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Dynamics of physicochemical factors shaping phytoplankton distribution in the Sundarbans mangrove ecosystem

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Abstract
The Indian Sundarbans, a UNESCO World Heritage Site, represent one of the world's largest and most dynamic ecosystems. Phytoplankton, as primary producers, form the foundation of the aquatic food web and play a crucial role in carbon sequestration within this estuarine deltaic landscape. However, the ecosystem is increasingly being influenced by fluctuations in salinity, nutrient influx, and climate-related stressors. The present study investigates the ecological relationship between physicochemical parameters and phytoplankton population in selected regions of the Indian Sundarbans. The study was conducted over one year, from November, 2023 to October, 2024 across four sampling stations along the Ganga River - Godkhali, Gosaba, Canning, and Jharkhali. Water samples were analysed for key physicochemical parameters, including temperature, pH, biological oxygen demand (BOD), and chemical oxygen demand (COD).
Seasonally, the highest water temperature was recorded at Canning, while the lowest was observed at Jharkhali. Maximum pH was recorded at Canning during the pre-monsoon period, whereas the minimum was noted at Godkhali and Gosaba in the post-monsoon season. BOD peaked during the monsoon at Canning and reached its lowest at Godkhali in post-monsoon. Similarly, COD was highest at Canning in pre-monsoon and lowest at Godkhali in post-monsoon. Phytoplankton density was highest during the post-monsoon period, followed by pre-monsoon and monsoon. Canning and Godkhali consistently showing the highest and lowest density of phytoplankton in each season respectively. Bacillariophyceae dominated at most sites. One-way ANOVA, correlation study and regression analysis revealed that phytoplankton density was primarily influenced by BOD, followed by temperature. Two-way ANOVA indicated that seasonal and combined physicochemical interactions significantly affect phytoplankton dynamics.

Keywords: Indian Sundarbans, physicochemical factors, phytoplankton density, seasonal variation

Introduction

The term plankton derived from the Greek word, meaning drifter or wanderer, aptly describes a diverse assemblage of aquatic organisms that drift with water currents and lack the ability to swim against them [19]. Plankton are broadly classified into two major groups: phytoplankton and zooplankton. Among these, phytoplankton occupy a pivotal ecological position as primary producers, inhabiting the sunlit surface water where they harness solar energy through photosynthesis. In doing so, they convert carbon dioxide into organic matter and release oxygen, thereby sustaining life in both aquatic and terrestrial environments [15, 17, 22].

Although phytoplankton constitute merely about 1% of the Earth's total biomass, they are responsible for nearly 50% of global photosynthetic activity and approximately 90% of underwater primary production [21, 22]. Primary productivity of marine and coastal phytoplankton contributes to 15% of global oceanic production [11]. Phytoplankton biomass and primary production mainly depend on nutrient dynamics of coastal and estuarine ecosystems. Their immense contribution to carbon fixation and oxygen generation highlights their critical role in regulating the global carbon cycle and mitigating climate change. Furthermore, phytoplankton serve as the primary food source for a wide array of aquatic organisms, including zooplankton, finfish and shellfish; thereby facilitating energy transfer across trophic levels and maintaining ecosystem stability [23, 24, 30].

In ecologically significant regions such as the Sundarbans, the world's largest mangrove forest, covering approximately 10,000 sq. km across India and Bangladesh; plankton play a crucial role in sustaining one of the most productive estuarine ecosystems on Earth [6, 18]. The abundance, diversity, and dynamics of phytoplankton directly influence fish production and overall aquatic health, making them indispensable indicators of environmental change and ecosystem productivity [28, 33].

Plankton communities are highly sensitive to environmental fluctuations such as temperature, salinity, pH, and nutrient availability [16]. