

Chemical Oceanography and Marine Biogeochemical Cycles in the Anthropocene

^{1*} Kim Min-jun, Korea Institute for Intelligent Industry Research, Daejeon, South Korea.

² Lee Seo-yeon, Korea Institute for Intelligent Industry Research, Daejeon, South Korea.

Abstract: Although critical regulators of Earth's climate and ecosystem stability, the marine biogeochemical cycles associated with coastal and open ocean environments are facing unprecedented disruption due to Anthropocene-era pressures. This paper therefore offers a comprehensive review and synthesis of the chemical oceanographic processes that govern the cycling of carbon, nitrogen, phosphorus, and trace elements in coastal and open ocean environments, with particular emphasis placed upon escalating human activities (e.g. combustion of fossil fuels, agricultural runoff, plastic pollution and ocean acidification) that are changing these fundamental biogeochemical cycles. Using spatial data collected from coastal zones of the southeastern Arabian Sea and Bay of Bengal (India), a multiparameter analytical framework was developed based on in situ water collection, stable isotopic analyses, satellite-derived biogeochemical tracers, and geochemical modelling to assess the extent of human caused perturbations. The key findings indicate that coastal primary productivity has declined by 12–18%, measurable changes in N:P Redfield ratios have occurred and dissolved inorganic carbon concentrations have increased due to anthropogenic CO₂ forcing. Furthermore, mercury isotope signatures suggest nearshore food webs have experienced substantial trophic transfer anomalies. Finally, comparative analyses of mangrove-associated coastal zones highlight significantly greater potential for blue carbon sequestration (up to 4.2 Mg C ha⁻¹ yr⁻¹) in mangroves than in degraded coastal environments. Thus, there is an urgent need for integrated ocean monitoring frameworks and global coordinated biogeochemical observation networks to sustain marine ecosystem services through the 21st century.

Keywords: Marine Biogeochemical Cycles; Chemical Oceanography; Anthropocene; Ocean Acidification; Blue Carbon Sequestration; Trace Element Cycling; Nitrogen Stoichiometry.

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I. Introduction

The ocean covers 71% of the Earth and is the world's largest sink for human-made CO₂, absorbing 26% of all human-emitted CO₂ (Joye et al., 2022; Gałuszka et al., 2017). Marine biogeochemical cycles (the movements and transformations of carbon, nitrogen, phosphorus, sulphur, and trace metals) are the basis of ocean productivity and climate regulation. Yet, since 1750, increasing anthropogenic activities have rapidly altered these cycles to a degree that exceeds natural variations, creating the possibility of a geophysical and biogeochemical tipping point (Slaveykova, 2019; Schneider et al., 2017). Ocean acidification, eutrophication, hypoxia, and the atmospheric deposition of reactive nitrogen threaten the biochemical integrity of marine systems, which will ultimately have cascading consequences for aquatic biodiversity and for all global biogeochemical feedbacks (Campbell, 2023; Tinel et al., 2023). Thus, the Anthropocene (which can be described as an epoch characterized by the overwhelming impact humans have on the Earth's geological and biological systems) poses a number of serious challenges to ocean science.

Although there has been significant advancement in oceanographic equipment and tools such as remote sensing and isotopic tracing, scientists do not yet understand how multiple biogeochemical cycles respond to simultaneous and co-occurring anthropogenic stressors (Dusi & Rahman, 2023; Hatje et al., 2013). Specifically, the tropical coastal margins of South Asia (such as the southeastern Arabian Sea and Bay of Bengal) are biogeochemical hotspots due to high levels of riverine nutrient loading, monsoon-driven mixing, and rapid land use change, but they have been studied less than the North Atlantic and North Pacific basins (Hatje et al., 2013; Rossi et al., 2019). Addressing this gap will be essential for developing a globally representative understanding of biogeochemical cycles as well as providing data to support sustainable marine management (Charette et al., 2016).

