Drivers of Phytoplankton Community Dynamics across Tropical Coastal Habitats of Bangladesh

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Abstract

Phytoplankton regulate aquatic food webs and biogeochemical cycling, yet cross-habitat comparisons from tropical coastal systems remain limited. This study examined phytoplankton community structure and its environmental drivers across three contrasting coastal habitats of Bangladesh: the Meghna River estuary, the Teknaf mangrove coast, and the coral reef waters surrounding Saint Martin's Island. Samples were collected during the 2020-2021 dry season at 45 stations (15 per habitat). Temperature, salinity, dissolved oxygen, density, turbidity, chlorophyll concentration, silicate, nitrate, phosphate, phytoplankton abundance, and zooplankton abundance were assessed. Community patterns were summarized using Shannon diversity and non-metric multidimensional scaling, while generalized linear models were used to evaluate environmental drivers after multicollinearity screening and Akaike information criterion-based model selection. The three habitats showed distinct hydrographic and nutrient conditions. The estuary had the lowest salinity and highest turbidity and nutrient concentrations, whereas coral reef waters were more saline and comparatively nutrient-poor. Phytoplankton diversity was highest in the mangrove habitat (H = 2.89), followed by the estuary (H = 2.56) and coral reef habitat (H = 2.01). Diatoms dominated the estuary and mangrove habitats, while dinoflagellates dominated the coral reef habitat. Six selected predictors jointly explained 61%, 60%, and 63% of phytoplankton variability in the coral, mangrove, and estuarine habitats, respectively. Phosphate explained the largest share of variability in coral and mangrove waters, whereas silicate was the strongest explanatory variable in the estuary; zooplankton also contributed substantially in the coral habitat. These results indicate that nutrient gradients, modified by freshwater influence and habitat-specific trophic interactions, are major determinants of phytoplankton community dynamics across tropical coastal habitats in the northern Bay of Bengal.

Keywords: phytoplankton; tropical coastal habitats; Bay of Bengal; estuary; mangrove; coral reef; nutrients; zooplankton

1. Introduction

Phytoplankton are the principal primary producers in marine and coastal waters and form the energetic base of aquatic food webs. At the global scale, marine primary production makes a major contribution to carbon fixation and supports fisheries production, while phytoplankton also influence biogeochemical cycling and climate through carbon dioxide uptake and the release of climate-active compounds (Falkowski et al., 1998; Chassot et al., 2010; Andreae and Crutzen, 1997). Because phytoplankton communities respond rapidly to environmental variability, changes in their abundance and taxonomic composition can provide sensitive information about ecosystem functioning.

Phytoplankton growth and community composition are regulated by interacting physical, chemical, and biological processes. Temperature, salinity, light, water-column mixing, nutrient availability, and freshwater inputs shape resource availability and physiological conditions, while competition, grazing, and other biotic interactions further modify community structure (Calijuri et al., 2002; Segura et al., 2013; Wiltshire et al., 2015; Käse et al., 2021). The importance of individual drivers varies among regions and habitat types. In tropical coastal systems, where temperature and light may be less limiting during parts of the year, nutrient supply and hydrological exchange can become especially important controls on phytoplankton dynamics (Moore et al., 2013; Sarker et al., 2020a).

Coastal habitats occupy a relatively small fraction of the global ocean but are disproportionately productive and ecologically diverse (Field et al., 1998). Estuaries, mangrove-fringed coasts, and coral reef waters differ strongly in freshwater influence, turbidity, nutrient loading, residence time, and trophic structure. These contrasts can generate pronounced differences in phytoplankton functional groups and dominant taxa even within the same geographic region. Recent work from the Bangladesh coast has demonstrated strong spatial and temporal variation in phytoplankton assemblages and their relationships with oceanographic variables, but direct cross-habitat comparisons remain comparatively limited (Sarker et al., 2018; Sarker et al., 2023).

The Bangladesh coast provides an opportunity to compare three contrasting habitats within the northern Bay of Bengal: the Meghna River estuary, the Teknaf mangrove coast, and the coral reef waters surrounding Saint Martin's Island. The present study therefore aimed to (i) characterize environmental variability among these habitats, (ii) quantify habitat-specific phytoplankton community structure, and (iii) identify the environmental and biological variables that best explain variation in phytoplankton abundance.

2. Materials and Methods

2.1. Study Area

The study was conducted along the central and south-eastern coast of Bangladesh. The Meghna River estuary represented the estuarine habitat, the Teknaf coast represented the mangrove-influenced habitat, and the waters surrounding Saint Martin's Island represented the coral reef habitat. The Meghna estuary receives large freshwater and sediment inputs from the Ganges-Brahmaputra-Meghna river system. Teknaf lies along the south-eastern coast near the Naf River and is influenced by coastal runoff and mangrove-associated waters. Saint Martin's Island is separated from the Teknaf mainland by a channel and is directly exposed to marine waters of the Bay of Bengal.

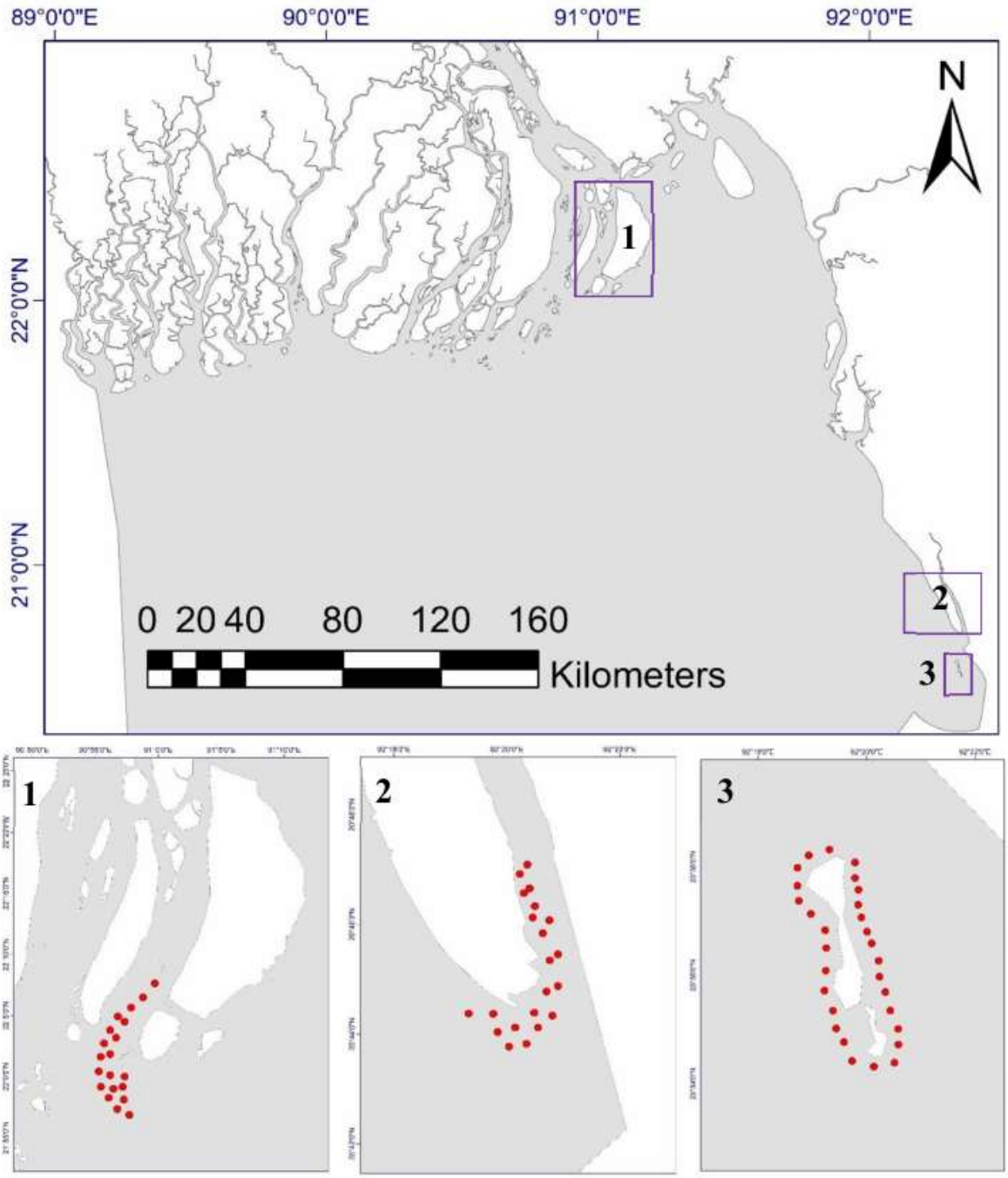

Figure 1. Location of the study area and sampling stations. The three habitat groups are (1) Meghna River estuary, (2) Teknaf coast, and (3) Saint Martin's Island. Red points indicate sampling stations.

2.2. Field Sampling and Environmental Measurements

Sampling was conducted during the 2020-2021 dry season (October-March). Fifteen stations were sampled within each habitat, giving a total of 45 stations. Environmental measurements included temperature, salinity, dissolved oxygen (DO), density, turbidity, chlorophyll concentration, silicate, nitrate, and phosphate. Vertical profiles of core hydrographic variables were collected in situ using a CTD90M multiparameter probe (Sea & Sun Technology, Germany), with the sensors available in the deployed configuration. Chlorophyll profiles were obtained using an AlgaeTorch 100 spectrofluorometer (bbe Moldaenke), and surface water was collected for nutrient analysis.

Phytoplankton and zooplankton were sampled using a plankton net with 44 um mesh, a 17 cm aperture, and a 100 cm net length. The net was towed slowly for approximately 5-10 min; a depressor was used under strong-current conditions to maintain the intended sampling position. A digital flow

meter was attached to estimate the volume of water filtered. Plankton samples were preserved in 3% formaldehyde and stored in a cool, dark location until laboratory analysis.

2.3. Laboratory Analysis

Nutrient concentrations were measured using an EASYCHEM 200 automated water analyzer (SYSTEA). Silicate, phosphate, and nitrate were analyzed using the molybdosilicate, semi-automated colorimetric, and automated hydrazine reduction methods, respectively, following the procedures reported in the source study. Phytoplankton samples were examined microscopically and counted on marked slide areas. Phytoplankton were identified to species level where possible, whereas zooplankton were quantified as total abundance.

2.4. Statistical Analysis

Distributional assumptions were evaluated using the Shapiro-Wilk test. Phytoplankton and zooplankton abundance were log-transformed before model-based analyses. Phytoplankton diversity within each habitat was summarized using the Shannon diversity index, H = -sum(p_i ln p_i), where p_i is the proportional abundance of species i.

Non-metric multidimensional scaling (nMDS) was used to visualize multivariate differences among habitats based on environmental and biological variables. To identify drivers of phytoplankton abundance, generalized linear models were fitted using environmental variables and zooplankton abundance as candidate predictors. Variance inflation factors (VIFs) were used to screen multicollinearity, with variables exceeding VIF > 3 removed from further modelling. Candidate predictor combinations were compared using Akaike information criterion (AIC), and the lowest-AIC model was retained for interpretation (Akaike, 1974; Austin, 1987). Analyses were performed in R.

2.5. Use of AI-Assisted Technology in Manuscript Preparation

During preparation of this preprint manuscript, OpenAI ChatGPT was used to assist with language editing, manuscript organization, and formatting. The tool was not used to generate, alter, or analyze the research data. The author is responsible for the final text and should verify all scientific statements, numerical results, citations, and declarations before submission.

3. Results

3.1. Environmental Variability among Habitats

All three habitats were vertically well mixed over the sampled depth range, but their hydrographic characteristics differed substantially. Surface temperature ranged from approximately 26.5-28.7 degrees C in the coral reef habitat, 27-28 degrees C in the mangrove habitat, and 25.8-26.2 degrees C in the estuary. Coral reef waters had the highest salinity (approximately 30-33), the estuary had the lowest salinity (approximately 10-12 in the vertical-profile comparison), and mangrove waters were intermediate (approximately 23-27). DO was highest in the coral reef habitat (approximately 6.5-7 mg/L), lowest in the mangrove habitat (approximately 5.5-6 mg/L), and intermediate in the estuary (approximately 6-6.5 mg/L). Relative density values were highest in coral waters and lowest in the estuary. Turbidity showed the opposite pattern, exceeding 200 FTU in the estuary, compared with approximately 110-130 FTU in the mangrove habitat and 60-80 FTU in coral reef waters.

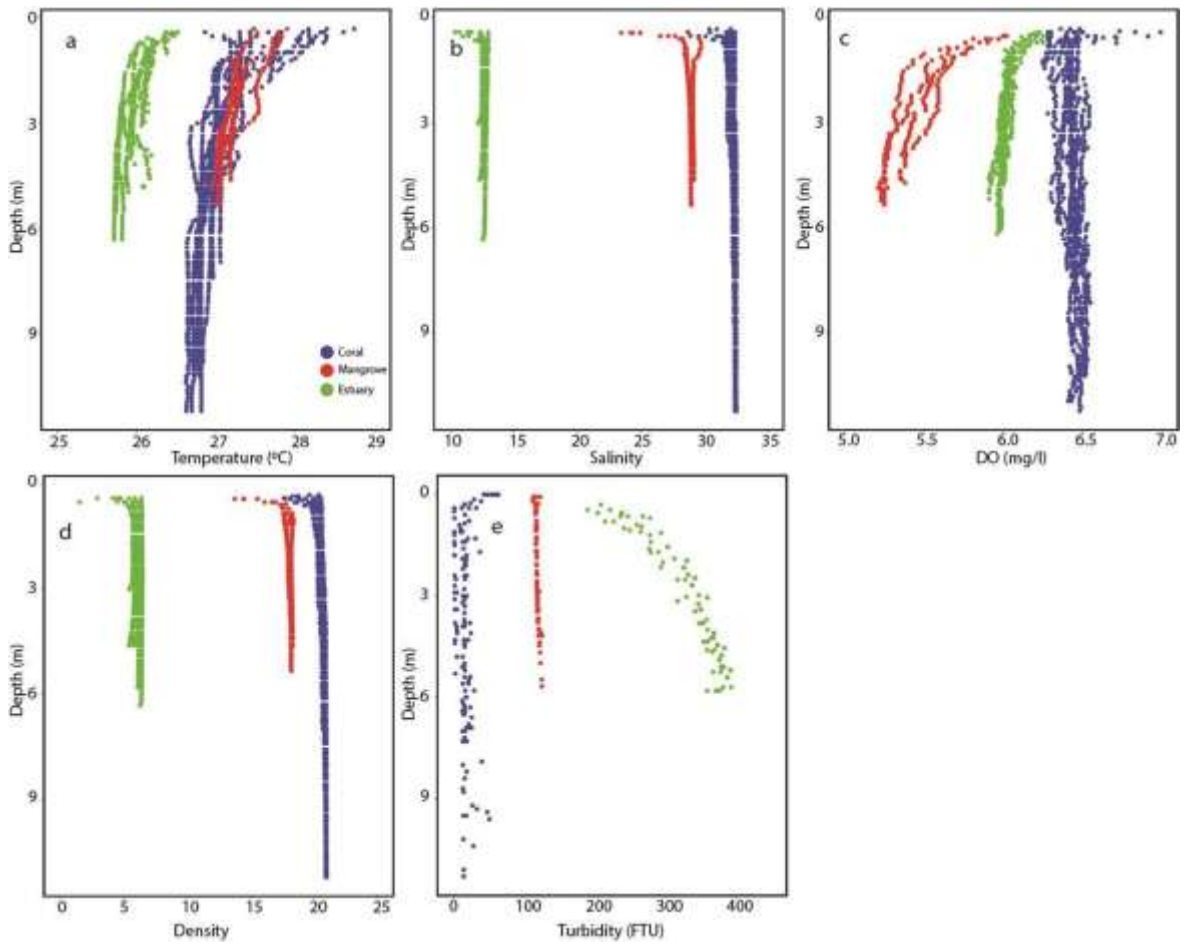

Figure 2. Vertical distributions of environmental variables in coral, mangrove, and estuarine habitats: (a) temperature, (b) salinity, (c) dissolved oxygen, (d) density, and (e) turbidity.

