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Spatiotemporal distribution and composition of phytoplankton assemblages in Bhitarkanika: A Mangrove Estuary

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Abstract

Phytoplankton form the foundation of aquatic food webs and are sensitive indicators of environmental conditions in estuarine ecosystems. This study assessed the spatiotemporal distribution of phytoplankton in the Bhitarkanika mangrove-estuarine ecosystem, Odisha, India, and examined their relationship with key physicochemical variables. Sampling was conducted at 28 stations across Bhitarkanika National Park, Dhamra River and Gahirmatha during pre-monsoon and post-monsoon seasons. Water quality parameters, including temperature, salinity, pH, dissolved oxygen, biological oxygen demand, total suspended solids, turbidity, and nutrients, were analysed using standard methods. Phytoplankton abundance, chlorophyll-a, and total chlorophyll were determined through laboratory and algal analyser-based assessments.

Results showed significant seasonal variations in environmental conditions and phytoplankton dynamics. Post-monsoon conditions were associated with lower salinity and temperature, higher nutrient availability, and greater phytoplankton abundance. Mean phytoplankton density increased from 251.5 ± 102.0 no. mL^{-1} in the pre-monsoon period to 589.0 ± 766.2 no. mL^{-1} in the post-monsoon period. Cyanobacteria (blue-green algae) increased markedly during the post-monsoon season, while diatoms and cryptophytes were comparatively less represented. Correlation analysis revealed positive relationships between phytoplankton abundance, chlorophyll concentrations, and nutrient levels, particularly nitrate, ammonia, and orthophosphate. In contrast, dissolved oxygen showed strong negative relationships with phytoplankton biomass and chlorophyll-a. Multivariate analyses identified salinity, nutrient availability, suspended solids, and turbidity as major factors influencing phytoplankton distribution and community structure.

These findings highlight the role of monsoon-driven hydrological and biogeochemical processes in regulating phytoplankton assemblages within the Bhitarkanika mangrove-estuarine ecosystem and provide baseline information for ecological monitoring, biodiversity assessment, and sustainable management of coastal and estuarine environments.

Keywords: Phytoplankton; mangrove estuary; Bhitarkanika; seasonal variation; chlorophyll-a; nutrient dynamics; water quality; phytoplankton abundance.

1.Introduction

Phytoplankton comprise a diverse group of microscopic photosynthetic organisms that sustain aquatic productivity and contribute to nutrient transformation within aquatic ecosystems. The nutrient-enriched waters of the Bay of Bengal support substantial phytoplankton diversity. In the Bhitarkanika mangrove region, the combined influence of freshwater inflow, estuarine conditions, and tidal fluctuations creates an environment conducive to the development and persistence of varied phytoplankton populations.

Several studies have highlighted the ecological significance of Bhitarkanika and its microbial diversity. Investigations by Palit and Das (2021), Panda et al. (2017), Thatoi et al. (2013), Amaral-Zettler et al. (2015), Mishra et al. (2015), and Dutta (2007) have provided valuable insights into the biodiversity and ecological functioning of this mangrove ecosystem. Mangrove habitats are highly productive ecosystems that serve as important breeding and nursery grounds for many commercially valuable fish and shrimp species (Kathiresan & Bingham, 2001). Understanding phytoplankton diversity in Bhitarkanika is therefore essential for assessing ecosystem health, productivity, and environmental sustainability.

Phytoplankton distribution in coastal ecosystems is regulated by seasonal circulation and various physicochemical and biological factors (Choudhury & Panigrahi, 1991). In mangrove environments, these factors strongly influence species composition and abundance, resulting in temporal variations in algal communities (Kannan & Vasantha, 1992). Post-monsoon nutrient enrichment from freshwater inflow and terrestrial runoff enhances phytoplankton productivity and alters community structure (Brando et al., 2006). Therefore, the present study investigates the relationship between environmental variables and algal diversity in the Bhitarkanika mangrove ecosystem. In addition to ensuring ecological services, phytoplankton species composition is considered an efficient bio-indicator of water quality as their distribution strongly correlates with various physical, chemical, biological, and hydro-logical factors as well as interactions among them (Paerl et al. 2008).

Objective: To evaluate the influence of spatio-temporal variations on phytoplankton dynamics by examining how algal abundance changes across different spatial locations and time periods in relation to key physicochemical parameters such as temperature, salinity, pH, dissolved oxygen, and nutrient concentration, thereby understanding the environmental controls governing phytoplankton distribution and variability in the study area.

2.Materials and Methods

Study sites- Both pre and post Monsoon samples from 28 stations belonging to three main regions of Bhitarkanika has been collected. Those are

i) Bhitarkanika national park (3 stations BH, BH2, BH3)- 10 samples
ii) Dhamra River (11 station DH1-DH11)- 11 samples
iii) Gahirmatha (14stations GH1-GH14)- 14 samples

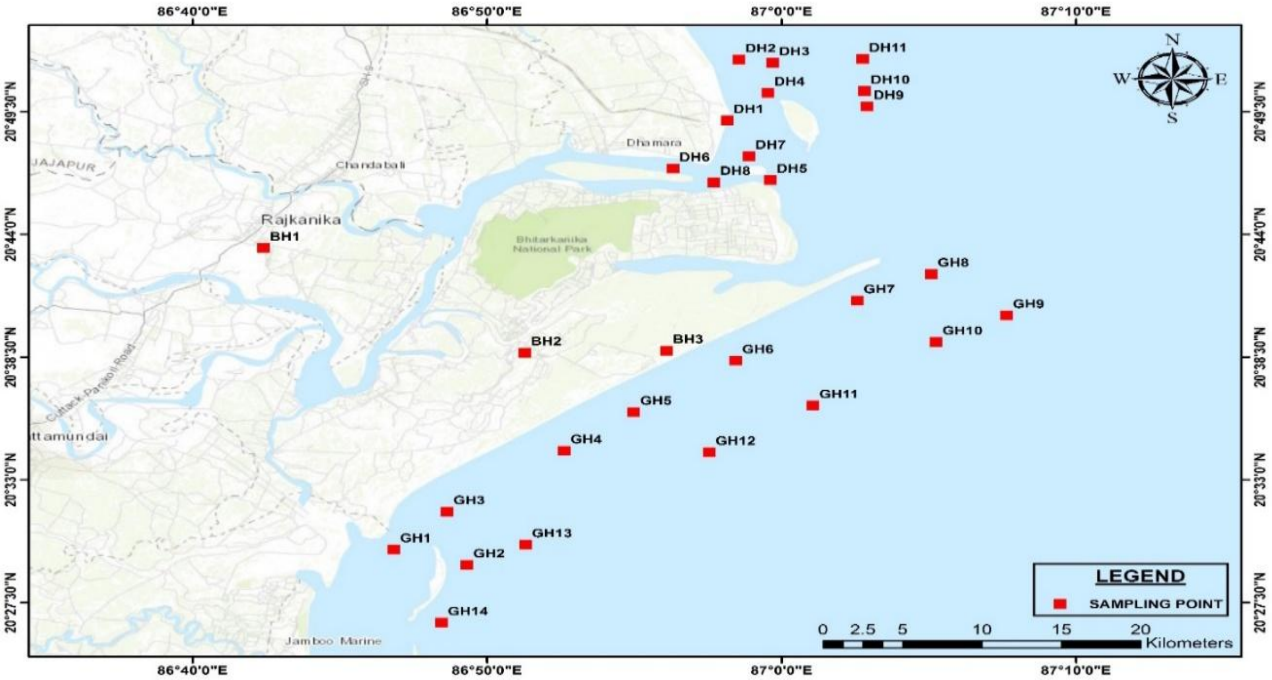


Figure 1 –Sampling points of Bhitarkanika national park (BH), Dhamra river (DH), Gahiramatha (GH)

Table no. 1 : Sampling Points:

SL. NO.	St. CODE	LATITUDE	LONGITUDE	Justification
1	DH1	20°49'6.01" N	86°58'0.92" N	Influence of port activity Riverine Influence Riverine influence (Brahmani, Baitarani, Dhamra, Maipura, Patasal) Geo morphological Impediments
2	DH2	20°51'49.26" N	86°58'3.34" N	
3	DH3	20°51'41.2" N	86°59'4.21" N	
4	DH4	20°50'20.19" N	86°59'3.23" N	
5	DH5	20°46'26" N	86°59'3.71" N	
6	DH6	20°46'56.67" N	86°56'1.9" N	
7	DH7	20°47'30.11" N	86°58'5.36" N	
8	DH8	20°46'19.84" N	86°57'4.19" N	
9	DH9	20°49'43.4" N	87°2'5.45" N	Influence of port activity
10	DH10	20°50'24.94" N	87°2'4.87" N	
11	DH11	20°51'51.22" N	87°2'4.55" N	
12	GH1	20°29'53.08" N	86°46'4.99" N	Riverine influence (Gobari,Hansua)
13	GH2	20°29'11.49" N	86°49'1.9" N	
14	GH3	20°31'34.72" N	86°48'3.86" N	
15	GH4	20°34'18.66" N	86°52'3.71" N	Sensitive zone of Gahiramatha marine transact, major tidal influence and few small riverine influence
16	GH5	20°36'1.98" N	86°54'5.89" N	
17	GH6	20°38'20.57" N	86°58'2.67" N	
18	GH7	20°41'1.76" N	87°2'3.43" N	

19	GH8	20°42'13.57" N	87°5'0.51" N	
20	GH9	20°40'21.9" N	87°7'3.83" N	
21	GH10	20°39'10.78" N	87°5'1.46" N	
22	GH11	20°36'19.95" N	87°1'0.4" N	
23	GH12	20°34'14.03" N	86°57'3.25" N	
24	GH13	20°30'6.04" N	86°51'1.85" N	Riverine Influence (Mahanadi, Gobari, Hansua))
25	GH14	20°26'36.16" N	86°48'2.71" N	
26	BH1	20°43'23.16" N	86°42'2.48" N	Satbhaya, Gupi, Kanika Sensitive Zone
27	BH2	20°38'41.97" N	86°51'1.68" N	
28	BH3	20°38'47.14" N	86°56'0.55" N	

Justification for selecting sampling points: The sampling points were chosen based on their proximity to the source and the various factors that could impact the results.

Port Influence: DH1, DH2, DH3, DH9, DH10, DH11
Riverine influence: DH4, DH5, DH6, DH7, DH8, GH1, GH2, GH3, GH13, GH14
Sensitive zone: GH4, GH5, GH6, GH7, GH8, GH9, GH10, GH11, GH12, BH1, BH2, BH3

2.1 Sampling

2.1.1 Collection period

Water samples has been collected two times in the year of 2022, covering PrM and PM season. Water samples has also been collected during High (HTS) and low tide (LTS) time. To study the gradient of diversity on the basis of seasonal changes (pre monsoon and post monsoon), 2 (one LTS and one HTS) samples from each site, total 56 samples has been collected two times during the year 2017-18 (BH- Satbhaya, Gupti, Kanika) 2022 (Dhamara-DH, Gahirmatha-GH). The first collection has been done during PrM period and the second in PM period. As the **PrM** period is in between **March to June** and the **PM** period is in between **October to February** the respective samples were collected within that duration.

- PrM samples has been collected in the month of June
- PM samples has been collected in the month of February

2.1.2 Sample collection, storage and Processing

Before sampling, samplers and sample containers had been meticulously cleaned by using 1N HCl in site the lab. The bottles had been washed twice with the same environmental water before collecting the actual sample. Care had been taken to avoid contamination from sewage ejection from boats or ships during sampling. For qualitative and quantitative enumeration of Phytoplankton, samples were collected by using horizontal haul of phytoplankton net (mesh size of 150µm). For phytoplankton assortment, nets were carefully washed and air-dried to avert mesh obstruction, and the flow meter was frequently calibrated. A digital flow meter (Hydro Bios) has been used for the determination of the volume of water filtered.

Water samples were collected through Teflon-coated Niskin samplers to evade any contact with any metal. After collecting the sample with a 5L Niskin sampler, all water were strained from its knob using silicone rubber tubes. The collected samples were preserved with 5% formaldehyde.

2.1.3 Sample Storage:

Sample for chlorophyll assessment were composed from surface water in sampling bottles. The water sample were filtered instantly and carried to laboratory by keeping the bottle in ice box. After filtration, from the filter base the filter was taken out, after complete filtration and the filter were folded and kept in a desiccator at -20°C up to 30 days for further analysis.

One set of samples were given for analysis by Algal analyser at Pollution Control Board, Bhubaneswar. Another set of samples was transported to the laboratory and were preserved for physical and chemical analysis. One more set of samples was stored in the refrigerator at -20°C for further use. Some of the samples were cultured in different culture media like ASN+ and ASN-media as these are marine species. The samples were also stored in tube well water and tab water to check their growth. This had provided a rough idea about Phyco-Diversity on the basis of their pigment content and concentration.