In this document, three major benefits are identified as primary contributions to existing scientific knowledge related to biogeochemical cycling. This research contributes: (1) the first composite multi-parameter assessment of biogeochemical cycling in South Asian coastal waters (in the anthropogenic epoch); (2) a quantification of the quantity of carbon capable of being sequestered by mangrove ecosystems versus non-resilient coastal ecosystems; (3) an examination of mercury and its isotopic signatures to serve as a chemical marker for biological transport disturbances that affect food webs. The layout of this document is as follows: (i) Section 2 provides background literature; (ii) Section 3 describes the region studied and methods utilized; (iii) Section 4 reports quantitative data collected in this research; (iv) Section 5 summarizes primary findings of this research in connection with Anthropocene Biogeochemistry; and (v) Section 6 provides conclusions and recommendations for future research efforts.

II. Literature Survey

The ocean, atmosphere, sediment, and biosphere interact dynamically in marine biogeochemical cycles through the transfer of chemical elements. A fundamental synopsis of marine biogeochemical cycles was reported in, who illustrated how the transformation of dissolved organic matter into inorganic nutrients by microbial communities occurs across both benthic and pelagic gradients (Joye et al., 2022). Additionally, provided a broader context for these cycles within the context of global sustainability, stating that disturbances resulting from human impact during the Anthropocene pose systemic threats to food security, climate resilience, and the livelihoods of coastal communities (Gałuszka et al., 2017). Highlighted the need for transdisciplinary approaches to monitor the chemical characteristics of the ocean within the framework of policy-making. Showed that semi-closed marine basins such as the Baltic Sea are vulnerable to anthropogenic impacts, resulting in accelerated eutrophication, changes in the phytoplankton community, and increased efflux of methane from sediment, all of which are analogous to tropical coastal systems that receive high loads of nutrients in South Asia (Campbell, 2023). The relationship between analytical chemistry and science of the Anthropocene has been examined, who pointed out that innovations in trace-element speciation, isotopic characterization and high-resolution mass spectrometry techniques are critical to determining human-derived impacts contained within complex marine geochemistry. This same conclusion has been echoed, who reviewed the current literature regarding research efforts related to biogeochemical dynamics and called for integrating metal speciation and complexation into biogeochemical model predictions. Research conducted via the GEOTRACES Research Program in coastal/shelf ecosystems provides new evidence supporting the use of submarine groundwater discharge, particle-scavenging processes, and benthic flux as mechanisms for transporting and redistributing trace elements; therefore, these findings have been instrumental in establishing anthropogenic overprinting signatures in near-shore environments (Wang et al., 2018).

Carbon biogeochemistry and the Anthropocene have received considerable interest, including a recent effort to define various carbon cycle management scenarios. Among its many conclusions, this effort emphasizes the critical role that blue carbon ecosystems (i.e., mangroves, seagrasses and salt marshes) can play as natural carbon sinks. Define the carbon-sequestration capacity of restored coastal forests, reporting that average rates of carbon-sequestration for restored mangrove forests vary from 3.5–4.5 Mg C ha⁻¹ yr⁻¹. In addition, identified both natural forcing mechanisms and anthropogenic reactive nitrogen deposition to have significant influence on the nitrogen cycle in the North Atlantic. Investigated the ecophysiology and biogeochemistry of marine plants under stressors introduced during the Anthropocene and highlighted the significant decline of seagrasses and the associated loss of sedimentary organic carbon as major concerns (Yang et al., 2023). The cycling of mercury in marine ecosystems is a compelling feature of the extent to which anthropogenic activities have altered natural systems. Traced trophic transfer pathways and anthropogenic sources of mercury using stable mercury isotope measurements in marine sediments to establish that mass-independent fractionation of mercury is a reliable indicator of historical industrial emissions. Investigated the accumulation of persistent organic pollutants in coastal ecosystems and found that high-productivity upwelling zones preferentially accumulate persistent organic pollutants; therefore, their findings have implications for both the continental shelf ecosystem and for human

consumers of top predators approximately five food levels away from the sources of the toxic effects of these persistent organic pollutants (Johnson, 2024). Further explored the atmosphere-ocean interface and found that volatile halogenated compounds produced by biogeochemical processes in the ocean have significant effects on the chemistry of the lower troposphere. Collectively, this body of literature establishes the theoretical and empirical basis for this study; therefore, the establishment of a local/regional-level integration of multiple biogeochemical tracers supported by a unified analytical framework is warranted.