3.2. Water-Mass Characteristics

The temperature-salinity diagram separated the three habitat types into distinct water-mass clusters. The Meghna estuarine stations occupied the low-salinity end of the gradient, Saint Martin's coral reef stations had the highest salinity, and Teknaf stations were intermediate. The pattern is consistent with strong freshwater influence in the estuary and greater marine influence around Saint Martin's Island.

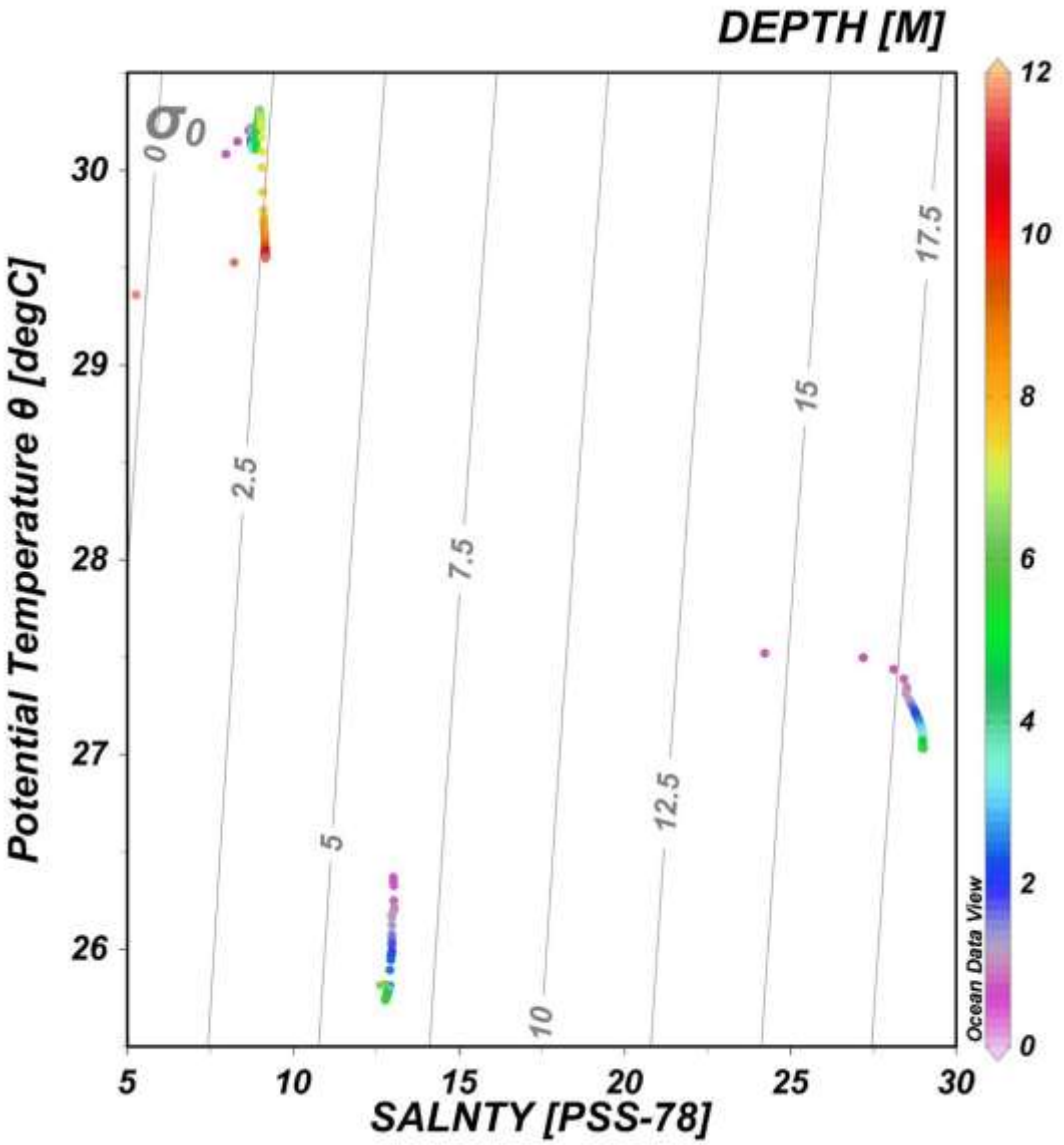

Figure 3. Temperature-salinity diagram for the three coastal habitats. Point color indicates sampling depth in the original analysis.

3.3. Nutrients and Chlorophyll

Nutrient concentrations were highest overall in the estuary. Mean silicate concentration was 1.42 +/- 0.21 mg/L in the estuary, 1.14 +/- 1.14 mg/L in the mangrove habitat, and 0.51 +/- 0.15 mg/L in the coral reef habitat. Nitrate was highest in the estuary (2.47 +/- 0.25 mg/L), followed by the mangrove habitat (2.10 +/- 0.21 mg/L) and coral reef habitat (1.50 +/- 0.20 mg/L). Phosphate was also highest in the estuary (0.21 +/- 0.02 mg/L), compared with 0.13 +/- 0.01 mg/L in mangrove waters and 0.15 +/- 0.02 mg/L in coral waters.

Chlorophyll concentration differed markedly among habitats. The estuary showed the highest vertical concentrations (approximately 4.5-6.5 ug/L), the mangrove habitat was intermediate (approximately 2.5-3.0 ug/L), and the coral reef habitat had the lowest concentrations (approximately 0.5-1.6 ug/L).