2.2 Analysis of Physico-chemical parameters:

Water quality parameters, including DO, BOD, nutrients, turbidity as well as TDS, was conducted following APHA (2005) guidelines. In-situ measurements included water temperature, pH, salinity, and conductivity. The Algal Lab Analyzer at CMC, Pollution Control Board, Bhubaneswar, was used to assess water samples from coastal stations, providing quantitative estimates of chlorophyll-a, phytoplankton cell counts, and the concentration of various algal groups, including green algae, blue algae, diatoms, and dinoflagellates. It also measured yellow substances, average activity, transmission, and overall cell density. The analysis offered valuable insights into phytoplankton dynamics, water quality, and ecosystem health.

A detailed laboratory assessment was carried out to evaluate essential water quality parameters, including DO, BOD, nutrient levels, turbidity, and TSS. These analyses adhered to the standardized procedures established by the American Public Health Association (Kayaalp et al., 2010; Wagner et al., 2005)to ensure precision and consistency. Additionally, on-site measurements of crucial physicochemical properties such as water temperature, pH, salinity, conductivity, and turbidity were conducted using a YSI water quality checker. This enabled real-time data collection, providing valuable insights into the immediate environmental conditions of the water body.

Table 2: Physico- Chemical Methods for Analytical Assessment

Physico-Chemical methods used for analytical Assessment		
Analytes	Methods	References *
Ph	potnetiometric electrode	(Jin et al., 2018)
Dissolved Oxygen	Winkler method	(Carpenter, 1965)
TDS	Gravimetric method	(Gilmore & Luong, 2016)
Turbidity	Nephlometric method	(Kitchener et al., 2017)
BOD	Incubation for 3 days with Winkler method	(Effluents, 1957)
Nitrites and Nitrate	Cadmium reduction method	(Cortas & Wakid, 1990)
Phosphate	Ascorbic acid method	(Towns, 1986)
Ammonia	Phenate method	(G. eun Park et al., 2009)
Silcate	Molibdo silicate	(Markad et al., 2021)
Chlorophyll a	Spectrophotometric Method	(Ergun et al., 2004)
Total Chlorophyll	Spectrophotometric Method	(Ergun et al., 2004)

2.3 Statistical Analysis:

The analysis by statistic was conducted to examine the interrelationships and interdependencies among various variables, including phytoplankton abundance and biomass (chlorophyll-a), in relation to different water parameters. A comprehensive statistical approach was employed to interpret the data effectively. Descriptive statistical methods were utilized to summarize key aspects of the dataset, providing insights into central tendencies, variability, and distribution patterns. Karl Pearson's correlation coefficient and multivariate techniques were applied to identify significant patterns and key factors influencing spatiotemporal variations in water quality, particularly concerning phytoplankton abundance in PrM and PM samples(Basu et al., 2021). Correlation analysis was performed to assess the strength and direction of associations between different variables. Additionally, cluster analysis was used to group data into meaningful categories based on similarities, facilitating pattern recognition and interpretation. Dendrograms and clusters were generated using PRIMER-6 software, offering a structured visualization of hierarchical relationships within the dataset. This methodology aided in identifying distinct patterns and classifications. Moreover, MDH analysis was incorporated to further refine the understanding of the data. By integrating advanced statistical techniques, this step validated the observed trends and patterns, ensuring a more comprehensive and reliable analysis.

The Shannon Diversity Index (H') was determined by using the Shannon-Wiener statistical method, a widely recognized approach for evaluating species diversity within a community(Luo et al., 2016). This index account on both species richness (S) and species evenness (J’) to provide a comprehensive measure of biodiversity. Species richness (S) refers to the total number of species in a given area, whereas species evenness (J’) indicates how uniformly individuals are distributed among these species. A higher evenness value suggests a balanced distribution, while a lower value indicates that a few species dominate the community. The index is calculated using the quantity of individual organisms of each species (n) in relation to the total number of individuals (N) in the dataset. Additionally, Shannon equitability (J') expresses evenness on a scale from 0 to 1, where a value of 1 represents perfect evenness. This analytical approach provides valuable insights into ecological stability, species composition, and community structure, making it a fundamental tool in biodiversity studies.

2.4 Study by Algae Lab Analyzer

The algal lab analyzer from ICZMP, Bhubaneswar was utilized to analyze water samples collected from various coastal stations. The analyzer enabled the quantitative estimation of chlorophyll-a, phytoplankton cell counts, and other algal parameters. The data generated from this analysis provided valuable insights into the phytoplankton dynamics, water quality, and ecosystem health of the coastal waters.

For algal analysis, a water sample of approximately 1000 ml, underwent filtration using a membrane filter, such as a Glass Fiber (GF/C or GF/F) filter, to effectively separate algal cells from the surrounding water. This filtration step ensured that only the desired algal components were retained, while excess water and dissolved materials passed through.

To prevent deterioration and preserve the structural integrity of the algal cells for future analysis, a suitable fixative, 4% Formalin- seawater solution was added. Commonly used preservatives include Lugol's iodine, which enhances visibility under a microscope while stabilizing the sample, or formaldehyde, which prevents microbial decay and structural breakdown. The preserved samples were then stored under controlled conditions for further microscopic or biochemical examination.

Algal Analysis Parameters: Total chlorophyll determination and determination of photosynthetically active substances were done through algal analyzer.

1. Quantification of algal classes: Algal cells were identified and quantified for the following classes: Green algae, Blue-green algae (Cyanophyceae), Brown algae (Cryptophyceae).
2. Determination of total chlorophyll: Total chlorophyll concentration was measured using spectrophotometry.
3. Determination of photosynthetically active substances: Photosynthetically active substances, such as chlorophyll-a and phaeophytin, were measured using algal analyzer.

3 Results and Discussion:

3.1 Physico-chemical Parameters Analysis for BH

Different parameters were examined and assessed, including the minimum, maximum, average, and standard deviation values. The seasonal variations in salinity, pH, total dissolved solids (TDS), and biological activity indicate the dynamic influence of monsoonal changes on aquatic ecosystems (Abdullah, H. H., 2018).

3.1.1 Salinity: At the time of pre monsoon the salt content of water is more, but at the arrival of monsoon the salinity decreases and nearly become negligible. Where as in post monsoon period it again slightly increases. The Phyco-diversity of Bhitarkanika vary on the basis of Salinity. Salinity is more before Monsoon, whereas PM the salinity decreases and almost becomes negligible as the water level increases.

Fig.2 showed that the salinity varies with a great extent with the change in the season. The salinity has been found to be varied from 2.3 ppt to 8.9 ppt during Pre monsoon and 1.9 ppt to 8.7 ppt during post monsoon period. While moving from the river junction region towards the sea the salinity gradually increases. It increased from the river junction to the sea, supporting diverse saline algal species. Hence a great diversity of saline algal species could be found while moving from river towards the sea. Fig. 2 is showing the value of salinity of pre monsoon samples are more in comparison to post monsoon samples.

Statistical analysis reveals an average salinity of 6.58 ppt in PrM and 5.88 ppt in PM, indicating a decline. Minimum values were recorded at 2.23 ppt (PrM) and 1.86 ppt (PM), while maximum values reached 8.9 ppt and 8.7 ppt, respectively. The standard deviation highlights site variations, and mean values of 5.34 ppt (PrM) and 4.64 ppt (PM) further confirm higher salinity in the pre-monsoon period. The observed increase in salinity from river junctions toward the sea supports the presence of diverse saline algal species. Additionally, the decline in average salinity from 6.58 ppt (PrM) to 5.88 ppt (PM) suggests a dilution effect caused by monsoonal freshwater inflow (Zhang, M., 2021).

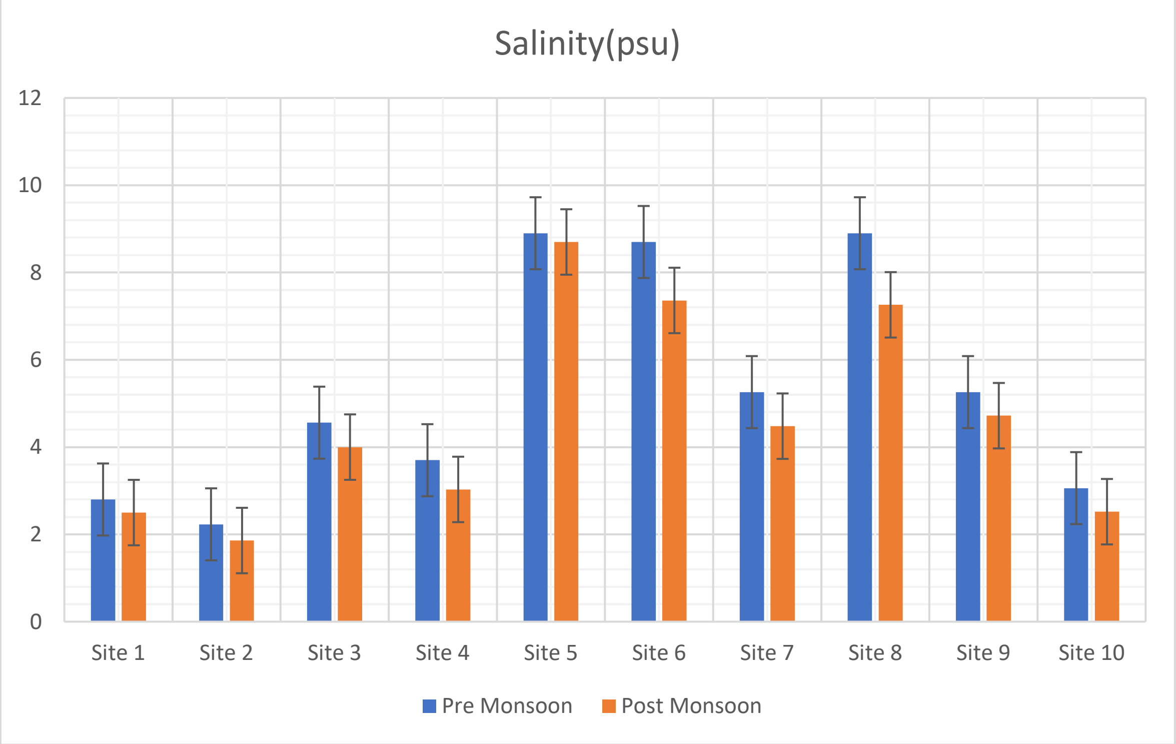


Fig. 2 Salinity of PrM and PM (BH)

3.1.2 pH: The pH levels exhibited considerable variation, with PrM ranging from 2.2 to 7.29 and PM fluctuating between 5.12 and 7.38. Although a noticeable gradient was observed across seasons, a distinct seasonal pattern was not evident. Some locations, such as sites 1, 2, and 4, recorded higher pH values before the monsoon, whereas other sites showed an increase post-monsoon. These variations indicate that localized environmental factors including organic matter decomposition, biological processes, and human activities may have a greater influence on pH fluctuations than seasonal changes alone (Omarjee, A., 2021).

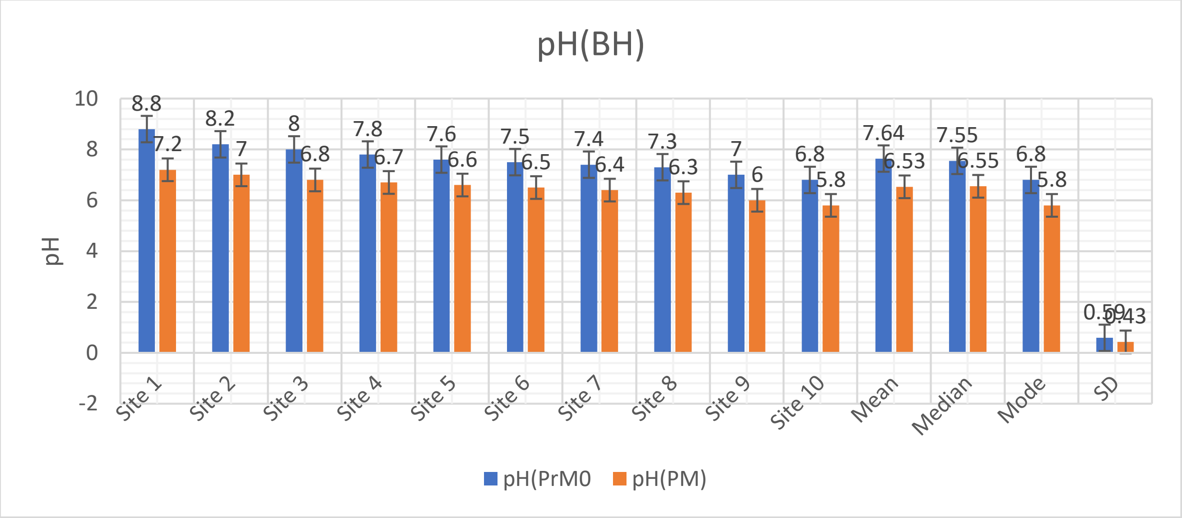


Fig. 3 pH of PrM and PM (BH)

3.1.3 Total dissolve solute: Figure number 4 is showing, the PrM TDS levels ranged from 212 ppm (site 2) to 875 ppm (site 7), while PM values diverse between 231 ppm (site 3) and 741 ppm (site 2). TDS levels showed a declining trend in the post-monsoon period, with the mean value decreasing from 455.6 mg/L in PrM to 407.9 mg/L in PM, likely due to dilution from rainfall. The increased standard deviation in PM (231.3) compared to PrM (204.7) suggests greater variability in TDS concentrations, potentially due to sediment resuspension and differential mixing of dissolved solids across sampling sites (Butler, B. A.,2018). The decrease in the most frequently occurring TDS value from 212 mg/L in PrM to 122 mg/L in PM further indicates a shift toward lower TDS concentrations post-monsoon.

