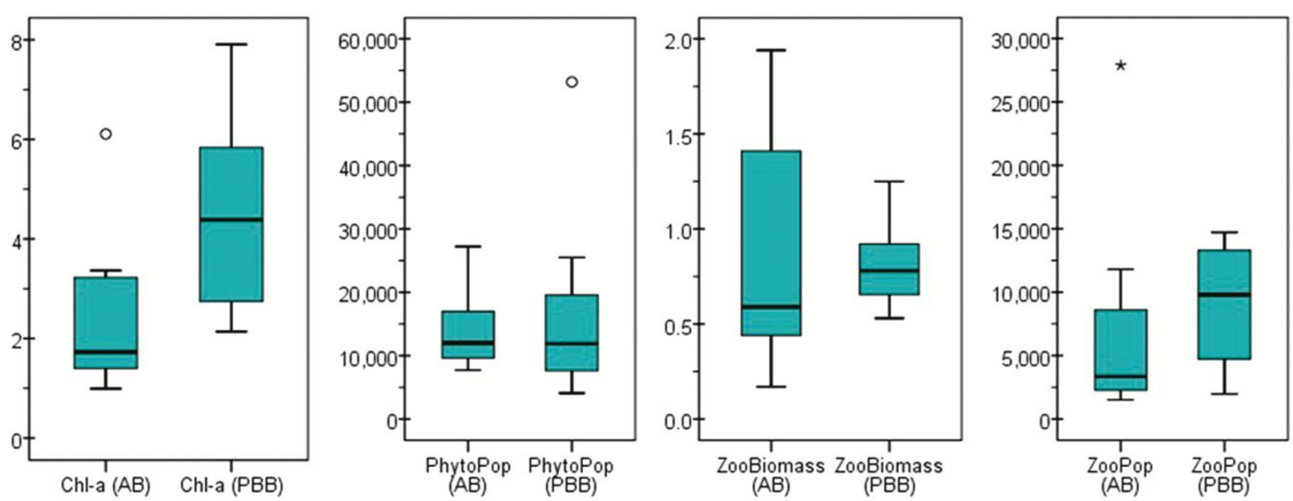

Fig. 3 — Boxplot showing variation of biological parameters in Aerial Bay (AB), and Port Blair Bay (PBB) [In each box plot, the central point represents the median, the box gives the interval between the 25 % and 75 % percentiles, and the whisker indicates the range. o, * : extreme high/low values]

26.6 to 28.2 °C (avg. 27.3±0.7 °C) in low tide (Fig. 2, Table S1). The average Secchi disc depth is from 2.1 to 11.8 m from the inner bay to open ocean water[33]. Transparency was found to decrease from outer to inner bay and was more during high tide than in low tide. Salinity values ranged from 28.86 to 30.36 PSU (avg. 29.74±0.63 PSU) in high tide and 28.07 to 31.81 PSU (avg. 29.83±1.53 PSU) in low tide (Fig. 2, Table S1). The lowest salinity of 28.07 PSU was found at station 3 (PBB), which is in the middle part of the bay influenced by the inflow of drainage water from the city. pH ranged from 8.00 to 8.14 and the average value was lower in low tide compared to high tide. This may be due to the influx of freshwater enriched with organic matter, sewage outfall and degradation of stranded mangroves of the intertidal area. DO values varied from 6.42 to 6.74 mg/L in both high tide (avg. 6.61±0.18 mg/L) and low tide (avg. 6.48±0.14 mg/L) (Fig. 2, Table S1). The average DO saturation was below 100 % in low tide. Nutrient concentrations were found to be high in anthropogenic influenced areas like Junglighat Bay and Phoenix Bay. Chl-*a* values ranged from 1.42 to 7.91 mg/m^3 (avg. 5.02±2.39 mg/m^3) in high tide and from 2.14 to 6.02 mg/m^3 (avg. 3.62± 1.60 mg/m^3) in low tide (Fig. 3, Table S1). The highest Chl-*a* values were from the innermost bay. The N:P ratio was 3.8 – 9.6 and 6.1 – 12.7 during low tide and high tide, respectively. The Si:N ratio was 1.9 – 10.8 and 2.1 – 14.9 during low tide and high tide, respectively. From the above, it seems nitrate is the limiting factor for phytoplankton growth in this bay (Table S1). Statistically, there was no significant tidal variation of parameters in PBB except for water temperature ($p < 0.01$, n = 10).