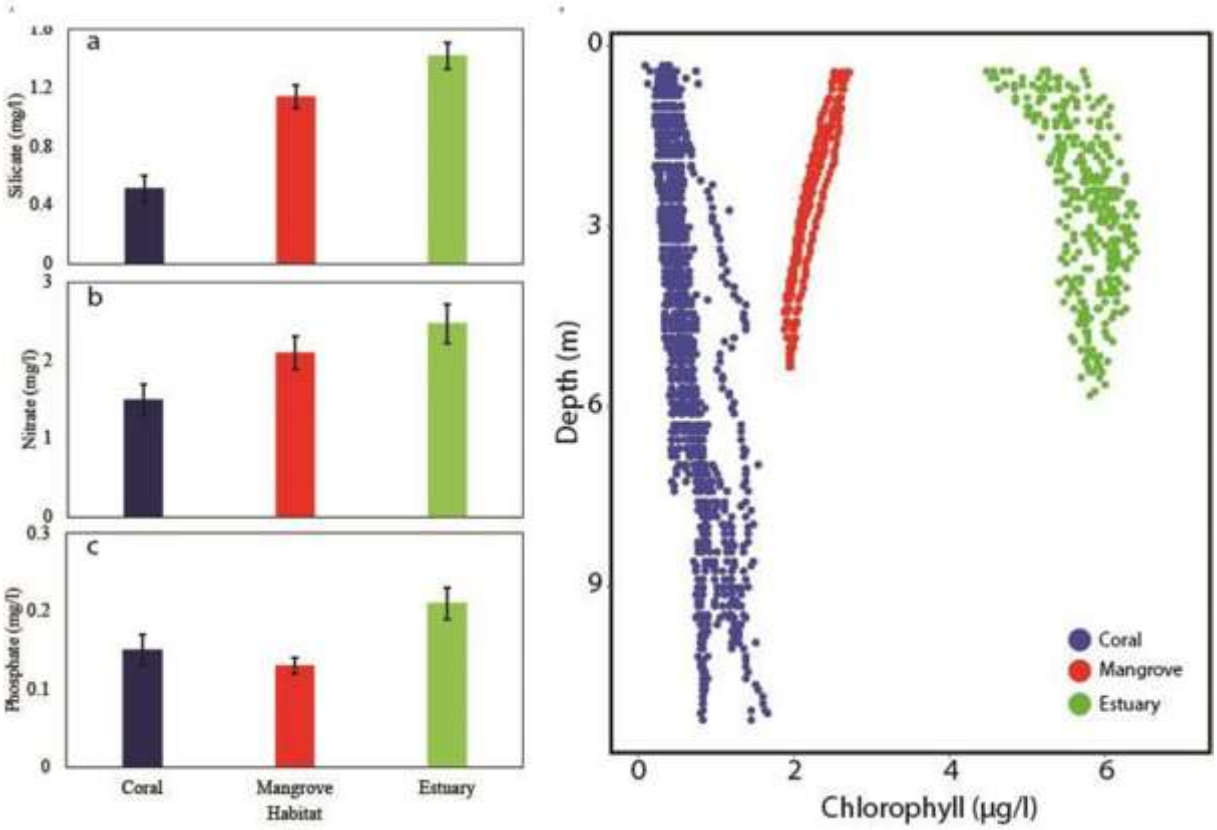

Figure 4. Nutrient and chlorophyll patterns across habitats. (A) Mean silicate, nitrate, and phosphate concentrations with standard-deviation error bars. (B) Vertical distribution of chlorophyll concentration in coral, mangrove, and estuarine habitats.

3.4. Species-Level Associations with Environmental Variables

Species-level heat maps indicated heterogeneous responses to the measured environmental gradients. Silicate showed comparatively strong associations with several taxa, including Triceratium, Leptocylindrus, Chaetoceros, Tintinnopsis, Prorocentrum, Dinophysis, and Coscinodiscus taxa. Across many taxa, the apparent effects of temperature, zooplankton abundance, and turbidity were smaller than those associated with nutrients, although the magnitude and direction of relationships varied among species.

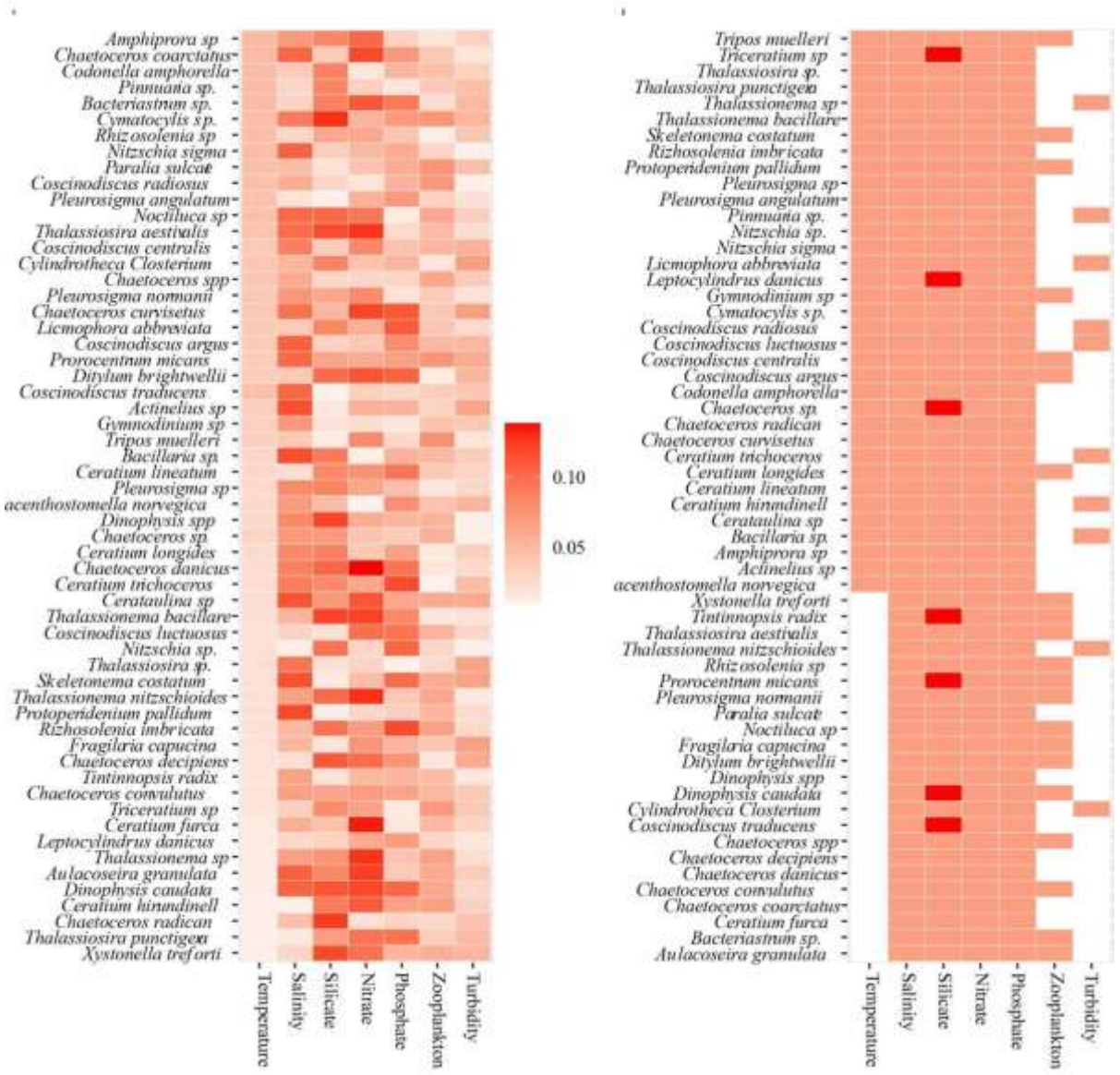

Figure 5. Species-level environmental associations from the original analysis. (A) Relative magnitude of variance associated with individual explanatory variables across phytoplankton taxa. (B) Heat map of environmental effects across taxa as presented in the source analysis. Darker cells indicate stronger effects in the original figures.

3.5. Plankton Community Structure

Shannon diversity differed among habitats. The mangrove habitat had the highest phytoplankton diversity (H = 2.89), followed by the estuary (H = 2.56), while the coral reef habitat had the lowest diversity (H = 2.01). Functional-group composition also differed. Dinoflagellates contributed approximately 60% of phytoplankton abundance in the coral reef habitat, whereas diatoms dominated the mangrove and estuarine habitats, contributing approximately 55% and 90%, respectively. Zooplankton abundance was highest in the estuary (log abundance = 5.79), followed by the mangrove (5.14) and coral reef (approximately 5.0) habitats.