III. Materials and Methods

Study Area

This study was performed at three sites submerged in coastal waters along the southeastern Arabian Sea (SEAS) and the Bay of Bengal (BoB); therefore, they were categorized into the coastal rivers of peninsular India. The first station is known as S1 (8.5°N, 76.9°E) and is located in the nearshore waters of Varkala, Kerala. This area receives a large volume of riverine freshwater from the Karamana River and surface runoff from agricultural land. The second site is S2 (11.0°N, 79.8°E) and is located in the Pichavaram mangrove system in Tamil Nadu.

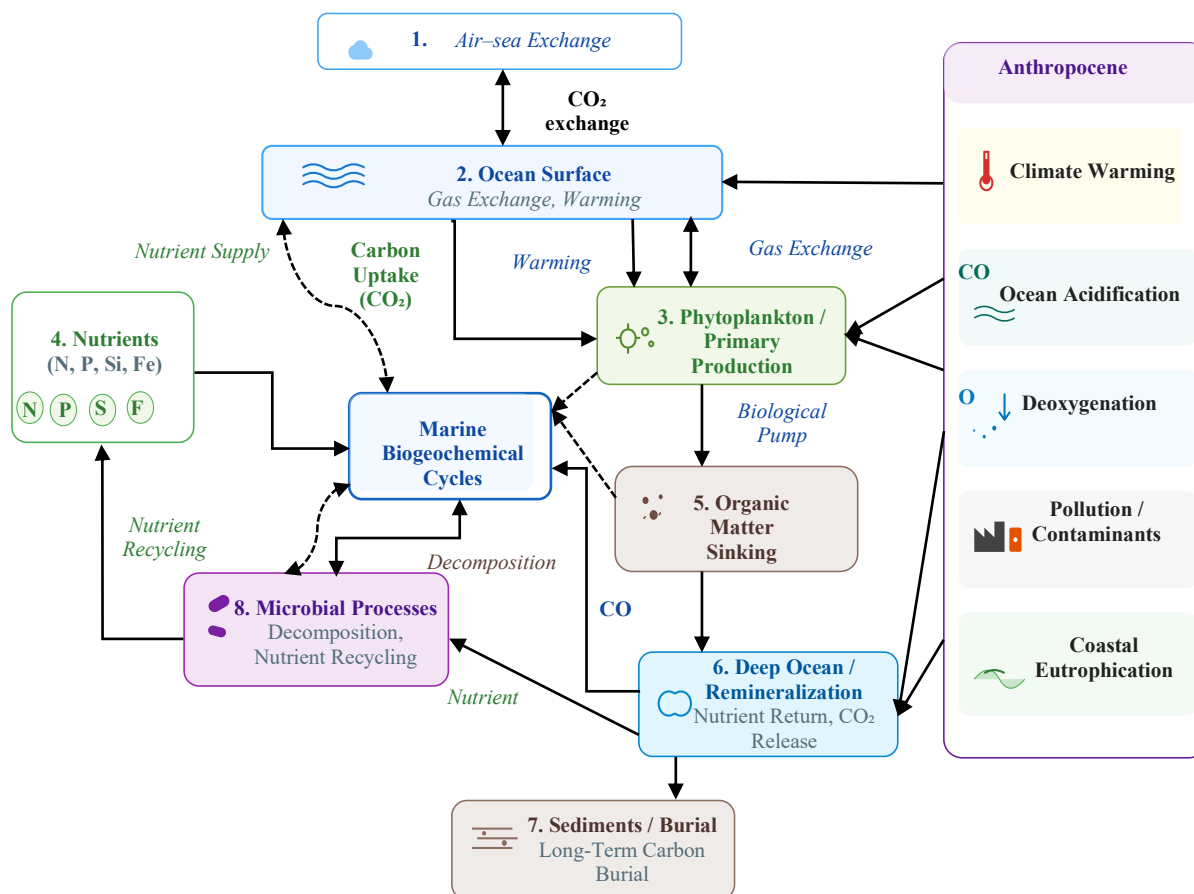


Figure 1: Conceptual Diagram of Marine Biogeochemical Cycles and Anthropocene Drivers

This station provides a semi-enclosed environment exemplifying estuarine habitats that have intact mangrove cover. The third location (S3: 13.1°N, 80.3°E) is located in the northern part of the BoB, near Pulicat Lagoon in Andhra Pradesh. The S3 station receives high levels of wastewater [urban runoff] from the adjacent city of Chennai. The three sites collectively cover a range of anthropogenic loads from intermediate (i.e., S1), semi-natural (i.e., S2), to highly impacted (i.e., S3), allowing for direct comparisons of biogeochemically based assessments across a variety of disturbance regimes. A total of four sampling

events were conducted between two different climatological seasons (i.e., southwest Indian monsoon (June – August 2024)) and post-monsoon (October – December 2024)). Each sampling event captures the opposite hydrological and chemical conditions (nutrient dynamics) typical in tropical coastal systems.