The major differences between the two bays were that the lowest salinity was observed in AB compared to PBB. Higher TSS was observed in PBB. This may be due to the inundation of the coastal area. The average concentrations of nitrite, nitrate and ammonium were high in PBB compared to AB. In contrast, the average silicate and phosphate concentrations were high in AB. The N:P ratio was high in PBB, whereas the Si:N ratio was high in AB. Similarly, average TN and TP concentrations were high in PBB. Average Chl-*a* concentration was found high in PBB. Statistically, there was no significant variation in parameters between AB and PBB except for water temperature ($p < 0.01$, n = 18), DO ($p < 0.01$, n = 18) and TP ($p < 0.05$, n = 18). There are two reasons for the higher concentration of nutrients in PBB as compared to AB – (i) accumulation of large dead organic biomass in the inundated area, and (ii) more anthropogenic influence (sewage outfall, land drainage, fishing harbor activities, etc.)[32,33]. Junglighat and Phoenix Bay are potential sources of pollution in PBB[32]. There are also reports on diatom and dinoflagellate blooms in the PBB due to nutrient enrichment[31,32,35-36]. Usually oceanic island bays are influenced mainly by the open ocean water, so there are chances of immediate flush out of nutrients to the open ocean. However, localized effects like blooms may create a nuisance in some areas of PBB. Among these two bays, PBB is in the close vicinity of Port Blair city. Further, the livelihoods of local people are dependent on the waterways around them, whether through fishing, shipping, tourism, or other related businesses; hence, this bay receives more domestic and municipal sewage. Therefore, PBB experiences higher anthropogenic pressure than AB. On the other hand, AB is surrounded by a rural agricultural population; thus, land run-off from these agricultural fields may facilitate phosphate accumulation in this coastal ecosystem[34]. Unlike other inorganic nutrients, dissolved silicate content in water is typically controlled by the weathering of terrestrial silicate rocks and is seldom altered by human activity[37]. Furthermore, diatom biogenic silica synthesis plays an important function in controlling silicate concentration in the coastal environment, sometimes making it a limiting nutrient for diatom proliferation. Rivulet runoff in the AB brings year-round freshwater discharge, resulting in the accumulation of silicate in the coastal waters of AB.

Phytoplankton abundance and composition

In AB, a total of 60 phytoplankton species were observed, of which diatoms constitute 52 species (centric 22, pennate 30), dinoflagellates 7 species, and blue-green algae (cyanobacteria) 1 species. The phytoplankton abundance varied from 7720 – 27200 Cells/L (avg. 15030±8590 Cells/L) in high tide and 9400 – 19400 Cells/L (avg. 13000±4630 Cells/L) in low tide (Fig. 3, Table S1). The highest abundance (27200 Cells/L) was from Station 2 (AB) during high tide. Centric diatoms dominated the phytoplankton abundance in both low tide (57.7 %) and high tide (66.1 %), followed by pennate diatoms. The dinoflagellates' share was 6.0 % and 8.0 % during low tide and high tide, respectively. The average Shannon Wiener diversity index was relatively higher during low tide (2.271±0.385) than high tide (1.982±0.527) (Table 1). There is no significant tidal variation observed in phytoplankton abundance.

In PBB, a total of 76 phytoplankton species were observed, of which diatoms constitute 60 species (centric 25, pennate 35), dinoflagellates 13 species, two species of blue-green algae (cyanobacteria), and one unidentified species. The phytoplankton abundance varied from 2820 to 25500 Cells/L (avg. 14640±8765 Cells/L) in high tide and 4080 to 53200 Cells/L (avg. 17108±20541 Cells/L) in low tide (Fig. 3, Table S1). The highest abundance (53200 Cells/L) was from Junglighat Bay during low tide. Centric diatoms were dominant in low tide (73.9 %) than high tide (51.8 %), followed by pennate diatoms. The dinoflagellates' share was 3.9 % and 7.6 % during low tide and high tide, respectively. Shannon Wiener's diversity index was 2.271±0.385 during low tide and 1.982±0.527 during high tide. The average Shannon Wiener diversity index was higher during high tide (2.693±0.096) than low tide (2.467±0.556). There was no significant tidal variation in phytoplankton abundance (Table S1) at PBB.

The major differences between the two bays were observed in species richness, which was higher in PBB than AB (Table 1). The highest phytoplankton density and centric diatom abundance was observed in PBB. Moreover, PBB had the highest diversity than AB. Higher diatom abundance in PBB is another reason for the relatively lower dissolved silicate concentration detected during the study as the proliferation of diatom utilizes silicate from the adjacent water[31]. The nMDS plot made groupings of stations of similar phytoplankton composition (Fig. 4). It can be inferred from the plot that the species composition differed a lot in both the bays. This is due to different physico-chemical regimes present in both bays.