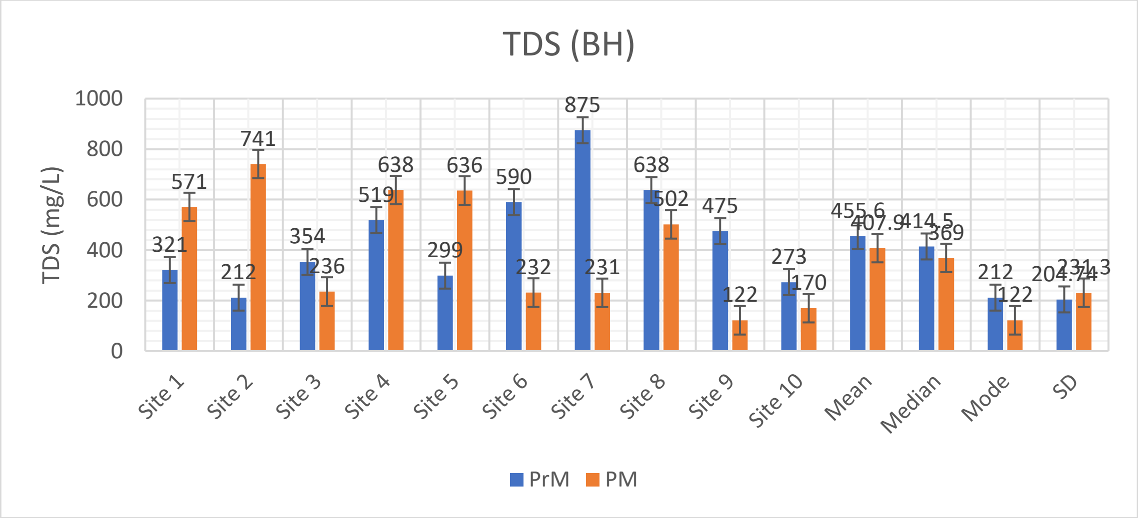


Fig. 4: TDS of PrM and PM (BH)

3.2 Data recorded by Algal analyser: The algal analyser recorded several parameters, including the overall concentration of organisms, as well as the number of green algae, blue-green algae, cryptophytes, diatoms, and yellow substances. It also quantified the average photosynthetic activity, average transmission, and the number of cells per millilitre.

3.2.1 Concentration of organisms: Figure 5 indicates that from PrM samples organisms were detected in samples from sites 4, 7, and 8, while the concentration of organisms in the remaining samples was zero.

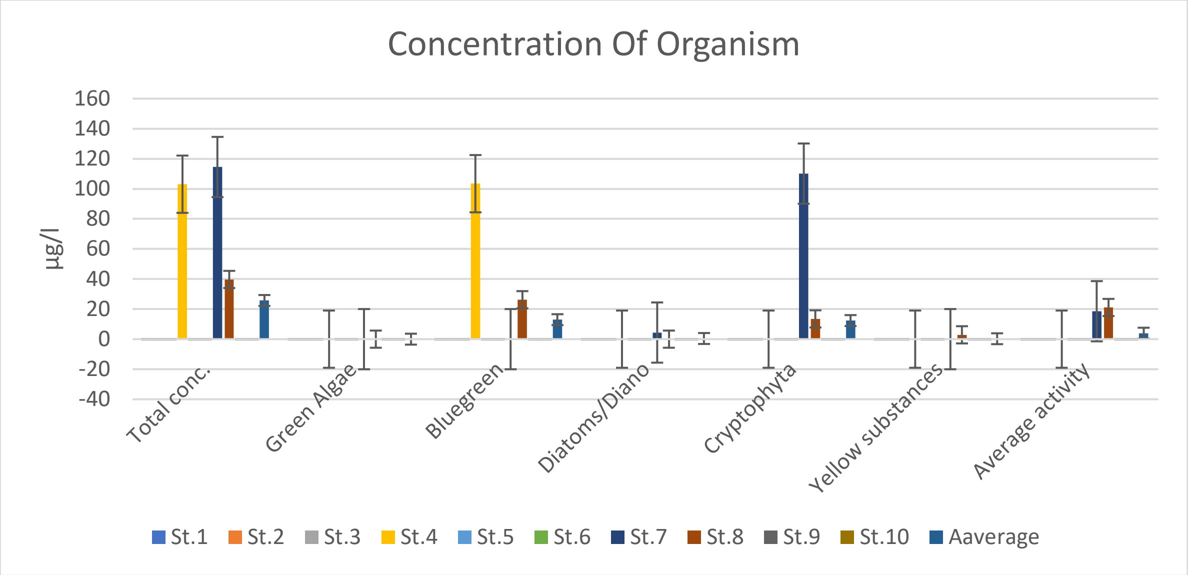


Fig. 5: Concentration of organisms in PrM data (BH)

Spatial Variability: The fact that only three sites have nonzero concentrations suggests that environmental conditions (such as nutrient levels, pH, light, or other habitat factors) might be more favourable at sites 4, 7, and 8.

In contrast, conditions at the other sites may be less conducive to the growth or survival of these organisms. Among the ten sample sites examined, only 30% showed the presence of detectable organisms. This implies that the remaining 70% lacked any detectable organisms, which may be attributed to differences in environmental factors or other influencing conditions across the sites.

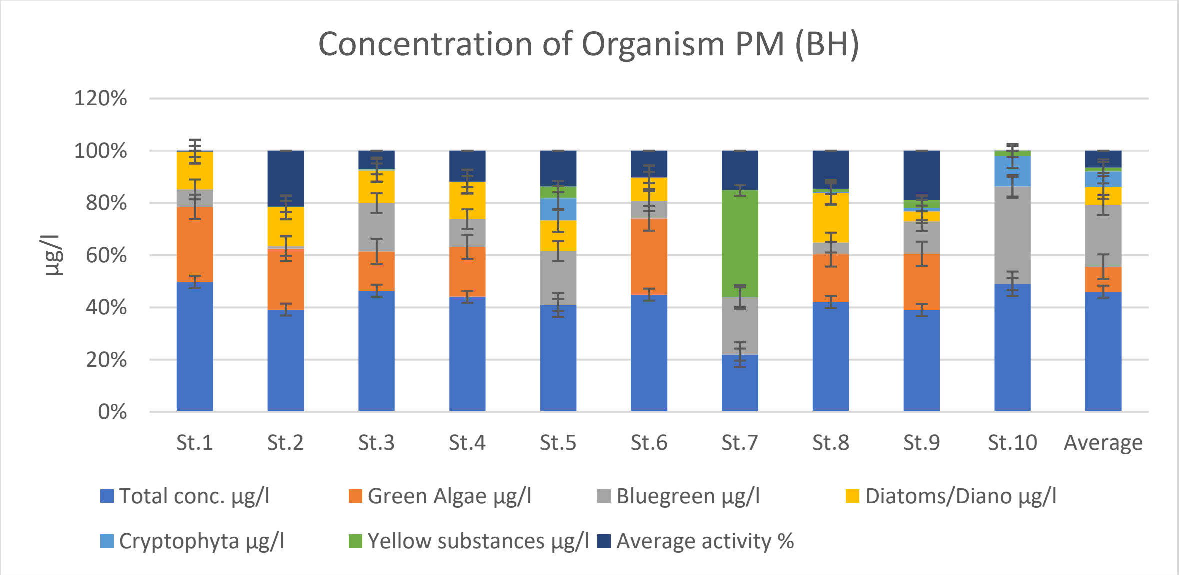


Fig. 6: Concentration of organisms in PM (BH)

From figure 6 it has been observed that in PM samples the highest concentration of organisms has been found in sample no 10 i.e. 1130.11 µg/l, whereas the lowest conc. has been recorded as 5.52 µg/l from sample no 7.

Presence vs. Absence: Overall, organisms were detected in most samples, in contrast to the selective presence seen in PrM samples.

Green Algae: These were absent in sites 5, 7, and 10, suggesting that conditions at these sites might not support their growth.

Bluegreen Algae: These are consistently present across every site, indicating they may be more resilient or better adapted to the local conditions.

Diatoms: Not detected in sites 7 and 10, which could reflect specific environmental limitations affecting their survival.

3.2.2 Spatial Variability:

- The absence of green algae in specific sites (5, 7, and 10) and diatoms in sites 7 and 10 implies that environmental factors—such as nutrient availability, light conditions, pH, or other habitat characteristics—might vary considerably between sites.

- The universal presence of Bluegreen algae suggests that they have a broader tolerance range and might be less sensitive to these spatial variations.

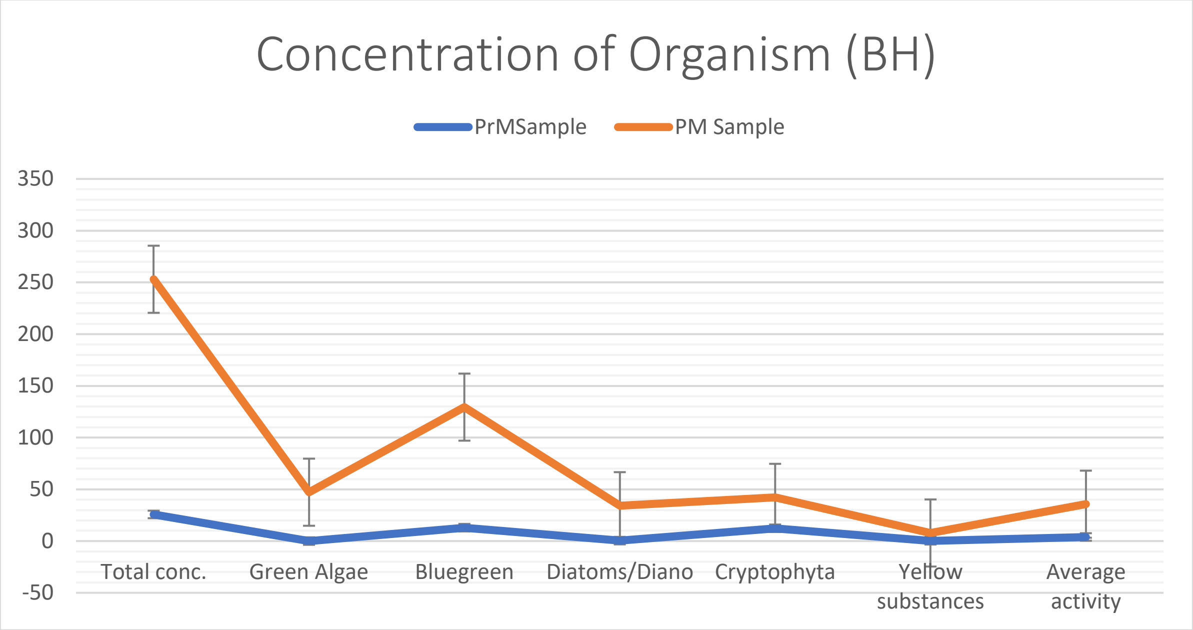


Fig.7: Comparison of Concentration of organisms in PrM and PM

Figure 7 illustrates the concentration of organisms (BH) across different categories for PrM Sample (blue line) and PM Sample (orange line). The PM Sample demonstrates a significantly higher total concentration of organisms compared to the PrM Sample, indicating greater biological activity.

A sharp decline in green algae concentration is evident in the PM Sample following its peak, whereas the PrM Sample remains relatively stable at a lower level. The PM Sample then exhibits a notable increase in blue-green algae, while the PrM Sample shows only a slight rise. After this peak, the PM Sample experiences a drop in diatoms/diano concentration, whereas the PrM Sample maintains a more uniform pattern.