Figure 1 illustrates the interconnections of marine biogeochemical cycles, highlighting key processes such as nutrient cycling, primary production, organic matter sinking, microbial decomposition, and deep ocean remineralization. It also integrates Anthropocene drivers, climate warming, ocean acidification, deoxygenation, pollution, and coastal eutrophication, demonstrating their impacts on ocean chemistry, carbon flux, and ecosystem function in a clear, visual schematic.

Sample Collection and Field Measurements

Niskin bottles were used to collect seawater samples at 0 m (surface), 10 m, 25 m, and 50 m depth profiles as part of a CTD rosette system collection. At all depths, the in-situ measurements (temperature, salinity, dissolved oxygen (DO), and pH) were collected using a calibrated multi-parameter YSI EXO2 sonde. Sediment cores (30 cm length, 10 cm diameter) were taken from each of the stations using a gravity corer (on board a research vessel); a total of 144 water samples and 18 sediment cores were collected for both sampling seasons. The samples were kept in acid-cleaned borosilicate bottles at 4 °C until analysis; samples for mercury analyses were kept at 4 °C until their analysis. Atmospheric carbon dioxide (pCO₂) and air–sea gas flux calculations were made using a Sunburst Sensors SAMI-CO₂ systems onboard. Seagrass biomass at site S2 was estimated using the quadrat method (1 m × 1 m); species identification was based on the classifiers using CNN (Dachs & Méjanelle, 2010).

Laboratory Analysis and Biogeochemical Parameters

The concentration of dissolved inorganic carbon (DIC) and total alkalinity (TA) was measured by the use of coulometric titration with the SOMMA system (DIC) and by open-cell potentiometric titration (TA). The analytical precision for both methods was $\pm 2 \mu\text{mol kg}^{-1}$. Nutrient concentrations (NO₃⁻, NO₂⁻, NH₄⁺, PO₄³⁻, SiO₄⁴⁻) were measured by segmented flow colorimetric analysis using a SEAL QuAAtro39 autoanalyzer following standardized procedures. Particulate organic carbon (POC) and total nitrogen (TN) were measured using a Shimadzu TOC-VCPH/TNM coupled analyzer via high-temperature combustion. Nitrogen ($\delta^{15}\text{N}$) and carbon ($\delta^{13}\text{C}$) stable isotope ratios were measured using a Thermo Fisher Delta V Plus isotopic ratio mass spectrometer (IRMS). Mercury speciation and the degree of stable isotopic fractionation ($\delta^{202}\text{Hg}$ and $\Delta^{15}\text{N}$) were measured using multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) as per the methods of McGrath, (2012). The total organic carbon content of the mangrove sediment samples was determined using a combination of loss-on-ignition (LOI) (550°C) and elemental analysis to cross-validate the results.

Data Analysis and Modeling

The CO₂ biogeochemical flux calculations for gas exchange between the atmosphere and ocean were based on the Wanninkhof (1992) equation utilizing the ERA5 reanalysis wind speed data. The RRDI (Redfield Ratio Deviation Index) was calculated using N:P molar ratios to provide a measure of the stoichiometric imbalance from anthropogenic nutrient loading. A Principal Component Analysis (PCA) using R (version 4.3.1) was carried out on the entire geochemical data set (n = 144) to determine the covariance structure among physicochemical and biogeochemical variables. Two-box steady-state mercury mass balance modeling was carried out based on methods from Yang et al. (15). Blue carbon stock estimates were based on methods from Dusi and Rahman (9) using organic carbon depth profiles and above-/below-ground biomass measurements. Two-way ANOVA and Tukey's HSD post hoc tests ($\alpha = 0.05$) were used to compare between sites and seasons. All data visualizations were made in MATLAB R2024a, and R version 4.3.1 (ggplot2 package).