In AB, diatoms like *Dactyliosolen fragilissimus* (44.5 %), *Guinardia flaccida* (7.1 %), *Leptocylindrus danicus* (2.9 %), *Chaetoceros curvisetus* (2.9 %), *Nitzschia closterium* (2.8 %), and *Chaetoceros lorenzianus* (2.8 %) were dominant of total populations at all the stations. In dinoflagellates, *Peridinium globulum* (3.8 %), *Tripos furca* (=*Ceratium furca*) (0.8 %), *Peridinium achromaticum* (0.5 %), and *Tripos lineatum* (=*Ceratium lineatum*) (0.5 %) species dominated the population. In previous studies made of nearshore and offshore waters of AB, the diatoms *Thalassionema nitzschioides*, *Eucampia zodiacus*, *Chaetoceros curvisetus*, and *Thalassiothrix longissima* dominated the species composition during pre-monsoon period[18]. The blue-green algae *Anabaena* sp. dominated with 34.0 % at station 4 (AB) in the inner bay during low tide. *Anabaena* spp. are recognized as a key fraction of freshwater plankton and of various saline lakes[37]. The species' presence in this station may be due to low salinity (22.0 PSU) through the freshwater discharge from rivulets. The diatom species *Dactyliosolen*

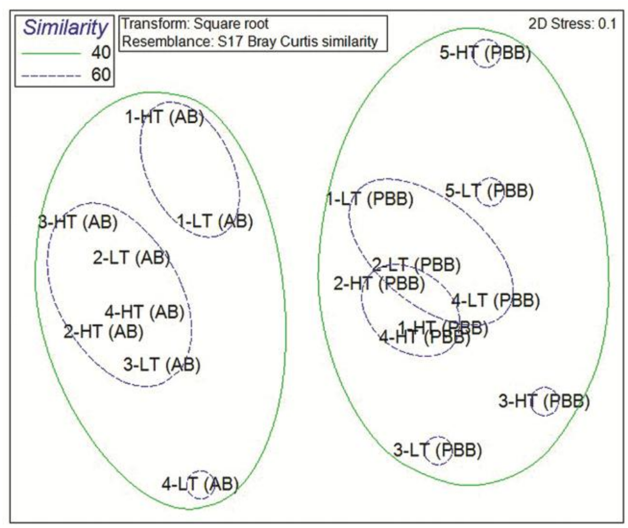

Fig. 4 — Grouping of stations by using non-parametric Multidimensional Scaling (nMDS) based on phytoplankton composition [AB: Aerial Bay, PBB: Port Blair Bay, HT: High Tide, LT: Low Tide]

Table 1 — Univariate diversity indices of phytoplankton in Aerial and Port Blair Bay (Values in Avg±SD [min – max])

	Aerial Bay		Port Blair Bay	
	High tide	Low tide	High tide	Low tide
Margalef's species richness (d)	2.565±0.733 [1.834 – 3.546]	2.584±0.795 [1.640 – 3.473]	3.154±0.715 [2.140 – 3.769]	3.473±0.639 [2.481 – 4.180]
Pielou's evenness (J')	0.613±0.117 [0.456 – 0.739]	0.718±0.148 [0.503 – 0.829]	0.797±0.062 [0.746 – 0.902]	0.707±0.156 [0.481 – 0.888]
Shannon Wiener diversity (H')	1.982±0.527 [1.388 – 2.626]	2.271±0.385 [1.775 – 2.714]	2.693±0.096 [2.607 – 2.853]	2.467±0.556 [1.603 – 3.078]
Simpson's dominance (D)	0.318±0.130 [0.172 – 0.483]	0.216±0.107 [0.138 – 0.372]	0.900±0.017 [0.875 – 0.921]	0.818±0.142 [0.576 – 0.939]

fragilissimus was dominant in all stations except 4 (AB) station during low tide and this may be due to the low salinity in this station which favoured other species to flourish.