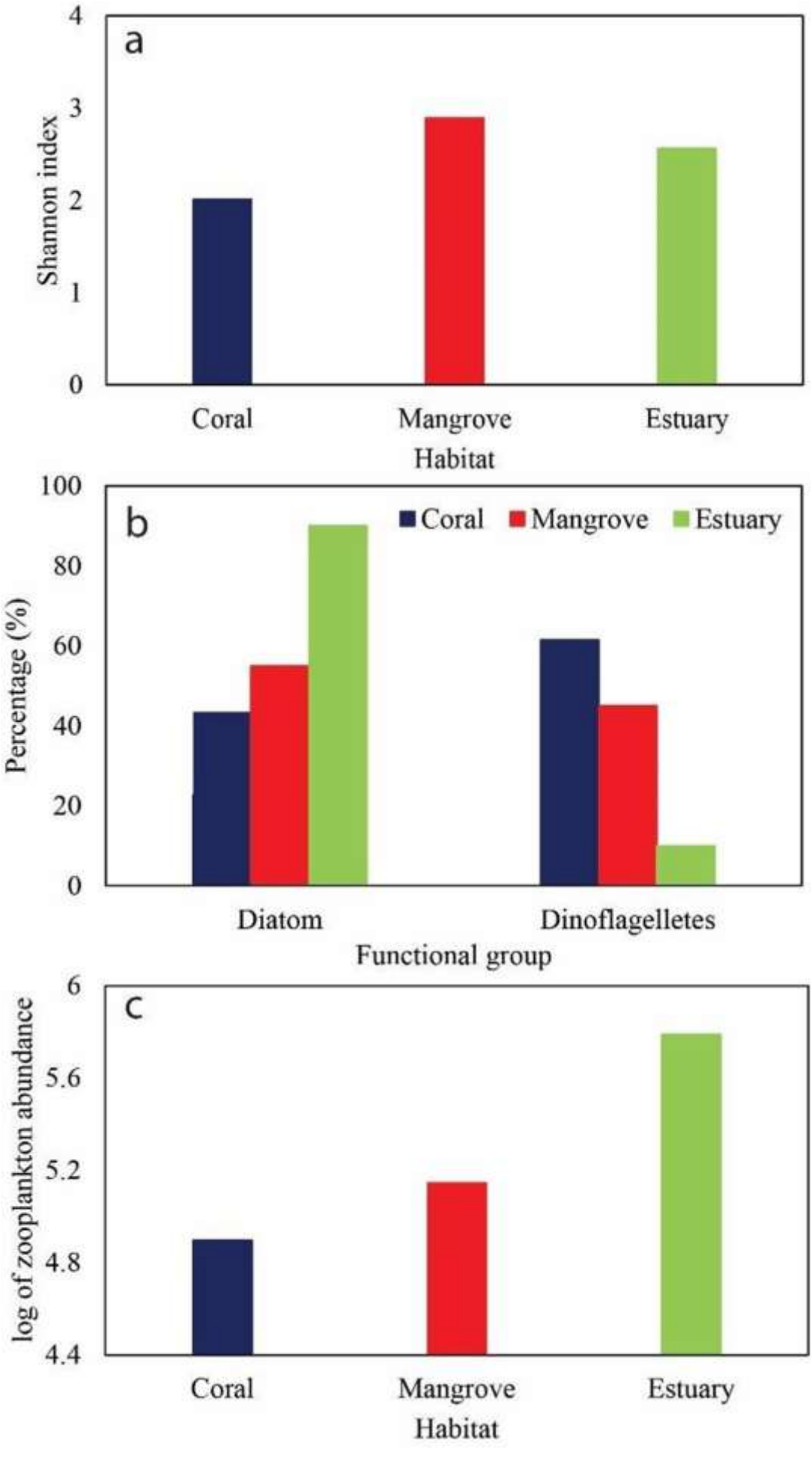
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Figure 6. Plankton community characteristics in coral, mangrove, and estuarine habitats: (a) Shannon diversity index, (b) contribution of major phytoplankton functional groups, and (c) log-transformed zooplankton abundance.

3.6. Dominant Taxa and Habitat Differentiation

Dominant taxa varied among habitats. In coral reef waters, Ceratium trichoceros contributed approximately 15% of total phytoplankton abundance, followed by Cylindrotheca closterium (11%), Ceratium furca (10%), Dinophysis sp. (9%), Chaetoceros coarctatus (8%), and Rhizosolenia sp. (7%). Collectively, Ceratium and Chaetoceros taxa contributed about 24% and 13% of total abundance, respectively. In the mangrove habitat, Coscinodiscus traducens (13%), C. argus (12%), Chaetoceros decipiens (7%), and Xystonella treforti (6%) were major contributors; Coscinodiscus and Chaetoceros taxa together contributed about 42% and 14%, respectively. The estuary was strongly dominated by Coscinodiscus taxa, which contributed about 65% of total phytoplankton abundance.

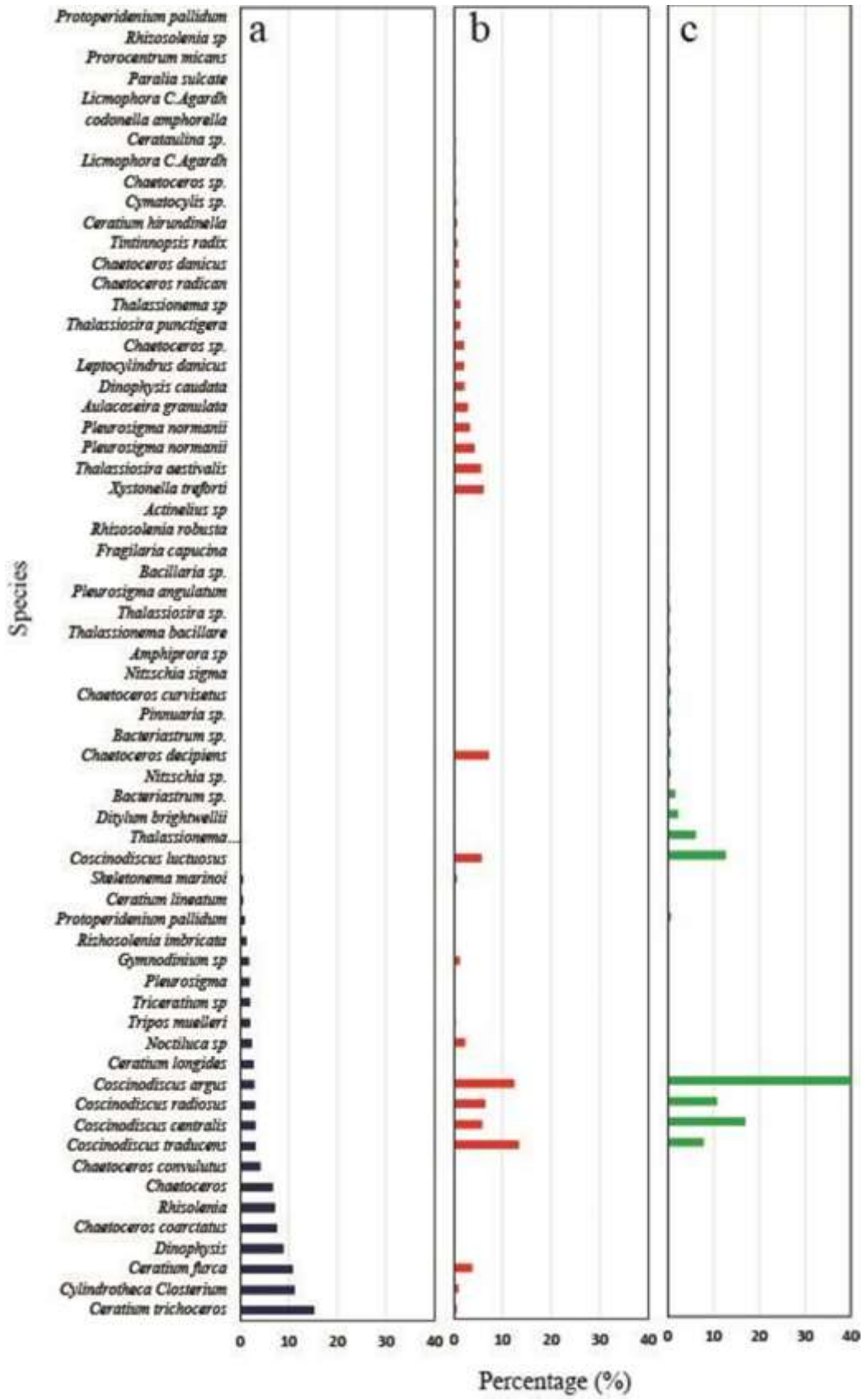


Figure 7. Contribution of major individual phytoplankton taxa to total abundance in (a) coral reef, (b) mangrove, and (c) estuarine habitats.