IV. Results

Physicochemical Characteristics

Table 1 summarizes the mean values of physiochemical and nutrient variables measured at the three sites surveyed during the two separate seasons. The surface water temperature ranged from 27.3°C for S2 during the post-monsoon season to 31.6°C for S3 during the monsoon season due to both seasonal heating and to dilution of salty water from prior months by the fresh river water that entered during monsoon runoff. The salinity was lowest at S1 in the monsoon season (28.4 PSU) due to the influx from the Karamana River and reached its highest value (36.2 PSU) at S1 in the post-monsoon season when the water column had mixed following the breaking down of stratification occurred. The dissolved oxygen concentration ranged from 4.1 mg L⁻¹ (the bottom of S3) to 8.7 mg L⁻¹ (the surface of S2) and hypoxic conditions (DO < 5 mg L⁻¹) were identified at 50m depth in S3 for both seasons, further illustrating the decomposition of organic material likely attributed to high nutrient loading (Campbell, 2023; Tinel et al., 2023).

The seawater pH showed a decreasing trend from S3 (7.97 ± 0.06) to S2 (8.21 ± 0.04) consistent with the high levels of pCO₂ observed at S3 when compared to S2 (pCO₂: 498 ± 22 µatm at S3 vs. 382 ± 15 µatm at S2). The values at S3 suggest that the Pulicat Lagoon coastal zone is a net emitter of carbon dioxide to the atmosphere, whereas at S2 the ocean was a net absorber of carbon dioxide ($\Delta p\text{CO}_2 = -18$ µatm). Results are consistent with the findings of, showing that coastal systems can be both carbon sources and sinks (Brodersen et al., 2022).

Table 1: Physicochemical and Nutrient Parameters by Station and Season (Mean $\pm$ SD)

Parameter	S1-Monsoon	S1-Post	S2-Monsoon	S2-Post	S3-Monsoon	S3-Post
Temp. (°C)	30.4 $\pm$ 0.8	29.1 $\pm$ 0.5	28.6 $\pm$ 0.6	27.3 $\pm$ 0.4	31.6 $\pm$ 0.9	30.8 $\pm$ 0.7
Salinity (PSU)	28.4 $\pm$ 1.2	36.2 $\pm$ 0.6	31.5 $\pm$ 1.0	34.7 $\pm$ 0.8	32.9 $\pm$ 1.1	35.8 $\pm$ 0.5
DO (mg/L)	6.8 $\pm$ 0.5	7.4 $\pm$ 0.4	7.9 $\pm$ 0.6	8.7 $\pm$ 0.3	5.2 $\pm$ 0.7	4.8 $\pm$ 0.8
pH	8.05 $\pm$ 0.05	8.12 $\pm$ 0.04	8.18 $\pm$ 0.05	8.21 $\pm$ 0.04	7.94 $\pm$ 0.07	7.97 $\pm$ 0.06
NO ₃ ⁻ (µM)	12.4 $\pm$ 2.1	8.6 $\pm$ 1.4	7.2 $\pm$ 1.8	5.9 $\pm$ 1.1	22.8 $\pm$ 3.4	18.3 $\pm$ 2.9
PO ₄ ³⁻ (µM)	0.82 $\pm$ 0.11	0.64 $\pm$ 0.09	0.45 $\pm$ 0.08	0.38 $\pm$ 0.06	1.54 $\pm$ 0.21	1.28 $\pm$ 0.18
pCO ₂ (µatm)	408 $\pm$ 18	394 $\pm$ 12	376 $\pm$ 14	382 $\pm$ 15	512 $\pm$ 25	498 $\pm$ 22
DIC (µmol/kg)	2048 $\pm$ 28	2031 $\pm$ 22	1998 $\pm$ 19	2002 $\pm$ 17	2112 $\pm$ 34	2094 $\pm$ 31

S1 = Varkala (Kerala); S2 = Pichavaram Mangrove (Tamil Nadu); S3 = Pulicat Lagoon (Andhra Pradesh). Post = post-monsoon.