In PBB, diatoms like *Skeletonema costatum* (25.0 %), *Leptocylindrus danicus* (8.7 %), *Chaetoceros curvisetus* (6.9 %), *Nitzschia closterium* (24.3 %), *Dactyliosolen fragilissimus* (4.2 %), *Nitzcshia seriata* (4.0 %), *Rhizosolenia imbricata* (3.8 %), *Navicula directa* (2.9 %), and *Nitzschia longissima* (2.7 %) were dominant of total populations at all the stations. In dinoflagellates, *Tripos macroceros* (1.5 %), *Protoperidinium quarnerense* (1.4 %), *Prorocentrum gracile* (1.4 %), and *Protoperidinium achromaticum* (0.8 %) dominated the population. Blue-green algae (*Trichodesmium* sp.) formed 0.4 % (Table S2).

The potential bloom-forming species were many in diatoms, dinoflagellates and cyanobacteria, but the toxin-producing species were more in dinoflagellates. The toxin-producing and potentially harmful algal bloom-forming species were *Alexandrium* sp., *Nitzschia* sp., *Protoperidinium* sp., *Prorocentrum* sp., *Trichodesmium* sp., and *Anabaena* sp.

Phytoplankton species bloom in different seasons according to the availability of preferential nutrients in these bays. *Noctiluca scintillans* blooms were observed in PBB during the start and middle of the south-west monsoon and during the north-east monsoon[29,39]. While at the beginning of the south-west monsoon in 2010, a diatom (*Chaetoceros curvisetus*) bloom was observed[30] and a bloom of *Rhizosolenia imbricata* during the north-east monsoon[35-36]. The premonsoon (summer) season was dominated by cyanobacteria[30,40] and the bloom of dinoflagellates (*Protoperidinium quinquecorne*)[32]. Bloom of *Phaeocystis* species was observed near AB during the start of the south-west monsoon[41].

The univariate indices facilitate the understanding, conservation and utilization of living resources by creating a single annotated index of biological collections[42]. In AB, the Shannon Wiener diversity index (H') ranged from 1.388 to 2.714, and Margalef's species richness (d) ranged from 1.640 to 3.546, while it was 1.603 to 3.078 and 2.140 to 4.180 respectively, in PBB (Table 1).

Zooplankton biomass and population

In AB, zooplankton biomass ranged from 0.39 to 1.43 ml/m^3 (avg 0.97±0.52 ml/m^3) during low tide and from 0.17 to 1.94 ml/m^3 (avg 0.78±0.79 ml/m^3) during high tide (Fig. 3, Table S1). Higher zooplankton biomass was observed in the innermost bay. Zooplankton density ranged from 2247 to 27888 Nos./m^3 (avg 9906±12056 Nos./m^3) during low tide and from 1519 to 11812 Nos./m^3 (avg 4558±4857 Nos./m^3) during high tide (Fig. 3, Table S1). No trend was found in zooplankton density from the inner to the outer bay. There was no statistically significant variation in tidal data. The highest zooplankton density of 27888 Nos./m^3 was found at station 2 (AB) in the middle bay during low tide. In this station, the swarming of red-coloured copepods was observed. Flot[43] suggested this as an adaptive benefit for feeding, propagation, and protection. The red-coloured copepods were observed in coastal and offshore areas of Andaman, and this colour is mainly due to the presence of carotenoids[14].

In PBB, the biomass ranged from 0.53 to 1.25 ml/m^3 (avg 0.82±0.28 ml/m^3) during low tide and from 0.12 to 0.95 ml/m^3 (avg 0.60±0.32 ml/m^3) during high tide (Fig. 3, Table S1). There was a decreasing trend of biomass towards the outer bay. Zooplankton density ranged from 1974 to 14712 Nos./m^3 (avg 9554±5587 Nos./m^3) during low tide and from 718 to 13340 Nos./m^3 (avg 6232±4636 Nos./m^3) during high tide (Fig. 3, Table S1). There was no statistically significant variation in tidal data. Zooplankton density was in increasing trend from outer to inner bay. The highest zooplankton density of 14712 Nos./m^3 was found at station 1 (innermost bay [PBB]) during low tide. The zooplankton biomass and population did not vary much between the bays. The zooplankton biomass and abundance values are comparably high in these bays compared to tropical estuarine values[44-45]. The biomass remained comparable with coastal areas while the population was higher[46]. The biomass is comparatively low, and the population is high compared to upwelling shelf regions[47]. The comparisons are to be taken cautiously as there is a difference in the mesh size of zooplankton nets used in sampling.