The nMDS ordination showed clear separation among the three habitat types based on their combined environmental and biological characteristics, with the estuarine, mangrove, and coral samples forming distinct clusters.

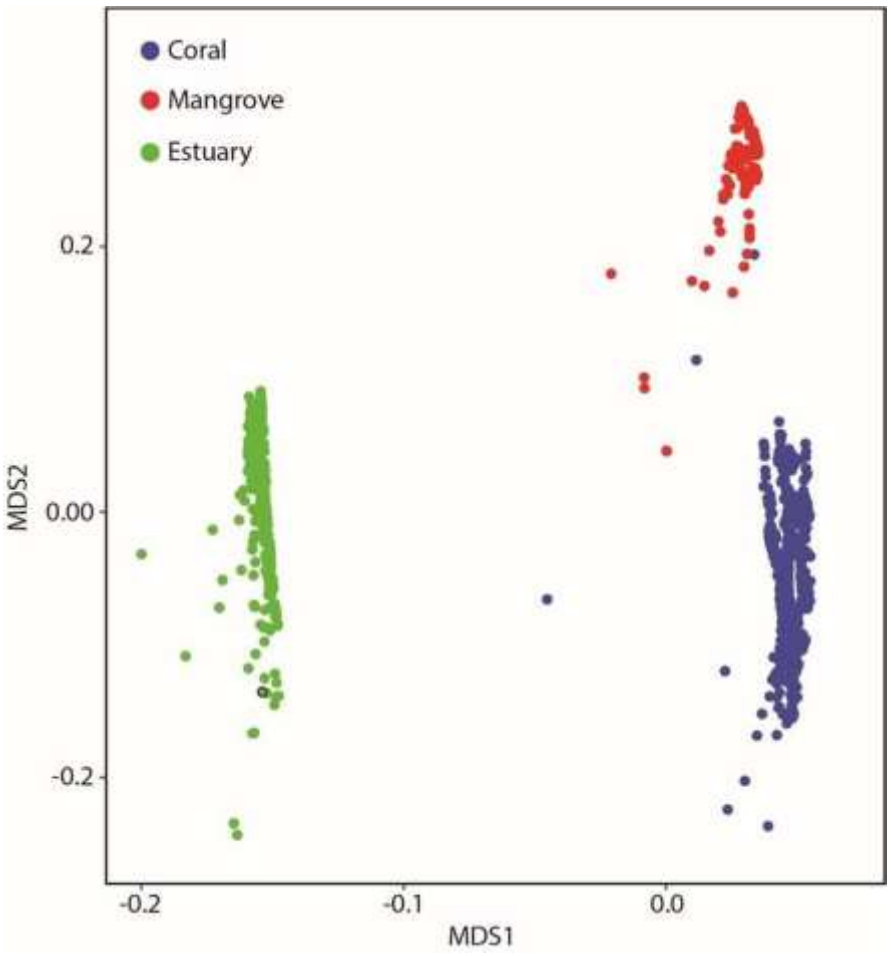


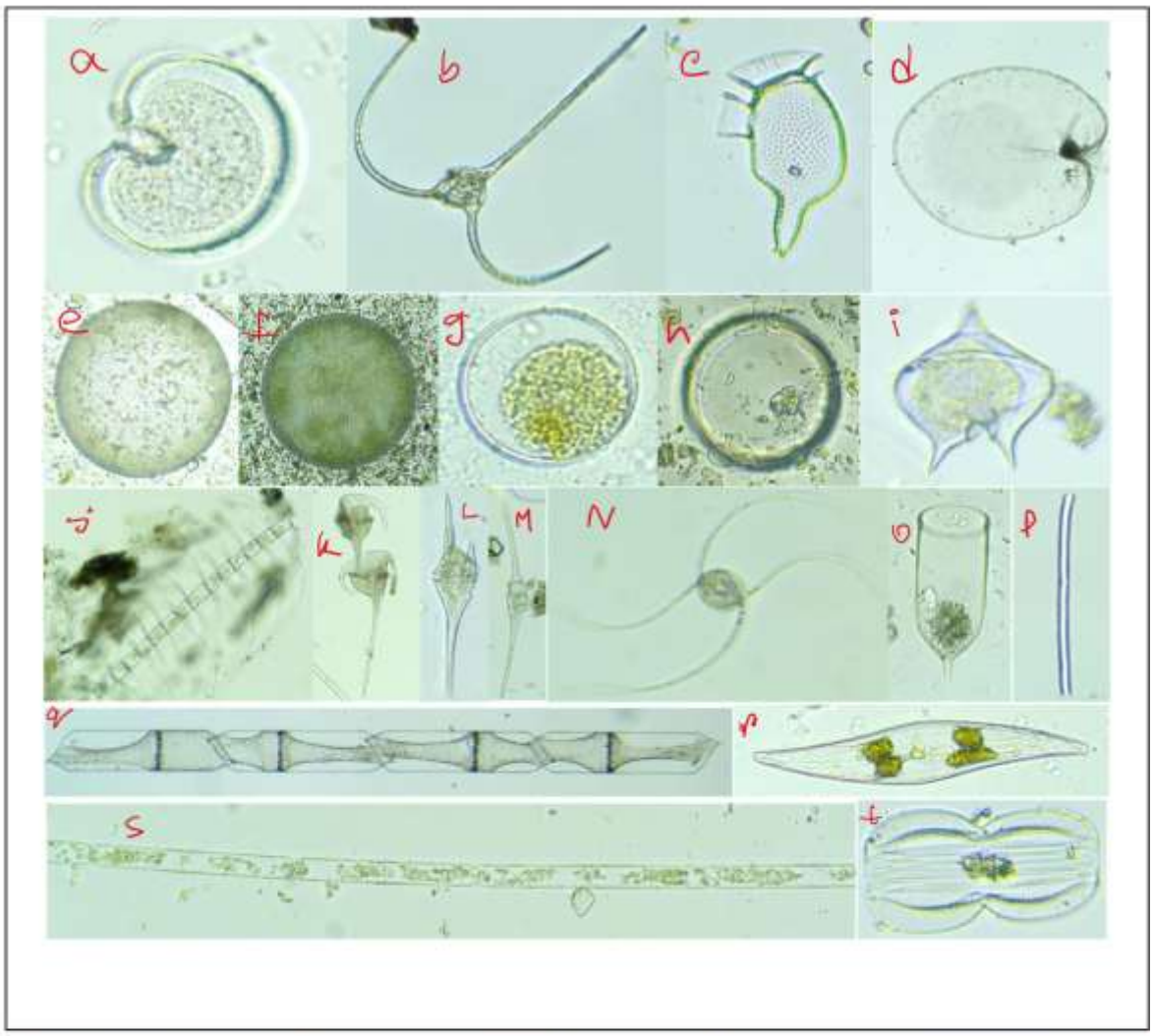
Figure 8. Non-metric multidimensional scaling (nMDS) ordination of habitat characteristics based on environmental and biological variables.