In the case of cryptophyta and yellow substances, both samples display low concentrations with slight variations. Finally, the average activity remains higher in the PM Sample compared to the PrM Sample, further emphasizing its greater biological presence. The PM Sample exhibits a higher total organism concentration than the PrM Sample, indicating increased biological activity. Green algae decline sharply post-peak in the PM Sample, while the PrM Sample remains stable at lower levels. Blue-green algae rise significantly in the PM Sample but only slightly in the PrM Sample. Diatoms concentrations drop post-peak in the PM Sample, whereas the PrM Sample maintains a uniform pattern. Cryptophyta and yellow substances show low concentrations with minor variations in both samples. Overall, the PM Sample's higher biological activity suggests favourable conditions for microbial and algal growth, likely influenced by environmental factors such as nutrient availability due to upwelling (D'Silva, M. S.,2012).

3.2.3 Transmission by Organisms present in the samples

The average transmission of sample no 10 in Pre-Monsoon sample has been found to be the highest i.e. 90.155% and where as in post monsoon period it has become 25.15%.

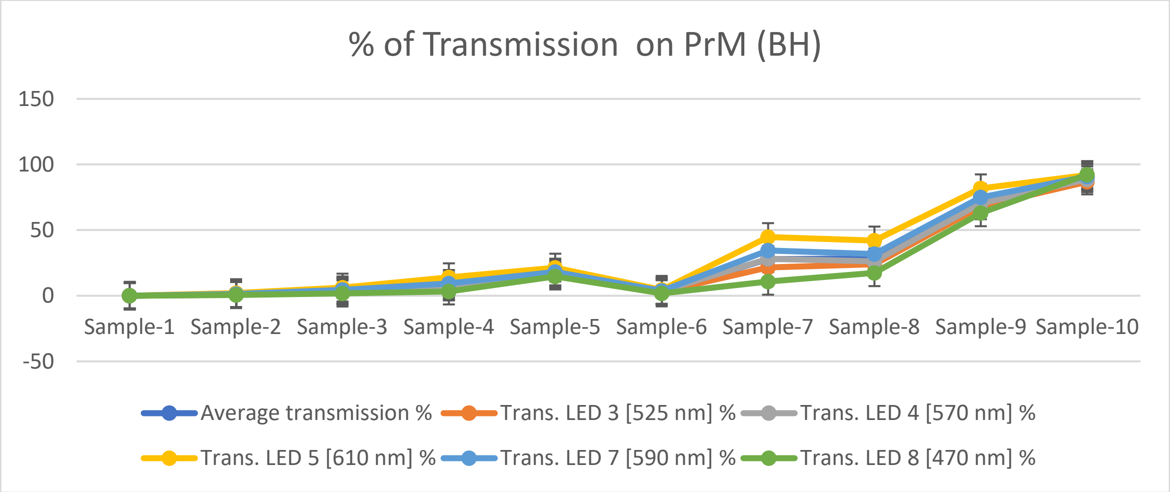


Fig. 8: Transmission by PrM samples (BH)

The plotted graph in fig number 8 shows how transmission (%) varies across different LED wavelengths for each sample. Some wavelengths have higher transmission compared to others for specific samples. The ranking of samples based on their average transmission percentage reveals significant variations among them. Sample-10 exhibits the highest transmission at 90.155%, followed by Sample-9 with 71.615%. A notable drop is observed with Sample-8 and Sample-7, which have transmission values of 28.295% and 27.940%, respectively. Sample-5 ranks next with 17.175%, while Sample-4 shows a moderate transmission of 7.940%. The lower transmission group includes Sample-3 at 3.780%, Sample-6 at 3.330%, and Sample-2 at 1.135%. Lastly, Sample-1 records the least transmission at only 0.015%. This ranking indicates a clear disparity in transmission levels across the samples, suggesting differences in material properties, composition, or other influencing factors.

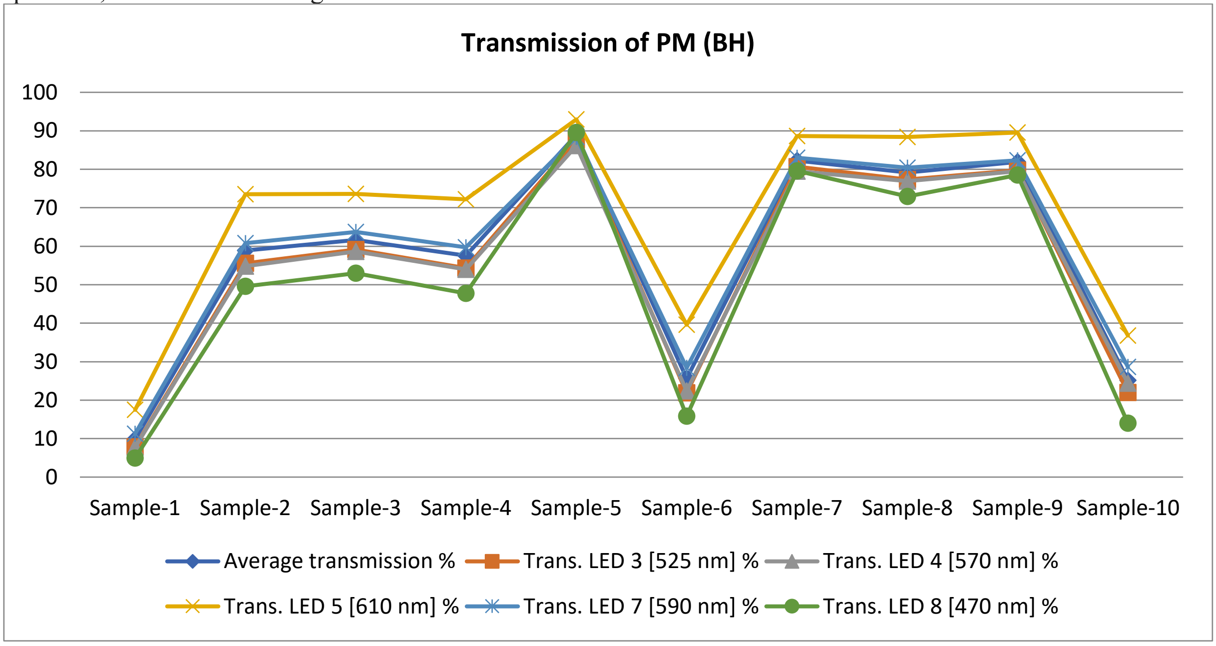


Fig.9: Transmission by PM samples (BH)

The transmission of PM (BH) across different wavelengths follows a consistent pattern, indicating stable optical properties. The transmission percentages remain relatively high for most samples, with some reaching close to 100%, suggesting high transparency. However, there are noticeable dips at specific points, which may be attributed to variations in material thickness, surface texture, or internal scattering effects. The transmission values for LED 5 (610 nm) and LED 7 (590 nm) appear slightly higher than others, implying minor wavelength-dependent differences. Despite these variations, the overall trend suggests that the material allows uniform light passage across multiple wavelengths. Further analysis, such as statistical comparisons and outlier detection, could provide deeper insights into the transmission behaviour.

Comparative study of average transmission:

The comparative study of average transmission has been provided by the graph (Fig .10), which represents that the average transmission of PM samples is relatively more than that of pre monsoon samples.

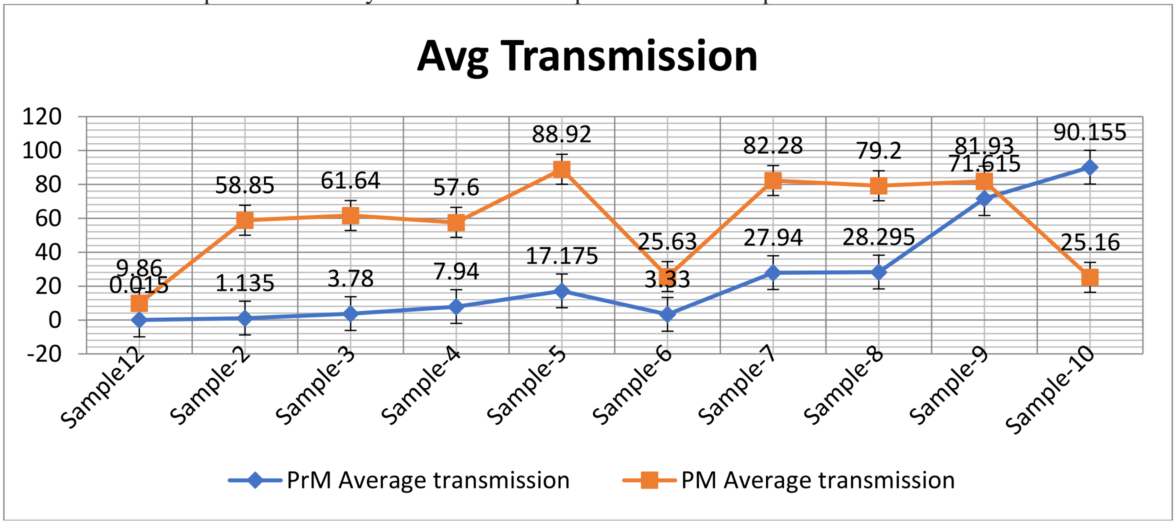


Fig. 10 Comparative study of average transmission

The analysis of Transmission (%) and Average (%) values across different samples reveals that the data does not follow a consistent declining trend. Instead, there are fluctuations where some values increase while others decrease. For instance, Transmission (%) values rise steadily from Sample2 to Sample5, followed by a sharp decline at Sample6, indicating variability rather than a uniform downward trend. Similarly, average (%) values exhibit irregular patterns, with significant increases and sudden drops, such as the sharp rise from Sample4 to Sample5 and a steep decrease at Sample6. It emphasizing the complex interplay of physical and biological factors influencing light penetration and water clarity (D'Silva, M. S., et al. 2012)

The differences between consecutive samples further highlight the inconsistency, with both positive and negative shifts occurring throughout the dataset. The presence of such variations suggests that external influences, such as environmental factors or measurement inconsistencies, might be affecting the recorded values. Since the changes are not gradual or systematic, it indicates that the data is influenced by multiple factors rather than following a predictable declining pattern.

3.3 Number of cells per samples

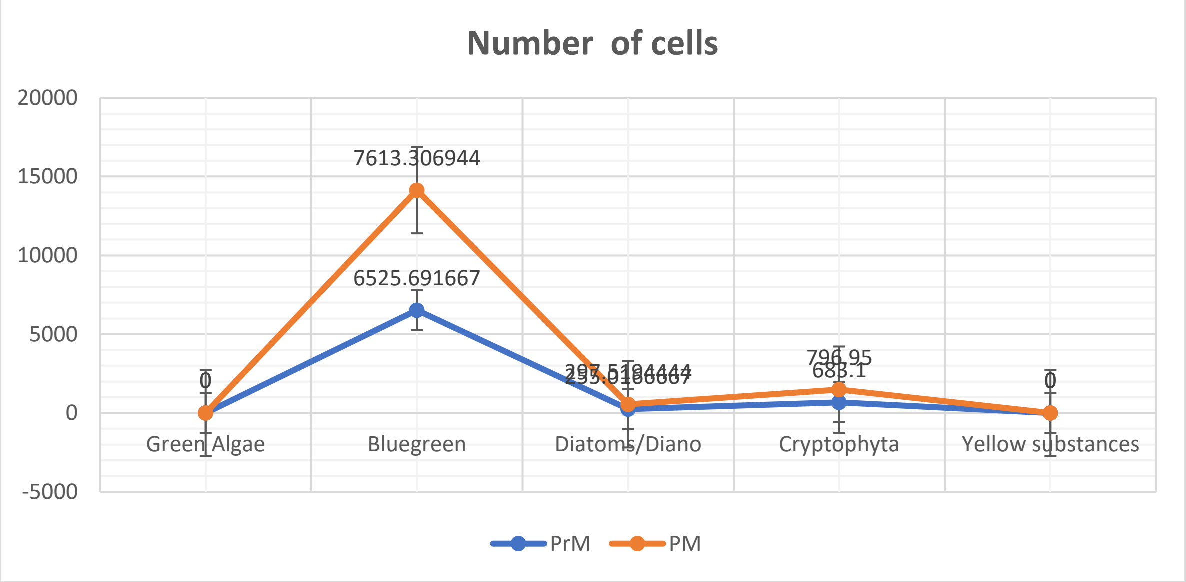


Fig. 11 Comparative Number of cells per samples

The no. of cells per ml of sample has represented in figure number 11. It has been found that more no. of cells is present in PM samples than PrM

Green Algae and Yellow Substances:

Both are absent (0 cells/ml) in pre-monsoon (PrM) and post-monsoon (PM) samples, indicating that conditions at these sites do not Favor their growth in either season.

Bluegreen Algae: Increase from PrM to PM: The cell count rises from about 6,526 (PrM) to over 7,613 (PM). This suggests that post-monsoon conditions (e.g., nutrient influx, temperature, or light availability) are more conducive to Bluegreen algae proliferation.