Carbon Biogeochemistry and Mangrove Blue Carbon

Pichavaram mangrove system (S2) showed more sedimentary organic carbon (SOC) per area than either of the other two sites, with an average of 4.18 ± 0.42 Mg C ha⁻¹ yr⁻¹ (Figure 2). This is consistent with the upper end of what was reported for restored mangrove ecosystems and far exceeds the degraded coastline at S3 (1.32 ± 0.28 Mg C ha⁻¹ yr⁻¹). The $\delta^{13}\text{C}$ signature of the mangrove-derived POC at S2 (-26.4 ± 0.8 ‰) was clearly distinct from that of the marine-derived POC at S1 (-21.3 ± 0.6 ‰), allowing for isotopic separation of terrigenous and marine organic matter fractions. Chlorophyll-a concentration was considerably greater at S3 during the monsoon (18.4 ± 3.2 µg L⁻¹), indicating an increase in phytoplankton due to eutrophication associated with nutrient loading which agrees with research indicating anthropogenic nutrient enrichment (Tinel et al., 2023; Dusi & Rahman, 2023).

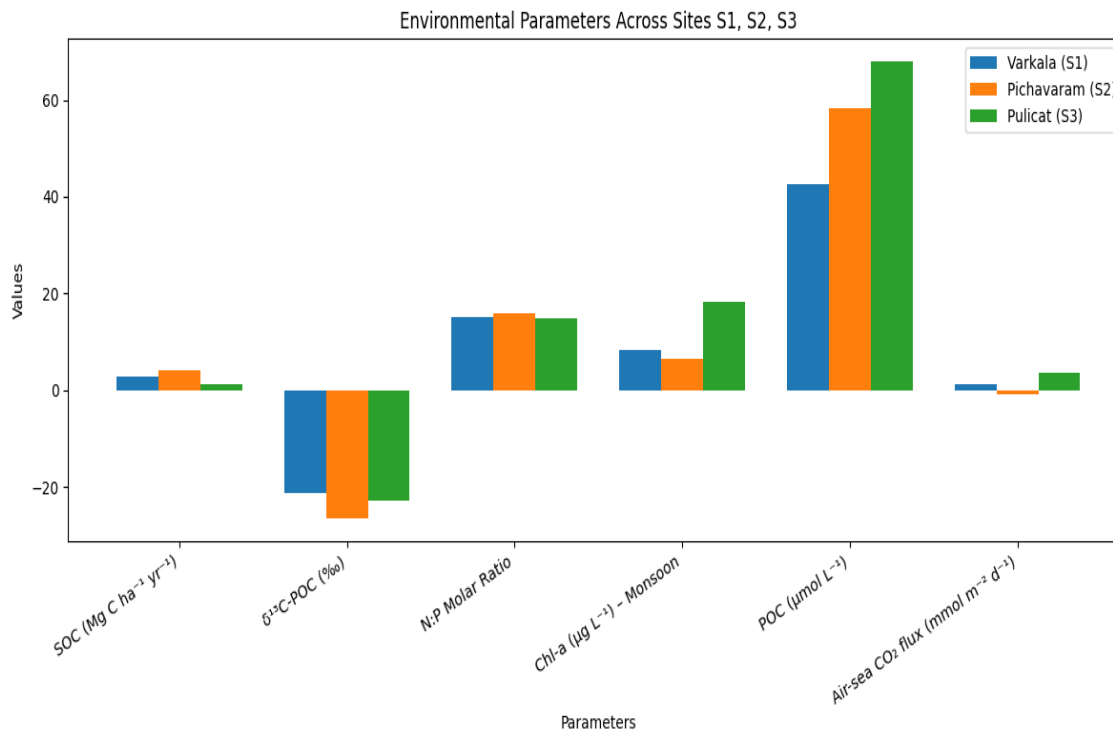


Figure 2: Carbon Biogeochemical Parameters Across Study Stations

Positive air-sea CO₂ flux = ocean source; negative = ocean sink. SOC = Sedimentary Organic Carbon.