Table 1. Major phytoplankton functional groups, genera, representative species, and approximate contribution to total phytoplankton abundance by habitat.

Habitat	Functional group	Genus	Representative species	Contribution
Coral	Dinoflagellates	Ceratium	C. trichoceros; C. furca; C. longipes; C. lineatum	~24%
Coral	Diatom	Chaetoceros	C. coarctatus; C. lauderi; C. diadema	~13%
Mangrove	Diatom	Coscinodiscus	C. traducens; C. argus; C. radiosus; C. centralis; C. luctuosus	~42%
Mangrove	Diatom	Chaetoceros	C. decipiens; C. convolutus; C. radicans; C. danicus	~14%
Estuary	Diatom	Coscinodiscus	C. argus; C. centralis; C. luctuosus; C. radiosus; C. traducens	~65%

3.7. Micrographic Documentation of Phytoplankton

Microscopic observations documented a taxonomically diverse assemblage across the three habitats, including representatives of Ceratium/Tripos, Coscinodiscus, Chaetoceros, Thalassiosira, Rhizosolenia, Pleurosigma, Dinophysis, and other genera. These image plates provide visual documentation of the taxa recorded in the source study.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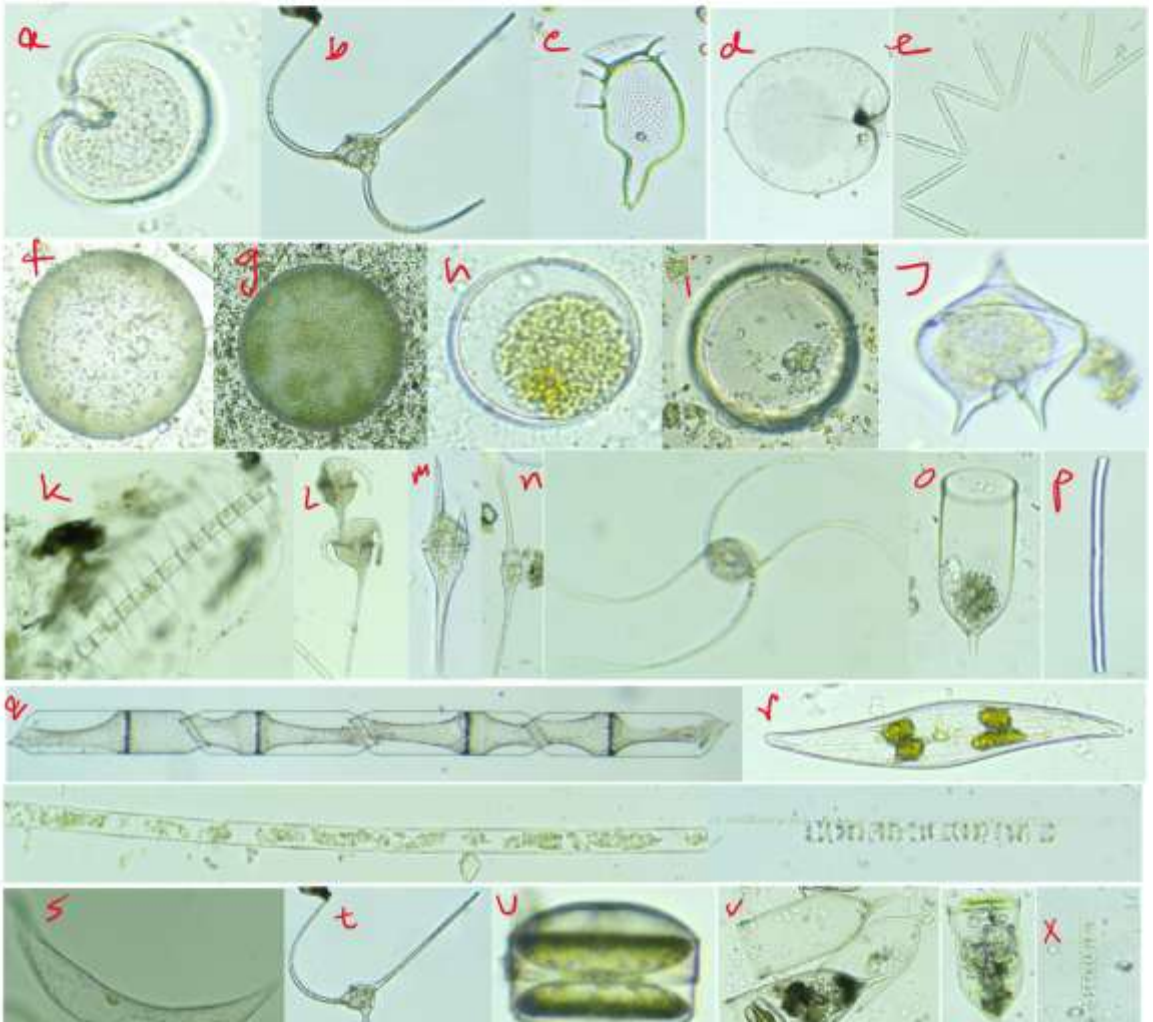
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Figure 9. Representative phytoplankton micrographs from the source study. (A) Teknaf coast, (B) Saint Martin's coast, and (C) Meghna River estuary. Letter labels correspond to the taxon annotations in the original image plates.

3.8. Drivers of Phytoplankton Variability

Multicollinearity screening indicated a strong relationship between turbidity and silicate, and turbidity was removed from the final multivariable analysis under the VIF criterion. Model selection further retained temperature, salinity, silicate, nitrate, phosphate, and zooplankton abundance as the six explanatory variables used for habitat-specific interpretation. Together, these variables explained 61% of phytoplankton variability in coral reef waters, 60% in mangrove waters, and 63% in the estuary.

The relative contribution of individual predictors differed by habitat. In the coral reef habitat, phosphate explained the largest share of variability (20%), followed by zooplankton abundance (15%), nitrate (10%), salinity (6%), temperature (5%), and silicate (5%). In the mangrove habitat, phosphate contributed 15%, silicate 14%, nitrate 12%, zooplankton 8%, temperature 6%, and salinity 5%. In the estuary, silicate was the strongest explanatory variable (22%), followed by phosphate (13%), nitrate (10%), zooplankton (7%), salinity (6%), and temperature (5%).