Diatoms: Slight Decline in PM: Diatom counts decrease from roughly 267 (PrM) to about 207 (PM). This reduction may indicate that diatoms are less competitive or less favoured by the post-monsoon conditions compared to blue-green algae.

Cryptophyta: (Moderate Decline in PM) Cryptophyta counts drop from around 797 (PrM) to about 683 (PM), suggesting a reduced abundance in the post-monsoon period, possibly due to shifting nutrient levels or other environmental changes in BH samples.

Overall Implications: The data point to a notable post-monsoon shift in algal community composition. While green algae and yellow substances remain absent in both seasons, blue-green algae thrive more in the post-monsoon environment, whereas diatoms and cryptophyta experience a decline. Overall, post-monsoon conditions Favor blue-green algae, while diatoms and cryptophyta decline, indicating a shift in algal community (Baliarsingh, S. K., 2013)

Physico-chemical Parameter of GH and DH samples:

3.4 Descriptive Statistics Analysis

The descriptive statistical summary of distribution of all the analysed physico-chemical and biological parameters in water samples of PrM and PM is given in figure no 12 and 13 respectively.

Temperature: The temperature of surface water is usually influenced by the intensity of solar radiation, evaporation, freshwater influx and cooling(*Surface Water - Robert. Bowen - Google Books*, n.d.). During the study period the surface water temperature of PrM has marginal variations ranging from min 29.36°C to max 30.92°C (Avg.30.15 ± 0.43°C) in all the stations of GH and DH in PrM whereas in PM it ranges from minimum 21.51 °C to maximum 24.45 °C (Avg.22.813 °C ± 0.941°C). Water temperature influences estuarine species through various mechanisms, such as thermal stress, particularly in ectothermic organisms(Madeira et al., 2012). It can also accelerate pollutant bioaccumulation by enhancing metabolic processes(T. Wang et al., 2020), modify the chemical composition of water through pollutant volatilization or degradation(Manzetti et al., 2014), and impact ecological communities by altering food-web interactions (Mahboob et al., 2019). Additionally, temperature can interact with other stressors like pH and contaminants, potentially intensifying or reducing their effects (Cabral et al., 2019, Niinemets et al., 2017), while also influencing pathogen behaviour in aquatic environments(Danovaro et al., 2011)

pH: The pH of the study areas is showed mostly alkaline in nature which values are ranged from 7.92 – 9.88 in PrM (Avg 8.72 ± 0.546) and 6.63- 9.12 in PM (Avg 8.02 ± 0.598). Hence pH is more in PrM than PM. Seasonal fluctuation of pH ascribed to factors like dilution of sea water by fresh water reflux, reduction of salinity, decomposition of organic matter and removal of CO2 by photosynthesis by carbon degradation.

Salinity: Salinity levels varied between 22.83 PSU and 31.35 PSU (avg. 28.52 ± 1.91 PSU) in the PrM period, and between 18.45 and 31.93 PSU (avg. 26.75 ± 4.14 PSU) in the PM period. Statistical analysis reveals a strong positive correlation between pH and salinity.

DO: DO levels ranged from 3.91-7.31 mg/L (average: 5.96 ± 0.80 mg/L) in the PrM period, and from 5.29-7.15 mg/L (average: 6.32 ± 0.45 mg/L) in the PM period.

BOD: BOD levels varied from 0.59-2.9 mg/L (average: 1.44 ± 0.76 mg/L) in PrM, and from 0.48-2.15 mg/L (average: 1.11 ± 0.49 mg/L) in PM

TSS: Total Suspended Solids (TSS) of PrM ranged from 7.30-136.35 mg/L, with an average of 41.24 ± 30.74 mg/L. Total Suspended Solids (TSS) in PM ranged from 22.80-155.64 mg/L, with an average of 64.03 ± 32.04 mg/L.

Turbidity: Turbidity ranged from a minimum of 2.70 NTU to a maximum of 625.58 NTU, with an average value of 112.291 ± 190.547 NTU in PrM where as it ranges from a minimum of 0.75 NTU to a maximum of 50.1 NTU, with an average value of 8.802 ± 11.873 NTU in PM

Nitrite: Nitrite levels are ranged from a minimum of 0.065 μmol/L to a maximum of 1.055 μmol/L, with an average value of 0.497 ± 0.238 μmol/L in PrM, whereas in PM, nitrite levels ranged from a minimum of 0.034μmol/L to a maximum of 2.908 μmol/L, with an average value of 0.586 ± 0.670μmol/L.

Nitrate: Nitrate levels ranged from a minimum of 0.166μmol/L to a maximum of 6.409 μmol/L, with an average value of 2.988 ± 1.863 μmol/L in PrM, whereas in PM, nitrite levels ranged from a minimum of 0.161μmol/L to a maximum of 12.797 μmol/L, with an average value of 3.209 ± 2.547 μmol/L.

Ammonia: Ammonia levels ranged from a minimum of 8.038μmol/L to a maximum of 24.946 μmol/L, with an average value of 17.738 ± 5.031 μmol/L in PrM, whereas in PM, nitrite levels ranged from a minimum of 5.543 μmol/L to a maximum of 125.287 μmol/L, with an average value of 27.530 ± 26.347 μmol/L.

Ortho- Phosphate: Orthophosphate levels ranged from a minimum of 0.315 μmol/L to a maximum of μmol/L, with an average value of 1.616 ± 1.060 μmol/L in PrM, whereas in PM, nitrite levels ranged from a minimum of 0.315μmol/L to a maximum of 14.688 μmol/L, with an average value of 3.554± 4.414 μmol/L.

Silicate: In PrM, silicate levels varied from 38.038-328.96 μg/L, averaging 118.98 ± 89.562 μg/L. In contrast, PM silicate levels ranged from 0.1.524-46.534 μg/L, with a higher average of 7.241 ± 10.439 μg/L.

Descriptive Statistics Analysis of PrM Samples of GH AND DH:

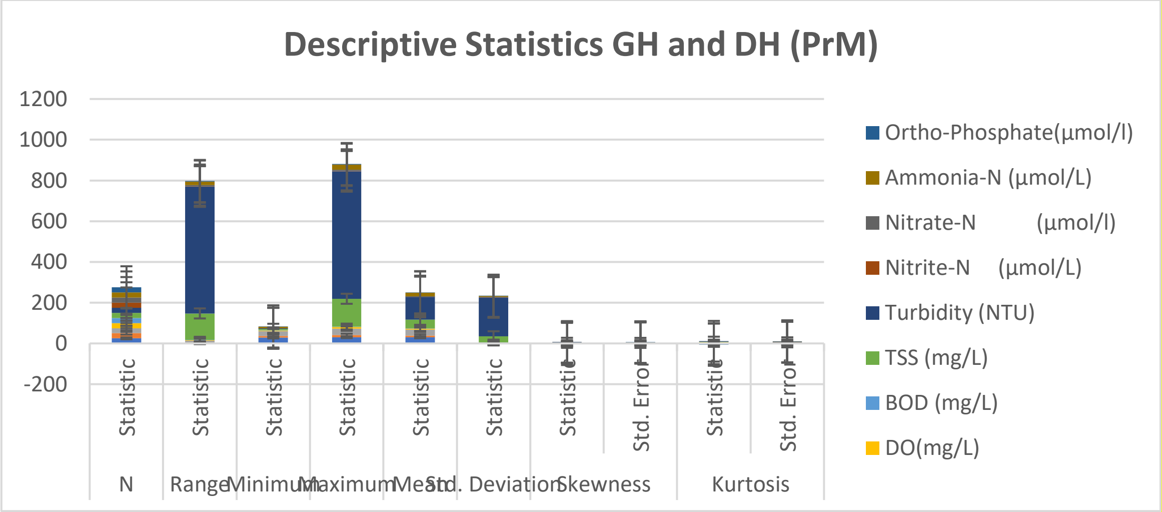


Fig.12: Descriptive Statistics GH and DH (PrM)

The bar chart showing in figure number 12 presents descriptive statistics for various water quality parameters at GH and DH during the pre-monsoon (PrM) period. Ortho-Phosphate and Ammonia-N exhibit significant variability, as reflected in their high maximum values and standard deviations. This suggests potential nutrient enrichment from sources like agricultural runoff and industrial discharge. The presence of elevated nutrient levels during the pre-monsoon period may be linked to reduced water flow and increased anthropogenic inputs(Patra et al., 2016). Other parameters, including turbidity and total suspended solids (TSS), show moderate variation, indicating localized influences on water quality.

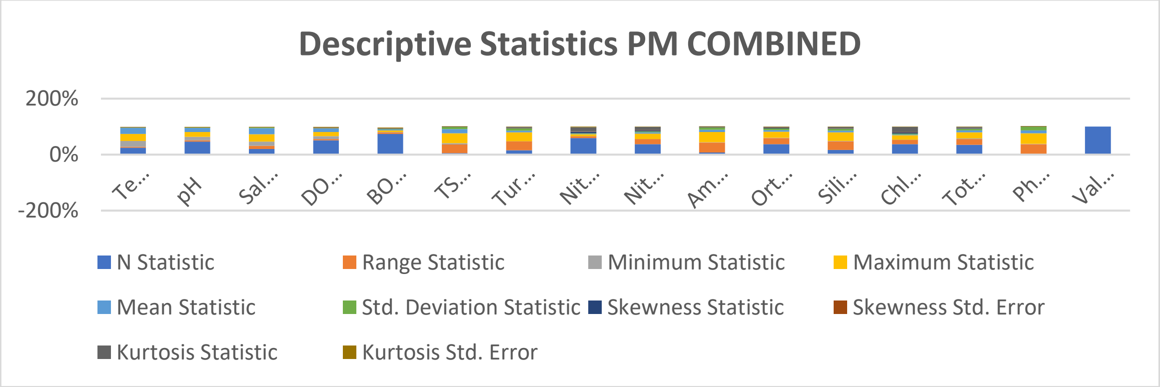


Fig. 13 : Descriptive Statistics GH and DH (PM)

The bar chart in figure number 13, illustrates the descriptive statistics of various physicochemical and biological parameters for the pre-monsoon (PM) period. High variability in parameters such as Ortho-Phosphate, Ammonia-N, and Total Chlorophyll suggests nutrient enrichment, possibly from agricultural runoff and anthropogenic activities(Alprol et al., 2021). The presence of high skewness and kurtosis in some variables indicates non-uniform distribution patterns, which may be influenced by seasonal changes and localized pollution sources.

Comparison of PrM and PM Water parameters:

The seasonal variation in water parameters between the pre-monsoon (PrM) and post-monsoon (PM) periods demonstrates significant environmental changes. Following the monsoon, both temperature and salinity declined, whereas dissolved oxygen (DO) showed a slight increase. Total Suspended Solids (TSS) exhibited an upward trend, while turbidity decreased considerably. Additionally, ammonia, nitrate, and ortho-phosphate concentrations rose, likely due to runoff from surrounding areas. In contrast, silicate levels dropped sharply. A decline in chlorophyll-a was also observed, indicating reduced phytoplankton biomass. These shifts emphasize the influence of monsoonal changes on water quality and ecosystem balance.