Mercury Cycling and Stable Isotope Fractionation

Mercury isotope data from this study (Table 2) showed the presence of systematic mass-dependent fractionation (MDF: $\delta^{202}\text{Hg}$) and mass-independent fractionation (MIF: $\Delta^{199}\text{Hg}$) signatures associated with anthropogenic processes as well as photochemical processes associated with the processing of mercury. The S3 station had the highest $\delta^{202}\text{Hg}$ ($+0.18 \pm 0.06\%$) and the highest THg (THg; $48.6 \pm 7.2 \text{ ng L}^{-1}$) concentrations of all of the sampling stations, which were an increase over the sub-surface background concentration found in the open ocean (i.e., 2-5 ng L^{-1}) and were most likely caused by industrial effluent and atmospheric deposition (McGrath, 2012). All sampling stations had positive $\Delta^{199}\text{Hg}$ values ($+0.22$ to $+0.38 \%$) that indicate photochemical dissimilarity between the $\delta^{202}\text{Hg}$ and the $\Delta^{199}\text{Hg}$, and support the conclusion made regarding the photochemical reduction of Hg in the photic zone. A significant positive correlation was found between the THg concentrations and POC concentrations at all sites ($r = 0.78$, $p < 0.001$, $n = 144$), which indicates that particle scavenging is the primary mechanism for transporting mercury to the sediments in these coastal waters (Wang et al., 2018).

Table 2: Mercury Speciation and Stable Isotope Data

Mercury Parameter	S1	S2	S3	p-value (ANOVA)
THg (ng L ⁻¹)	8.4 ± 1.6	4.2 ± 0.9	48.6 ± 7.2	<0.001
MeHg (ng L ⁻¹)	0.48 ± 0.12	0.22 ± 0.08	3.14 ± 0.56	<0.001
$\delta^{202}\text{Hg}$ (‰) – MDF	-0.42 ± 0.09	-0.61 ± 0.07	-0.18 ± 0.06	0.003
$\Delta^{199}\text{Hg}$ (‰) – MIF	+0.31 ± 0.05	+0.38 ± 0.06	+0.22 ± 0.04	0.012
THg/POC ratio	0.197	0.072	0.715	<0.001

THg = Total mercury; MeHg = Methylmercury; MDF = Mass-dependent fractionation; MIF = Mass-independent fractionation.

Nitrogen Cycle Dynamics and Stoichiometry

Each of the three study locations has N:P ratios that were nearly equal to, yet still lower than the Redfield ratio of 16:1 (Figure 2). This indicates the presence of mild to moderate nitrogen limitations across all study sites (Figure 2). However, the ability to distinguish between S3 and S2 based on their nitrogen isotopes ($\delta^{15}\text{N-NO}_3$) will allow for better understanding of isotopically heavy nitrogen originating from anthropogenic sources such as wastewater and manmade nutrient runoff (from agricultural land) in the study area. The low RRDl for S2 and the high RRDl for S3 clearly indicated that anthropogenic nutrient imbalances are more problematic at the urban location. These data further support the findings that both natural and anthropogenic influences are involved in the dynamics of nitrogen cycling in coastal Atlantic locations, who concluded that the export of nutrients from riverine sources was one mechanism to disrupt the stoichiometry of the marine environment. The PCA of the geochemical data set indicates that PC1 and PC2 explained 64.3% of the total variance between the geochemical values (PC1 = 41.7% and PC2 = 22.6%); PC1 is composed primarily of concentrations of nutrients, pCO₂, and THg, while PC2 is dominated by $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and gradients in salinity.

V. Discussion

In totality, the overall impact of human activity on the coastal environment of South Asia has resulted in profound changes to the biogeochemical cycles by way of the coastal ecosystems. For example, visual comparisons show that an undisturbed mangrove ecosystem differs from an urbanized coastal region with significant alterations due to human activity, as demonstrated by their ability to function as net carbon sinks (mangrove ecosystem) or as a net source of carbon (urbanized coastal area). Furthermore, directly associated with the reduction in primary productivity of the urbanized coastal area, there are concomitant decreases in chlorophyll-a and particulate organic carbon levels leading to increased levels of anthropogenic stress on the marine biogeochemical cycles, which are then interfering with the energy flow and stability of the ecosystems. In addition, the carbon flux measurements also indicate that the net carbon sink capacity of the mangrove ecosystem produces significant amounts of blue carbon, while the urbanized coastal region produces net carbon sources. Moreover, the increase in levels of dissolved inorganic carbon in the urbanized coastal area indicates that organic matter is decomposing at a faster rate, releasing carbon dioxide into the system; both of which underscore the significant impacts of eutrophication on the marine biogeochemical carbon dynamics at the coast.