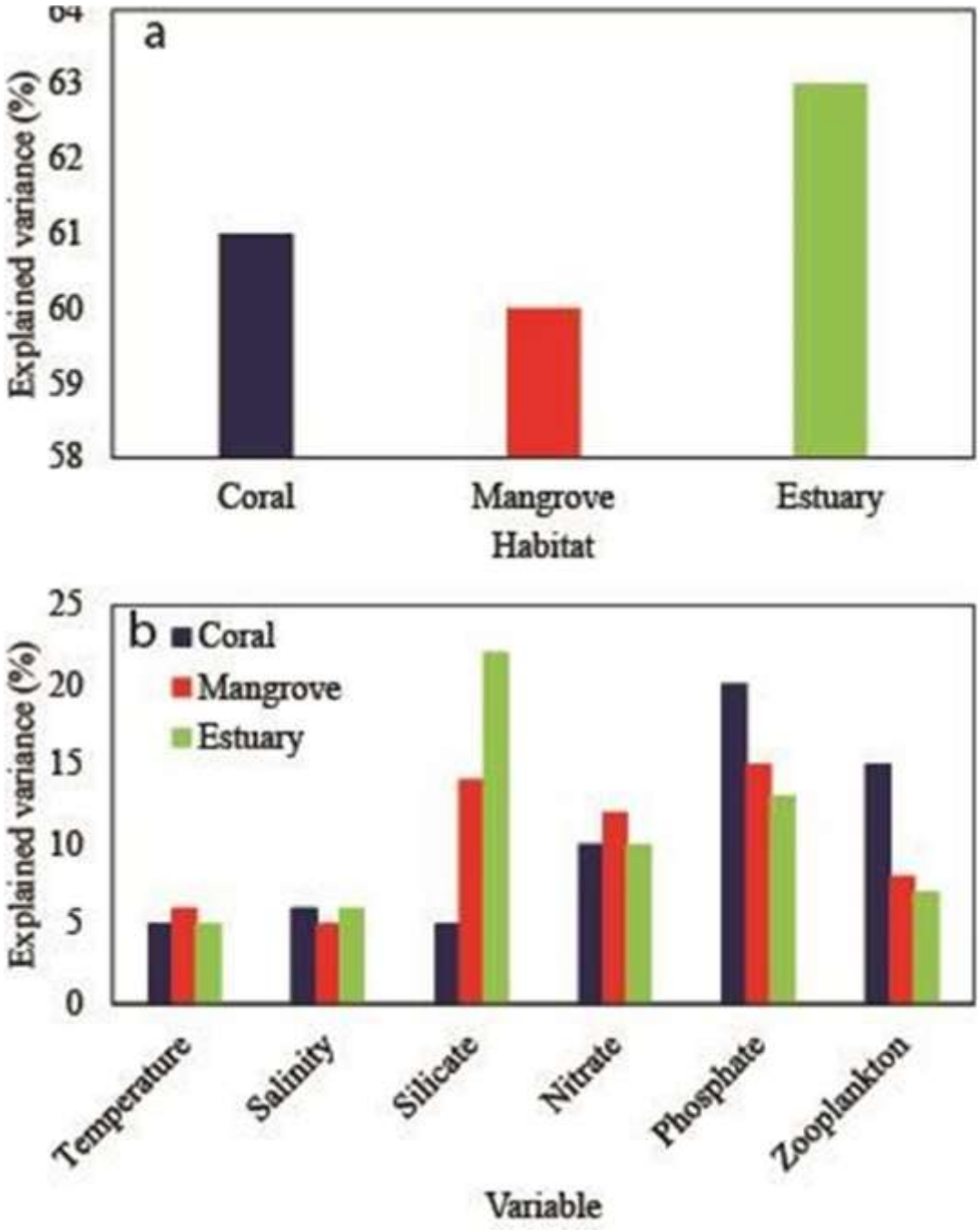

Figure 10. Proportion of phytoplankton variability explained by the selected predictors. (a) Joint explained variability of the six-predictor models across habitats. (b) Relative contribution of individual explanatory variables.

4. Discussion

4.1. Habitat-Scale Environmental Contrasts

The three habitats differed strongly in salinity, turbidity, nutrient status, chlorophyll concentration, and plankton community structure. These contrasts are consistent with their differing hydrological settings. The Meghna estuary receives large freshwater and sediment inputs and therefore exhibited low salinity, high turbidity, and high nutrient concentrations. The mangrove-influenced Teknaf coast showed intermediate conditions, while Saint Martin's coral waters were more marine, less turbid, and comparatively nutrient-poor. Such habitat-scale gradients are expected to affect phytoplankton through changes in nutrient delivery, light climate, residence time, and physical mixing (Moore et al., 2013; Sarker et al., 2020a).

The high estuarine chlorophyll concentrations are consistent with the high nutrient concentrations measured in the same habitat. By contrast, lower chlorophyll around Saint Martin's Island coincided with lower nutrient availability. This pattern supports the view that nutrient supply is a major control on phytoplankton biomass in these coastal habitats, although the present dry-season sampling design does not resolve seasonal variability.

4.2. Nutrient and Zooplankton Controls

The habitat-specific models consistently identified nutrient variables as important explanatory factors. Phosphate accounted for the largest individual share of phytoplankton variability in coral and mangrove waters, while silicate was the strongest predictor in the estuary. Nutrient limitation is a well-established control on marine primary producers, and shifts in the relative availability of nitrogen, phosphorus, and silicate can influence both total biomass and community composition (Howarth, 1988; Moore et al., 2013). The strong silicate signal in the estuary is especially consistent with the dominance of diatoms, which require silica for frustule formation and are often favored where silicate supply is high (Kim et al., 2007; Sarker, 2018).

Zooplankton abundance also explained a notable share of variability, particularly in coral reef waters. Phytoplankton provide the primary food resource for many zooplankton, and grazing can feed back on phytoplankton abundance and taxonomic composition (Sarker and Wiltshire, 2017; Wiltshire and Boersma, 2016). The comparatively large zooplankton contribution in the coral habitat therefore suggests that trophic interactions may be especially important where nutrient concentrations are lower. Because only total zooplankton abundance was available, however, the analysis cannot identify which grazer groups were responsible for this relationship.

4.3. Habitat-Specific Community Composition

Community composition differed markedly across the habitat gradient. The estuary and mangrove habitat were diatom-dominated, whereas the coral habitat was dominated by dinoflagellates. Coscinodiscus taxa contributed about 65% of estuarine phytoplankton abundance and about 42% in the mangrove habitat. In coral reef waters, Ceratium/Tripos and Chaetoceros taxa were prominent, and dinoflagellates contributed the largest functional-group share. These patterns are consistent with the idea that nutrient regime, salinity, mixing, and grazing pressure jointly filter phytoplankton taxa across coastal habitats (Dagenais-Bellefeuille and Morse, 2013; Mutshinda et al., 2013; Wiltshire et al., 2015).

The nMDS ordination reinforced the strong ecological differentiation among the three habitats. Because the source analysis did not report a separate permutation-based hypothesis test for the ordination, the present manuscript interprets the nMDS as evidence of clear multivariate separation rather than as a formal test of statistical significance.

4.4. Study Limitations and Implications

Two limitations are particularly important. First, sampling was restricted to the dry season, so the results do not capture monsoon-driven changes in freshwater discharge, nutrient loading, turbidity, and salinity. Seasonal sampling could therefore alter both the magnitude and ranking of environmental drivers. Second, zooplankton were represented by total abundance rather than taxonomic or functional composition; more detailed grazer data would allow stronger inference about trophic controls on phytoplankton.

Despite these limitations, the study provides a direct cross-habitat comparison of estuarine, mangrove-influenced, and coral reef waters along the Bangladesh coast. The results emphasize that

nutrient supply is a common control across habitats, but the dominant nutrient and the relative importance of zooplankton differ among ecosystems. This habitat-specificity should be considered when interpreting coastal productivity and ecosystem responses to changes in river discharge, nutrient loading, and coastal environmental conditions.

5. Conclusions

Phytoplankton community dynamics differed substantially among the Meghna River estuary, Teknaf mangrove coast, and Saint Martin's coral reef waters. The estuary was characterized by low salinity, high turbidity, high nutrient concentrations, high chlorophyll, and strong dominance by diatoms, particularly Coscinodiscus. The mangrove habitat also supported a diatom-dominated community and had the highest Shannon diversity, whereas the coral reef habitat was more saline, nutrient-poor, and dominated by dinoflagellates. Across habitats, nutrient variables were the principal explanatory factors, with phosphate most important in coral and mangrove waters and silicate most important in the estuary; zooplankton also played a substantial role in coral waters. These findings demonstrate that phytoplankton dynamics across tropical coastal habitats are structured by habitat-specific combinations of nutrient supply, hydrographic setting, and trophic interactions. Future work should incorporate wet-season sampling and taxonomically resolved zooplankton data to evaluate how these controls vary through time.

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Institutional Review Board Statement

Not applicable. This study involved environmental sampling and plankton observations and did not involve human participants or experimental animals.

Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

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