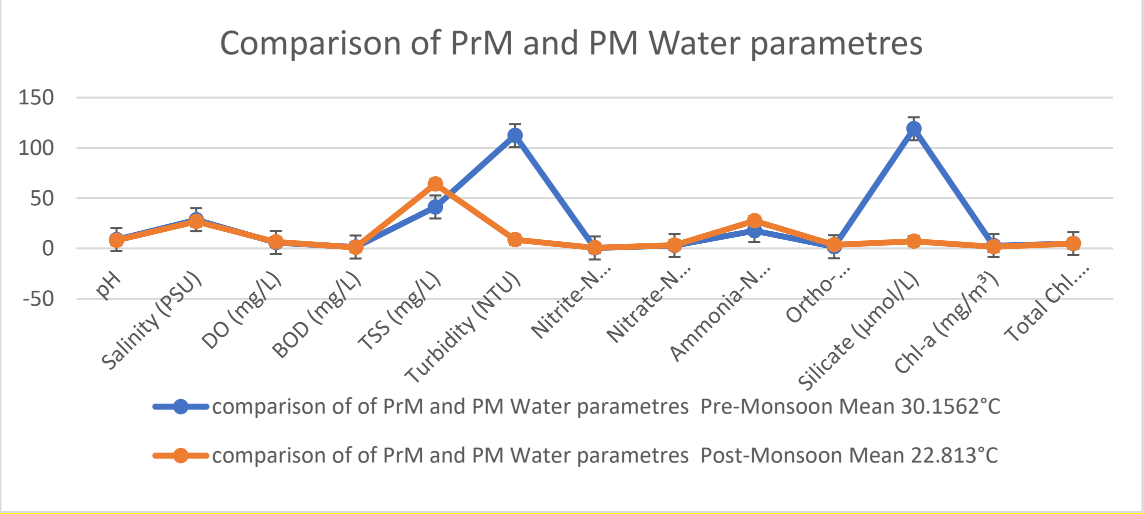
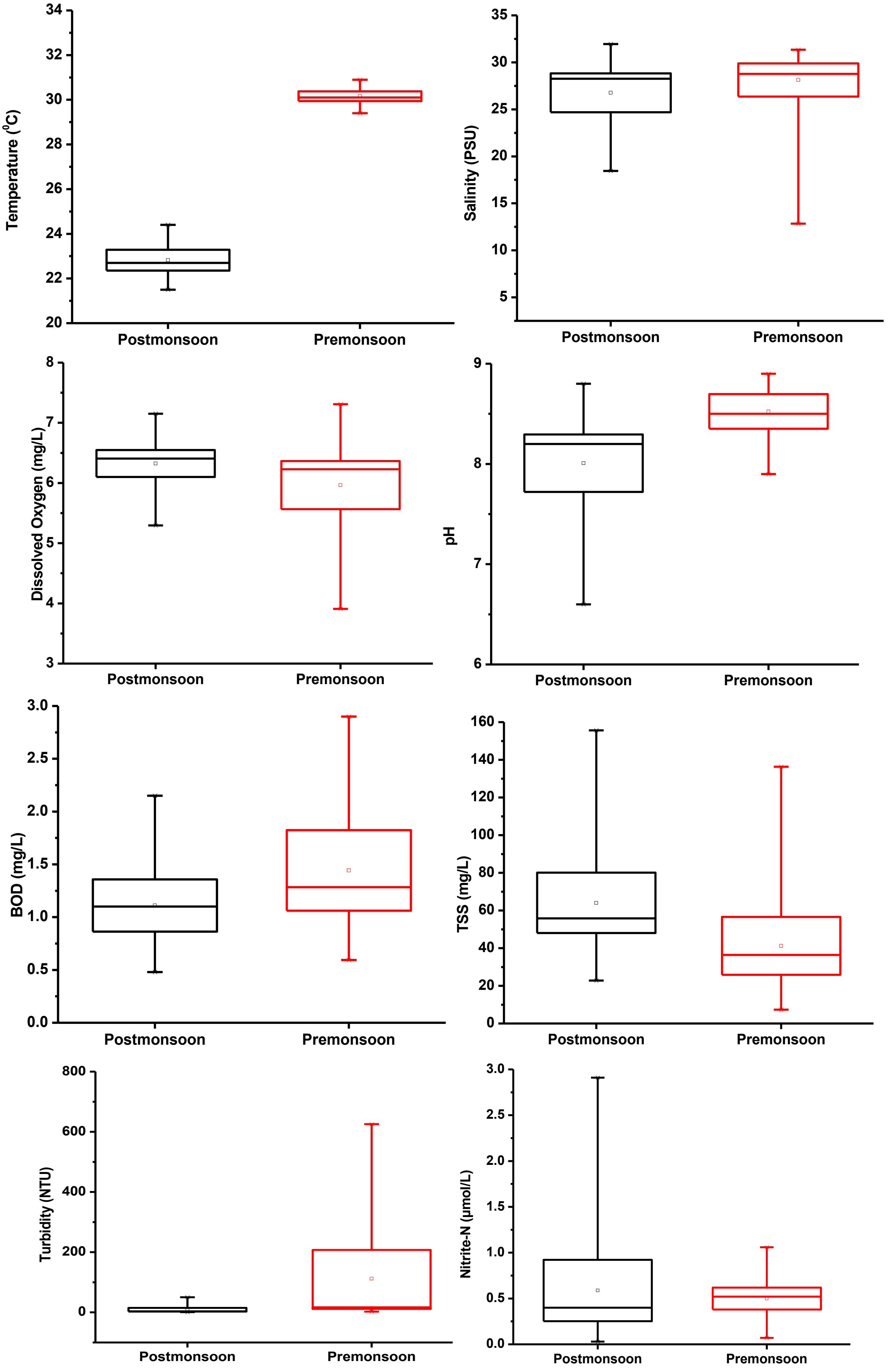


Fig.14: Comparison of PrM and PM Water Parameters

The box plot in figure 14, comparing various water parameters between the pre-monsoon (PrM) and post-monsoon (PM) periods highlights significant differences in stability and distribution. Temperature, pH, and salinity exhibit greater stability during PrM, whereas PM shows increased variability. Certain water parameters, such as DO and BOD, display noticeable differences in range and distribution.


Temperature (°C)
34
32
30
28
26
24
22
20
Postmonsoon
Premonsoon
Salinity (PSU)
35
30
25
20
15
10
5
Postmonsoon
Premonsoon
Dissolved Oxygen (mg/L)
8
7
6
5
4
3
Postmonsoon
Premonsoon
pH
9
8
7
6
Postmonsoon
Premonsoon
BOD (mg/L)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Postmonsoon
Premonsoon
TSS (mg/L)
160
140
120
100
80
60
40
20
0
Postmonsoon
Premonsoon
Turbidity (NTU)
800
600
400
200
0
Postmonsoon
Premonsoon
Nitrite-N (µmol/L)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Postmonsoon
Premonsoon

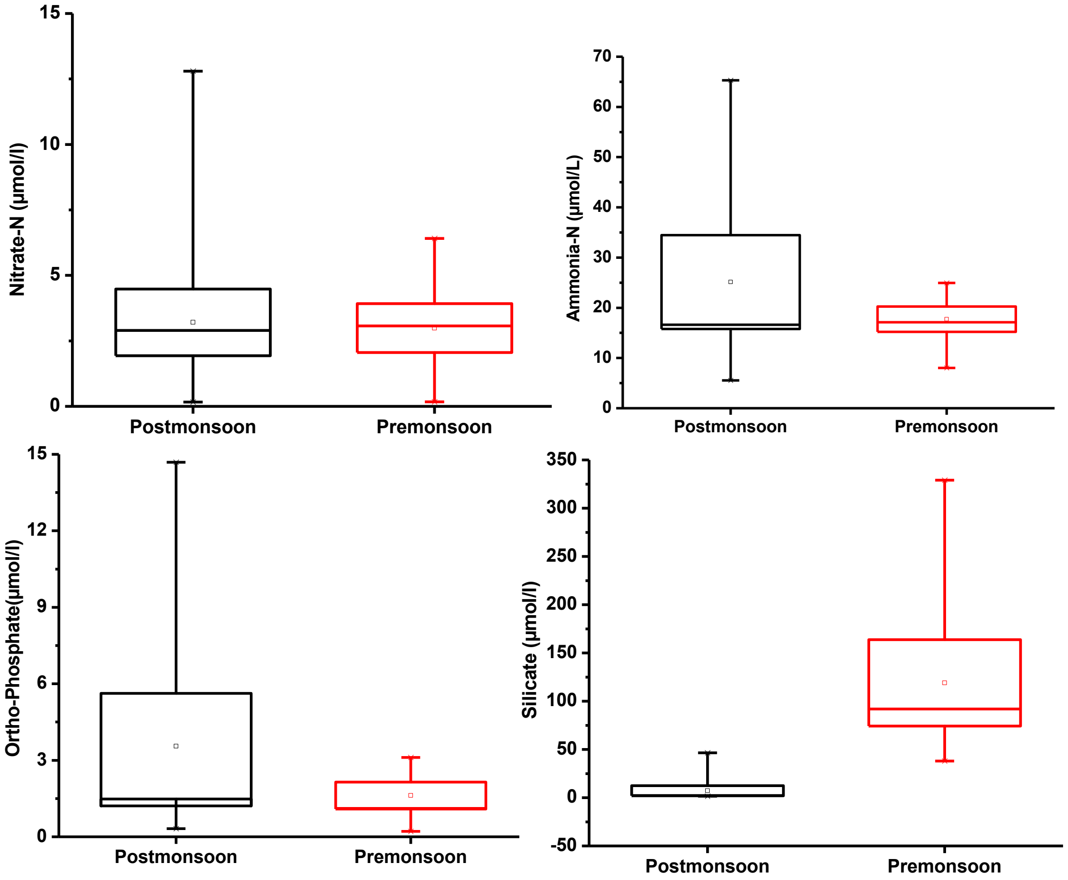
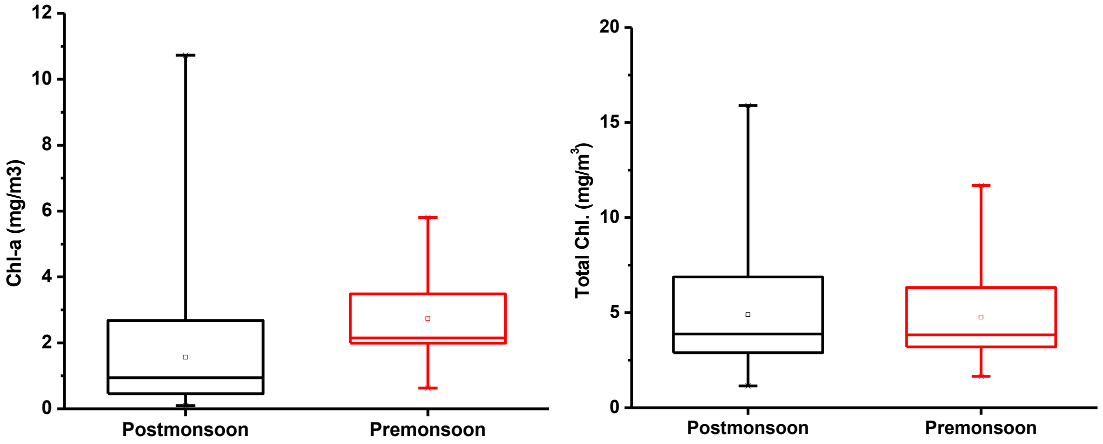


Figure 15: BOX PLOT Comparing water parameters of PrM and PM Results

Chlorophyll a: Chlorophyll-a (Chl-a) levels ranged from 0.625-5.812 mg/m^3, with an average of 2.736 ± 1.491 mg/m^3. in PrM. In PM Chlorophyll-a (Chl-a) levels ranged from 0.096-10.727 mg/m^3, with an average of 1.566 ± 2.223 mg/m^3

Total Chlorophyll: Total Chlorophyll levels ranged from 0.625-5.812 mg/m^3, with an average of 4.759 ± 3.126 mg/m^3. in PrM. In PM total Chlorophyll levels ranged from 1.147-15.903 mg/m^3, with an average of 4.888 ± 3.988 mg/m^3

Phyto- Abundance: Pre-Monsoon (PrM): Phytoplankton abundance ranged from 96.5-472.0 no/mL, with an average of 251.5 ± 102.0 no/Ml in PrM. Phytoplankton abundance ranged from 11.5-2099.0 no/mL, with an average of 589.0 ± 766.2 no/mL in PM.



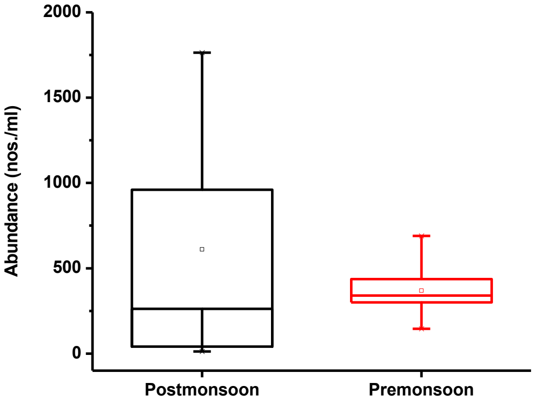


Figure 16: BOX PLOT Comparing PrM and PM Results of Chlorophyll data

3.5 Phytoplankton Abundance in PrM vs. PM

Typically, the post-monsoon season in the sea, witnesses a surge in marine life abundance, surpassing pre-monsoon levels. This phenomenon is attributed to the monsoon rains, which wash nutrients from the land into the ocean, stimulating phytoplankton growth. This, in turn, supports the entire marine food chain.