The dominant zooplankton groups in AB were copepods, chaetognaths, *Lucifer* spp., siphonophore, cladocera, appendicularia, pteropods, *Branchiostoma* spp., etc. The rare groups were ascidian tadpole, tornaria larvae, phoronid larvae, polyclad flatworms, mysids, phyllosoma larvae, etc. In PBB, the dominant groups were copepods, chaetognaths, bivalve and gastropod larvae, appendicularia, polychaete larvae, doliolum, pteropods, etc. The rare groups were ophiopluteus larvae, echinopluteus larvae, *Branchiostoma* spp., sea anemone larvae, brachiopod larvae, rotifer, and phoronid larvae. One interesting observation was that in one station, the pteropods formed 16 % of zooplankton abundance in PBB and 20 % of zooplankton abundance in AB.

Interrelation among physico-chemical and biological parameters

Aerial Bay

In AB, station 4 (AB, in low tide) remained far away from other stations in CCA (Fig. 5). This is the innermost area of the bay, and a major portion of this area is covered with mudflats, which become exposed during low tide. Station 3 (AB, in low tide) also remained far away from other stations in CCA. It is due to its unique position in the central bay with the freshwater flow. All the stations in high tide and other stations remained close to each other.

From the CCA, it is observed that the major nutrients are associated with station 4 (AB, in low tide). The position of nutrients, salinity, and station 4 (AB) shows that freshwater influx and the mud flats are the major sources of nutrients in this bay. The relation of nutrients and chlorophyll-*a* indicates sufficient nutrients for the primary production during the study period (monsoon season).

Chaetoceros simplex is associated with the low salinity of station 4 (AB) at low tide as the species prefers low salinity (~18 PSU) for its optimum growth[48]. Station 3 (AB) at low tide is associated with four phytoplankton species - *Pleurosigma elongatum*, *Hemidiscus cuneiformis*, *Diploneis smithii*, and *Gyrosigma balticum*. The positions of other species are near the centre of the graph, denoting their distribution in the whole bay.

Port Blair Bay

In PBB, station 3 and 5 (PBB, in both low and high tide) remained far away from other stations in CCA (Fig. 5). This bay is housed by a major fishing harbor, two main-land and inland-bound shipping harbours and hence experiences major anthropogenic influence with higher sewage disposal[33-34]. Extensive phytoplankton blooms were also observed in this area[31].

From the CCA, it is observed that the major nutrients are associated with station 3 (PBB, in high