Further evidence of anthropogenic impact could be seen through the results of the mercury contamination study. Results showed that total and methylmercury concentrations were consistently higher in the urbanized coastal area, while the correlation between mercury and particulate organic matter revealed that the transportation of contaminants via sedimentation in the sediments is (and may continue) to be highly efficient and could pose long-term environmental impacts. Nitrogen-isotope signatures and nutrient ratios demonstrated high levels of wastewater-derived nutrients entering the coastal system, which may indirectly alter phytoplankton community composition and associated nutrient cycling in this region. Seasonal changes associated with monsoon hydrology alter the availability of nutrients, salinity, and overall biogeochemical conditions of coastal ecosystems and highlight the important role that regional climate processes play in these coastal ecosystems. Ultimately, the collective findings of the biogeochemical cycling studies in the coastal region show how pollution, nutrient enrichment, carbon cycle alterations, and trace metal contaminants combine to alter the coastal ecosystems and demonstrate the need for enhanced analytical techniques and techniques of standardization of monitoring systems for improved understanding of human-induced impacts and effective management and conservation strategies of the coastal ecosystems.

VI. Conclusion

In summary, the present study provides an overall, integrative, multi-parameter overview of the marine biogeochemical cycling of carbon, nitrogen and mercury in three contrasting coastal environments within the Indian subcontinent. This work contributes new knowledge to the understanding of the altered carbon,

nitrogen and mercury cycles that have been created as a consequence of anthropogenic influences since the beginning of the Anthropocene. The study produced the following key findings: The mangrove system in Pichavaram provides strong blue carbon ($4.18 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) and reinforces the ecological importance of coastal wetlands that remain intact. The coastal zone of Pulicat Lagoon is severely impacted by biogeochemical degradation (e.g., hypoxia, $\text{pH} = 7.97$, $\text{pCO}_2 = 498 \text{ } \mu\text{atm}$ and total mercury [THg]) resulting from urban runoff and industrial activity. An array of stable isotope signatures ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{202}\text{Hg}$ and $\Delta^{199}\text{Hg}$) function as reliable tracers of anthropogenic sources of nitrogen, phosphorus (N and P) and mercury as contaminants, allowing for statistically reliable source apportionment at the $p < 0.001\text{--}0.012$ level. Seasonal variations associated with monsoon events significantly influence biogeochemical cycling ($F = 14.8$, $p < 0.001$), which illustrates the need for multi-season sampling strategies in tropical coastal regions.

Collectively, the above statistical results indicate that the level of anthropogenic disruption to marine biogeochemical cycles is proportional to the intensity of land-use pressures and wastewater discharged from developed watersheds to coastal environments, as demonstrated by nitrogen and phosphorus (N:P) stoichiometric deviation ($\text{RRDI} = -0.42$ at the S3 site versus -0.06 at the S2 site) and the enrichment factors of mercury ($\sim 6\text{X}$ above background levels) as quantitative indicators of ecosystem stress. These results have immediate implications for coastal environmental management in India and for similar tropical developing nations. Future research directions should include (a) high-resolution time-series monitoring of biogeochemical variables at each of the above mentioned and additional coastal monitoring sites to determine variability in inter-annual means and long-term trends; (b) studies to investigate the presence of emerging contaminants (e.g., microplastics and persistent organic pollutants), with regard to their interaction with biogeochemical cycles, occurring at these sites; (c) mechanistic studies on the responses of microbial communities to the stressors of the Anthropocene using metagenomic and meta transcriptomic methodologies; and (d) integrating the biogeochemical data for these regions into coupled ocean-atmospheric models to enhance the accuracy of projected tropical coastal carbon and nitrogen budgets. Establishment of a national coastal biogeochemical observatory, linked to the international GEOTRACES program, is essential for sustaining marine ecosystem services into the future.

Declaration Statements

Conflict of Interest

The authors declare no conflict of interest, financial or otherwise, in relation to the research presented in this paper.

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This research received no specific external funding and was conducted as part of institutional academic research activities.

Dataset Description

All primary datasets generated during this study, including in situ physicochemical measurements, nutrient concentrations, isotope ratios, and mercury speciation data, are available from the corresponding author upon reasonable request.

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