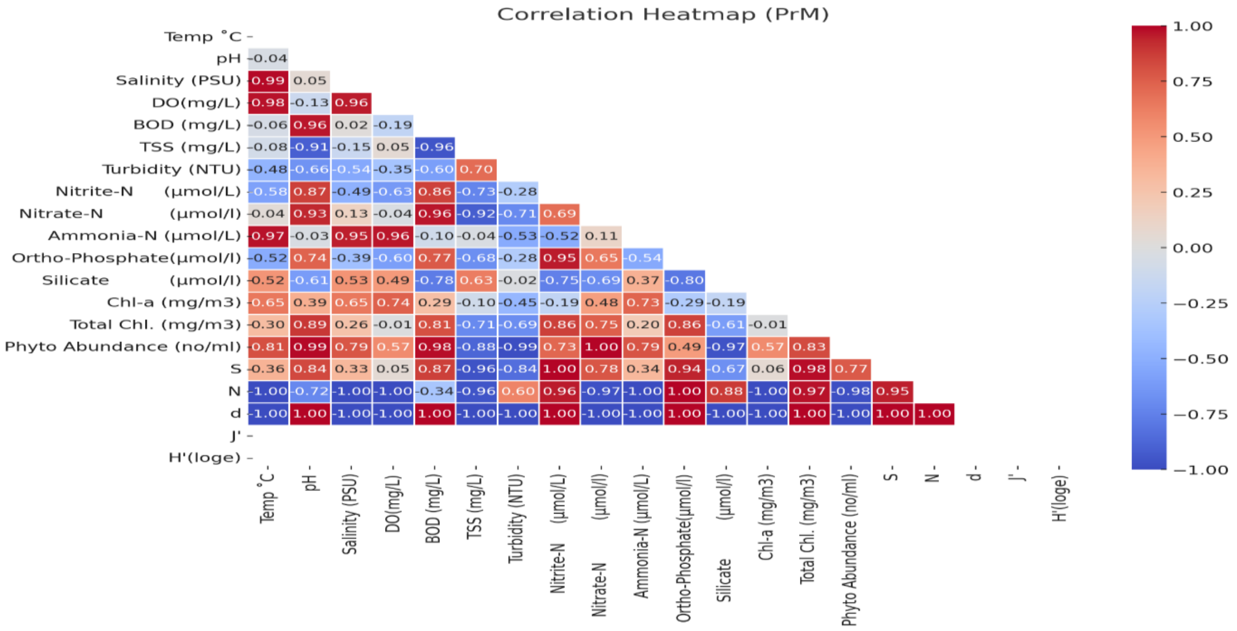
PrM	(96-289 no/mol average 251 .54)
PM	(11.5- 2099 no/mol average 589.00)

3.3.3.2 Correlation analysis:

Correlation Between Phytoplankton Abundance and Environmental Parameters

A Pearson correlation study was performed to investigate the interrelationships between phytoplankton abundance and several ecological parameters.

Correlation of PrM



	Temp °C	pH	Salinity (PSU)	DO(mg/L)	BOD (mg/L)	TSS (mg/L)	Turbidity (NTU)	Nitrite-N (µmol/L)	Nitrate-N (µmol/l)	Ammonia-N (µmol/L)	Ortho-Phosphate(µmol/l)	Silicate (µmol/l)	Chl-a (mg/m3)	Total Chl. (mg/m3)	Phyto Abundance (no/ml)	S	N	d	J'	H'(loge)
Temp °C																				
pH	-0.04																			
Salinity (PSU)	0.99	0.05																		
DO(mg/L)	0.98	-0.13	0.96																	
BOD (mg/L)	-0.06	0.96	0.02	-0.19																
TSS (mg/L)	-0.08	-0.91	-0.15	0.05	-0.96															
Turbidity (NTU)	-0.48	-0.66	-0.54	-0.35	-0.60	0.70														
Nitrite-N (µmol/L)	-0.58	0.87	-0.49	-0.63	0.86	-0.73	-0.28													
Nitrate-N (µmol/l)	0.04	0.93	0.13	-0.04	0.96	-0.92	-0.71	0.69												
Ammonia-N (µmol/L)	0.97	-0.03	0.95	0.96	-0.10	-0.04	-0.53	-0.52	0.11											
Ortho-Phosphate(µmol/l)	-0.52	0.74	-0.39	-0.60	0.77	-0.68	-0.28	0.95	0.65	-0.54										
Silicate (µmol/l)	0.52	-0.61	0.53	0.49	-0.78	0.63	-0.02	-0.75	-0.69	0.37	-0.80									
Chl-a (mg/m3)	0.65	0.39	0.65	0.74	0.29	-0.10	-0.45	-0.19	0.48	0.73	-0.29	-0.19								
Total Chl. (mg/m3)	0.30	0.89	0.26	-0.01	0.81	-0.71	-0.69	0.86	0.75	0.20	0.86	-0.61	-0.01							
Phyto Abundance (no/ml)	0.81	0.99	0.79	0.57	0.98	-0.88	-0.99	0.73	1.00	0.79	0.49	-0.97	0.57	0.83						
S	0.36	0.84	0.33	0.05	0.87	-0.96	-0.84	1.00	0.78	0.34	0.94	-0.67	0.06	0.98	0.77					
N	-1.00	-0.72	-1.00	-1.00	-0.34	-0.96	0.60	0.96	-0.97	-1.00	1.00	0.88	-1.00	0.97	-0.98	0.95				
d	-1.00	1.00	-1.00	-1.00	1.00	-1.00	-1.00	1.00	-1.00	-1.00	1.00	-1.00	-1.00	1.00	-1.00	1.00	1.00			
J'																				
H'(loge)																				

Correlation Heatmap of PrM

- Red Shades (Positive Correlation, closer to +1) → Strong direct relationships, indicating that as one variable increases, the other also increases.
- Blue Shades (Negative Correlation, closer to -1) → Strong inverse relationships, meaning that as one variable increases, the other decreases.
- White Areas (~0 Correlation) → No significant relationship between the variables.

The figure 17, showing the heatmap of PrM serves as a clear visual representation of the interactions between different parameters, such as temperature, pH, salinity, nutrients (nitrate, ammonia, phosphate), chlorophyll-a, and diversity indices (H', d, J').

Strong Positive Correlations (Highly Related)

Salinity and temperature show a strong correlation (~0.94), with salinity increasing as temperature rises, likely due to enhanced evaporation. BOD & TSS (~0.92), Salinity acts as a limiting factor in the abundance of living organisms and its validation caused by dilution and evaporation, which is maximum likely to influence the fauna in the intertidal zone(Raman et al., 2018). Variations in salinity within brackish water ecosystems, including estuaries, backwaters, and mangroves, result from freshwater influx due to monsoon-driven runoff or tidal fluctuations (Pednekar et al., 2011).

Turbidity & TSS (~0.90): Turbidity and Total Suspended Solids (TSS) exhibit a strong correlation (~0.90), indicating that as the concentration of suspended particles increases, water clarity decreases. This results in higher turbidity, making the water appear cloudier. Elevated TSS levels can initiate from natural sources such as soil erosion and organic matter or from human activities like construction, agriculture, and industrial discharge. Increased turbidity can negatively impact aquatic ecosystems by reducing light penetration, affecting photosynthesis, and potentially harming aquatic organisms. Turbidity principally results from the dispersion of suspended particles, with surface water turbidity in the Dhamra estuary ranging from 4.58 to 560 NTU. Unusually high turbidity levels are often linked to river discharge and maintenance dredging activities at Dhamra Port(Sangita et al., 2013). Observations indicate that turbidity tends to be higher in the estuarine region and gradually decreases toward offshore areas due to the natural mixing of seawater and freshwater.

Elevated Total Suspended Solids (TSS) are strongly associated with increased Biochemical Oxygen Demand (BOD), reflecting the presence of organic contaminants in the water. This connection indicates that a higher concentration of suspended particles, often consisting of organic matter, leads to greater oxygen consumption during decomposition. Consequently, high TSS levels can reduce dissolved oxygen availability, deteriorating water quality and affecting aquatic ecosystems. Biochemical Oxygen Demand (BOD) reflects the activity of microorganisms and the amount of oxygen they require to break down biodegradable substances. It is influenced by various factors, including temperature, the intensity of biochemical processes, the concentration of organic matter, and other related environmental conditions(Zhang et al., 2017).During the PM period, the decreased inflow of river water, coupled with the accumulation of decaying organic matter and sewage, stimulates biological activity at higher temperatures. This leads to increased microbial activity in the region. Thus, cause higher microbial decomposition in this region.

Ortho-Phosphate and Nitrite-N exhibit a strong correlation (~0.85), as both serve as key nutrients that impact water quality. Their elevated concentrations can accelerate eutrophication, leading to excessive algal growth, oxygen depletion, and potential disruption of aquatic ecosystems. Among the nine oxidation states of nitrogen (-3 to +5), nitrate is the most thermodynamically stable form of inorganic nitrogen in well-oxygenated waters. Variations in nitrate levels and its reduced inorganic forms occur due to biologically driven processes. In estuarine ecosystems, surface runoff and rapid uptake by phytoplankton are the primary factors influencing the large-scale spatial and temporal fluctuations of nitrate (Flindt et al., 1999). The elevated ammonia levels recorded during the PM season may be attributed to the decomposition of dead phytoplankton and the excretory processes of planktonic organisms. These biological activities contribute to the release of ammonia into the water, influencing nutrient dynamics in the ecosystem. Phosphate concentrations ranged from 0.0049 to 0.0620 mg/L during the pre-monsoon period, 0.2126 to 3.1071 mg/L in PrM, and 0.3159 to 14.6886 mg/L during the PM period. The rise in phosphate levels in the estuarine region was linked to the inflow of nutrient-rich river water into the marine environment and the resuspension of coastal sediments. Channel dredging further contributed to this increase by releasing phosphate into the water column (Johnston, 1981) Strong Negative Correlations (Inverse Relationships).

DO & BOD (~-0.87) - A high Biological Oxygen Demand (BOD) indicates increased decomposition of organic matter, which in turn reduces dissolved oxygen (DO) levels, potentially endangering aquatic organisms(V. Singh, 2024)

Temperature & DO (~-0.78) - Higher water temperatures reduce the capacity of water to retain dissolved oxygen (DO), which can impact aquatic ecosystems (Mallya & Thorarensen, 2007)

pH & Nitrite-N (~-0.80) – Elevated nutrient pollution, particularly from nitrogen-based sources, can contribute to increased water acidity (Mullungal *et al.*, 2024)

Moderate Correlations (Not Strong but Significant)

Chlorophyll-a & Nutrients- Chlorophyll-a exhibits a moderate correlation with silicate and phosphate, highlighting the influence of nutrient availability on algal proliferation,(P. S. Kumar et al., 2018)

Diversity Indices (Shannon Index H', Evenness J') & Water Quality- A moderate correlation suggests that high diversity indices indicate healthier ecosystems, while pollution reduces biodiversity(Lovett et al., 2009).

Interpretation & Environmental Impacts:

Water Quality Issues- High TSS, turbidity, and BOD suggest pollution from organic matter, leading to lower oxygen levels(Maddah, 2022) .High nutrient levels (Nitrite, Phosphate) indicate risks of eutrophication, which can trigger harmful algal blooms(Wurtsbaugh et al., 2019)

Climate & Seasonal Influence: The strong temperature-salinity correlation suggests seasonal changes like evaporation or freshwater influx(Mahanty et al., 2016). The inverse relationship between temperature and dissolved oxygen indicates potential risks due to climate change.

Correlation of Phytoplankton with respect to other water parameters:

The correlation heatmap visually represents the relationships between various water quality parameters and phycodiversity indicators, such as Chlorophyll-a (Chl-a), Total Chlorophyll (Total Chl.), and Phytoplankton Abundance. Here's a breakdown of key insights:

Temperature vs. Phycodiversity

Temperature shows a moderate positive correlation with **Chlorophyll-a (Chl-a), Total Chlorophyll (Total Chl.), and Phytoplankton Abundance** (ranging from ~0.69 to 0.77). This suggests that higher temperatures can enhance algal growth by accelerating metabolic processes and improving nutrient absorption. Warmer conditions may also stimulate phytoplankton activity, leading to increased chlorophyll concentrations and greater phytoplankton abundance. Additionally, elevated temperatures can influence enzyme functions and biochemical reactions within algae, further supporting their growth in aquatic ecosystems.

Dissolved Oxygen (DO) vs. Phycodiversity

Dissolved oxygen (DO) exhibits a strong negative correlation with **Chlorophyll-a (Chl-a) (-0.87), Total Chlorophyll (Total Chl.) (-0.89), and Phytoplankton Abundance (-0.85).** This proposes that an upsurge in phytoplankton biomass is related with a decline in oxygen levels, likely due to intensified organic matter decomposition and respiration. As phytoplankton proliferate, they contribute to higher organic production, which, upon decomposition by microorganisms, consumes significant amounts of oxygen. Additionally, during nighttime or periods of limited light availability, phytoplankton shift from photosynthesis to respiration, further reducing DO levels. This process can lead to hypoxic conditions, negatively impacting aquatic organisms and overall ecosystem health.

Nutrients (Nitrate, Ammonia, Ortho-Phosphate, and Silicate) vs. Phyco-diversity

Nitrate-N and Ammonia-N show a strong positive correlation with Chl-a (~0.80) and Total Chl. (~0.84), indicating that nitrogen plays a crucial role in algal growth(A. Kumar & Bera, 2020). Ortho-Phosphate also correlates positively (~0.78), reinforcing the role of phosphorus as a limiting factor for phytoplankton proliferation(Maat & Brussaard, 2016) **Silicate** has a moderate positive correlation (~0.69) with phyco-diversity, suggesting its role in diatom growth(Penna et al., 2003).