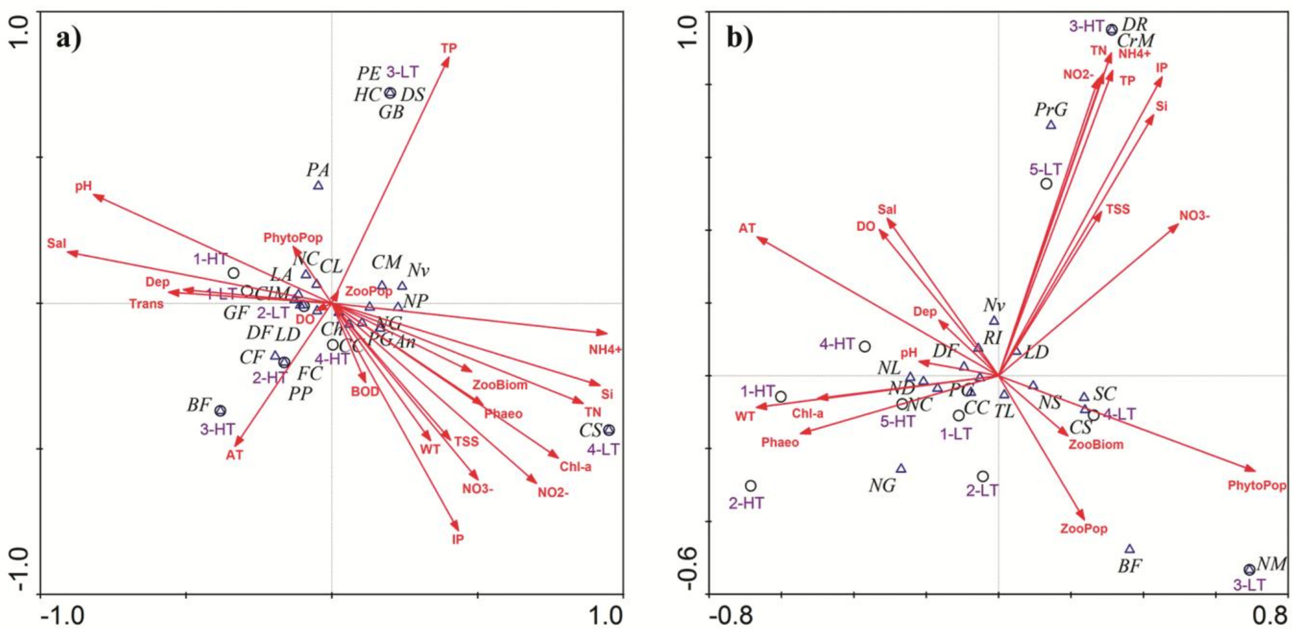

Fig. 5 — Canonical correspondence analysis (CCA) ordination diagram showing phytoplankton species in association with environmental parameters and stations: (A) Aerial Bay, and (B) Port Blair Bay [*DF: Dactyliosolen fragilissimus*, *An: Anabaena sp.*, *GF: Guinardia flaccida*, *CL: Chaetoceros lorenzianus*, *PE: Pleurosigma elongatum*, *PG: Peridinium globulum*, *NC: Nitzcshia closterium*, *LD: Leptocylindrus danicus*, *CC: Chaetoceros curvisetus*, *CS: Chaetoceros simplex*, *BF: Bacteriastrum furcatum*, *LA: Lycmophora abbreviata*, *Ch: Chaetoceros sp.*, *CM: Coscinodiscus marginatus*, *Nv: Navicula sp.*, *NP: Navicula pelagica*, *CF: Ceratium furca*, *ClM: Climacosphenia monilegera*, *FC: Fragilaria cylindrus*, *HC: Hemidiscus cuneiformis*, *GB: Gyrosigma balticum*, *DS: Diploneis smithii*, *PA: Peridinium achromaticum*, *PP: Peridinium pallidum*, *NG: Navicula granii*, *SC: Skeletonema costatum*, *NC: Nitzcshia closterium*, *NS: Nitzcshia seriata*, *RI: Rhizosolenia imbricata*, *ND: Navicula directa*, *NL: Nitzcshia longissima*, *CrM: Ceratium macroceros*, *DR: Diploneis robustus*, *PrG: Prorocentrum gracile*, *BF: Bacteriastrum furcatum*, *TL: Thalassiothrix longissima*, *NM: Nitzcshia migrans*]

tide) and station 5 (PBB, in low tide), showing that these are major sources of nutrients. Apart from this, rainfall in the watershed brings nutrients to the bay. The concentration of Chl-*a*, phytoplankton abundance, and zooplankton biomass and abundance are mostly dependent on the availability of nutrients and salinity.

The diatoms *Nitzschia migrans* and *Bacteriastrum furcatum* are associated with station 3 (PBB, in low tide). The diatoms *Diploneis robustus* and *Tripos macroceros* (=*Ceratium macroceros)* are associated with the same station during high tide. These variations may be due to the tidal currents that moves the water parcel along with the phytoplankton[30,33]. The dinoflagellate *Prorocentrum gracile* is associated with station 5 (PBB) during low tide. The position of other species near the centre of the graph denotes their distribution in the whole bay. The association of different species with specific stations is due to their preferential nutrient availability.

Conclusion

A study was conducted in two island bays of Andaman & Nicobar Islands – AB and PBB during the south-west monsoon to examine the phytoplankton community structure and gain insight into how the physico-chemical parameters drive the changes in both the bays. The PBB showed higher zonal nutrient concentrations. The N:P ratio was high in PBB, whereas the Si:N ratio was high in AB. Statistically, there was no significant variation in parameters between AB and PBB except for WT and TP. The average Chl-*a* concentration was high in PBB as compared to AB. The phytoplankton species composition was found to be dissimilar in both bays. The species richness is high in PBB compared to AB. The zooplankton biomass and abundance values are comparable in both the bays. In AB, the phytoplankton community is controlled by the nutrients from the tidal mudflats and rain-fed rivulets. In contrast, in PBB, the phytoplankton was controlled by the nutrients from land runoff, inundated coastal areas and anthropogenic sources. Nevertheless, the open ocean also controls it to some extent. These island bays must be explored further for region-specific endemism in marine plankton species.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at https://nopr.niscpr.res.in/jinfo/ijms/IJMS_52(02)79-90_SupplData.pdf

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Conflict of interest

The authors declare no conflict of interest.

Author Contributions

BKS: Formal analysis, Writing- Original draft preparation, software; PG: Writing- Original draft preparation; MB: Formal analysis, Writing- Original draft preparation; DKJ: Conceptualization, Formal analysis, software, Writing- Original draft preparation; NVV: Conceptualization, Writing- Reviewing and Editing, Project administration; GD: Project administration, Funding acquisition, Writing- Reviewing and Editing.

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