TSS, Turbidity, and BOD vs. Phyco-diversity

TSS and Turbidity have a moderate positive correlation with Chl-a (~0.70), Total Chl. (~0.72), and Phytoplankton Abundance (~0.74). This suggests that increased suspended solids and turbidity may be associated with algal growth, possibly due to nutrient enrichment from organic matter. BOD also correlates positively (~0.79) with phyco-diversity, indicating organic pollution-driven eutrophication.

Salinity vs. Phyco-diversity

Salinity exhibits a weak to moderate positive correlation (~0.60) with Chl-a and Total Chl., indicating that changes in salinity influence phytoplankton dynamics, possibly due to seasonal variations or freshwater inflows(Mezhoud et al., 2016).

Correlation of PM:

The Pearson correlation analysis revealed significant negative relationships between phytoplankton abundance and various environmental factors. This suggests that phytoplankton populations are affected by a complex relationship of multiple factors.

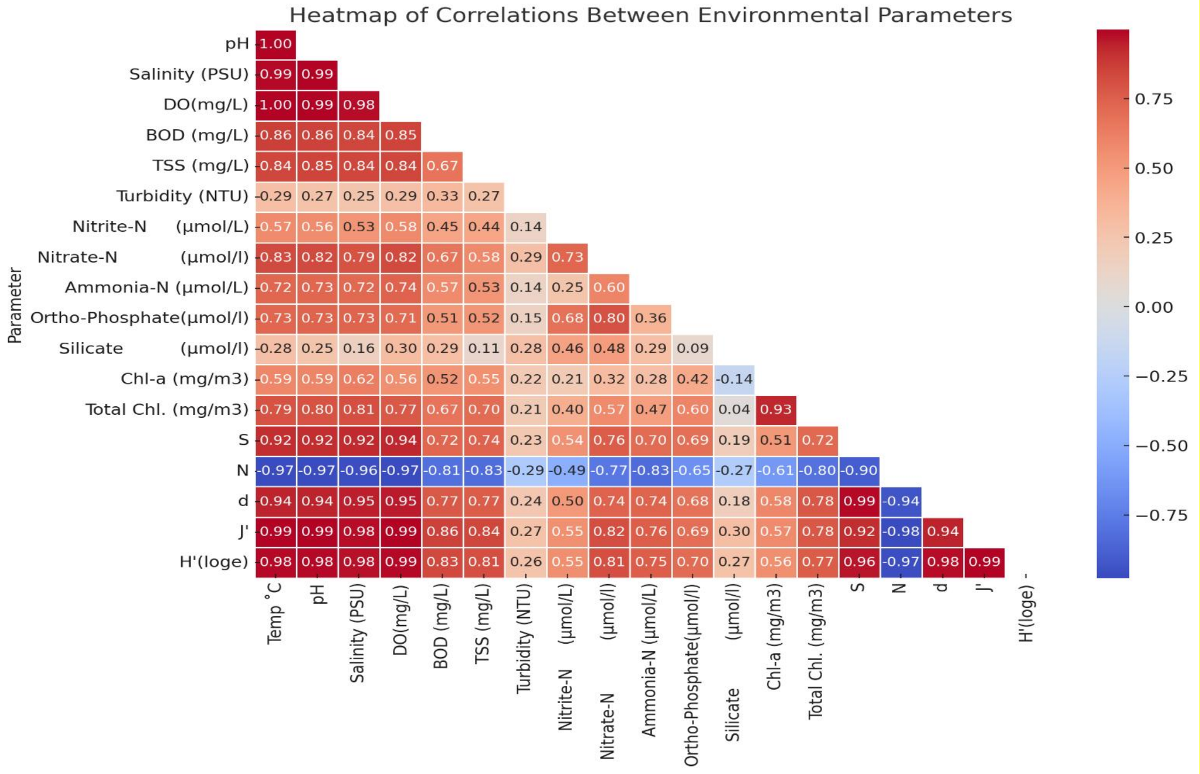


Figure 18: Correlation Heatmap PM

Figure number 18 is showing correlation between the different parameters of PM

Deep red → Strong positive correlation (close to 1).

Deep blue → Strong negative correlation (close to -1).

White or light grey → Weak or no correlation (close to 0)
Some parameters have strong correlations (close to 1), such as Temperature vs. pH (1.00), Temperature vs. Salinity (0.99), and DO vs. Temperature (1.00)

Strong Negative Correlations:

Higher Biochemical Oxygen Demand (BOD) is strongly correlated with lower Dissolved Oxygen (DO) levels (-0.98), indicating significant organic pollution in the system (Udeigwe & Wang, 2010)Similarly, DO shows a strong negative correlation with Total Chlorophyll (-0.89) and Chlorophyll-a (-0.93), suggesting that increased phytoplankton biomass can lead to oxygen depletion due to respiration and decomposition. In contrast, the relationship between silicate and Chlorophyll-a exhibits a weak negative correlation (-0.14), implying that silicate may not be a limiting factor for algal growth in this system.

The significant correlation between BOD and TSS (0.85) as well as Turbidity (0.84) suggests that organic matter pollution contributes to an increase in suspended solids and turbidity in water bodies. This indicates that higher levels of organic contaminants result in greater particulate matter accumulation, affecting water clarity. Similarly, the strong relationship between Total Chlorophyll and Chlorophyll-a (0.93) establishes Chlorophyll-a as a dependable indicator of total phytoplankton biomass, making it a key parameter for evaluating primary production in aquatic systems. Furthermore, the association between nitrogen-based nutrients and phytoplankton growth, as evidenced by Nitrate-N vs. Chl-a (0.73) and Ammonia-N vs. Chl-a (0.72), emphasizes the crucial role of nitrogen availability in supporting phytoplankton proliferation. These findings highlight the impact of nutrient concentrations on algal development and overall ecosystem balance.

Moderate Correlations Indicating Ecological Trends:

The relationship between salinity and Chlorophyll-a (0.72) highlights the impact of seasonal freshwater inflows on phytoplankton productivity(Tarafdar et al., 2021). Similarly, the correlation between turbidity and Chlorophyll-a (0.70) suggests that increased turbidity may result from algal proliferation or the presence of suspended particles. Additionally, the connection between temperature and Chlorophyll-a (0.72) indicates that warmer conditions enhance phytoplankton growth by accelerating metabolic processes(Fernandez Gonzalez, 2022).

Implications & Ecological Significance:

The relationship between salinity and chlorophyll-a (0.72) highlights the impact of seasonal freshwater inflows on phytoplankton productivity. Similarly, the correlation between turbidity and chlorophyll-a (0.70) suggests that increased turbidity may result from algal proliferation or the presence of suspended particles. Additionally, the connection between temperature and chlorophyll-a (0.72) indicates that warmer conditions enhance phytoplankton growth by accelerating metabolic processes(Fernandez Gonzalez, 2022)

Relationship of Total Chlorophyll with Other Parameters:

The correlation values indicate how Total Chlorophyll (mg/m³) is related to other environmental parameters:

Strong Positive Correlations:J' (0.777), **d (0.775)**, **H' (0.765)**, and **S (0.717)** These parameters may be linked to biodiversity measures, such as species richness or ecological diversity indices. Higher total chlorophyll concentrations could signal increased biological activity, which in turn may contribute to higher biodiversity levels.

Strong Negative Correlation:

N (-0.800). This may indicate nitrogen availability or a related nutrient factor. The negative correlation suggests that as total chlorophyll increases, nitrogen levels decrease, likely due to phytoplankton consumption of nitrogen from the water, as chlorophyll is a key component of phytoplankton cells.

High chlorophyll concentrations may signify elevated biological productivity within the water body. The strong negative correlation with nitrogen suggests that phytoplankton growth is rapidly depleting nitrogen levels, indicating an active uptake of nitrogen as they proliferate. Additionally, the positive correlations with species richness (S), diversity indices (H', J'), and evenness (d) suggest that increased chlorophyll levels may be linked to greater ecological diversity(Jeppesen et al., 2000). This implies a potential connection between phytoplankton growth and overall biodiversity within the aquatic ecosystem.

4. DISCUSSION

Seasonal variations in phytoplankton abundance and community composition in the Bhitarkanika mangrove-estuarine ecosystem were strongly influenced by changes in salinity, nutrient availability, temperature, and dissolved oxygen. Freshwater influx during the post-monsoon period altered salinity gradients and enhanced nutrient loading, thereby promoting phytoplankton growth (Pednekar et al., 2011; Mahanty et al., 2016; Flindt et al., 1999; Carpenter et al., 1998). The dominance of blue-green algae during the post-monsoon season suggests adaptation to nutrient-rich conditions, as reported in other coastal ecosystems (Paerl & Huisman, 2008; Baliarsingh et al., 2015; Patra et al., 2016). Variations in chlorophyll-a concentration reflected changes in phytoplankton biomass and productivity (Paerl et al., 2010; Tarafdar et al., 2021). Furthermore, the positive relationship between suspended particulate matter and phytoplankton abundance highlights the role of nutrient recycling and retention within the estuary (Patra et al., 2016; Sangita et al., 2013).

The observed relationships among dissolved oxygen, biological oxygen demand, chlorophyll-a, and biodiversity indicate the importance of phytoplankton in regulating ecosystem functioning and supporting aquatic food webs (Maddah, 2022; Udeigwe & Wang, 2010; Kathiresan & Bingham, 2001). Overall, the findings demonstrate that monsoon-driven environmental changes play a key role in shaping phytoplankton dynamics in the Bhitarkanika ecosystem.

5. Conclusion:

It is concluded from the BH samples that, seasonal factors, including rainfall, nutrient availability, and temperature, play a vital role in determining algal community composition and abundance. The data reveals significant post-monsoon changes, particularly in blue-green algae, which show a notable increase in cell count. In contrast, other groups such as green algae and Cryptophyta exhibit minor variations, while diatoms and dinoflagellates decline slightly. These trends suggest that monsoon-driven environmental changes influence algal dynamics, likely due to shifts in nutrient levels and marine flow. By knowing these seasonal impacts is vital for effective water resource management and ecosystem monitoring.

The study of GH and DH emphasizes the significant impact of seasonal changes, particularly monsoon-driven variations, on water quality and phytoplankton diversity. Key environmental factors such as rainfall, nutrient levels, temperature, and salinity impact the construction and abundance of algal communities. The findings indicate a notable rise in blue-green algae following the monsoon, likely due to increased nutrient availability that supports their growth. In contrast, certain algal groups, including diatoms and dinoflagellates, show a slight decline post-monsoon, suggesting that shifts in environmental conditions, such as salinity fluctuations and nutrient imbalances, may have influenced their distribution.

A crucial factor affecting phytoplankton dynamics is **turbidity and total suspended solids (TSS)**, which impact nutrient circulation and light penetration. While moderate turbidity promotes phytoplankton growth by keeping nutrients in suspension, excessive levels can reduce light availability and hinder photosynthesis. The observed correlation between TSS, turbidity, and chlorophyll (~0.70-0.74) highlights the influence of suspended particles on phytoplankton productivity, particularly in nutrient-enriched water bodies. This suggests that seasonal shifts in sedimentation and water movement significantly shape aquatic ecosystems.Additionally, **statistical analyses of GH and DH reveal strong interactions between temperature, pH, salinity, and dissolved oxygen**, which collectively regulate biological activity and ecosystem stability. Warmer temperatures and abundant nutrients generally support phytoplankton proliferation; however, increased competition and oxygen depletion may offset these benefits. The inverse correlation between total chlorophyll and nitrogen levels suggests that nitrogen is actively utilized during peak phytoplankton activity. Furthermore, biodiversity metrics indicate a positive relationship between chlorophyll concentration and species richness, reinforcing the essential role of phytoplankton in sustaining aquatic food webs.The hierarchical clustering and MDS analyses highlight spatial variations in water quality between GH and DH sites. GH locations exhibit more consistent environmental conditions and phytoplankton diversity, whereas DH sites display greater variability, possibly due to differences in nutrient influx, water flow, and human-induced influences. These clustering patterns underscore the role of factors such as salinity, turbidity, and organic matter (BOD) in structuring phytoplankton communities and influencing species distribution.The interdependence of **water value limits, phytopankton diversity, and ecological fluctuations** underscores the necessity of continuous monitoring and effective water resource management. The findings indicate that phytoplankton abundance and diversity respond dynamically to seasonal and anthropogenic changes, particularly shifts in nutrient supply, salinity, and turbidity. These interactions are essential for predicting ecological responses to environmental changes and implementing strategies for sustainable aquatic ecosystem management.

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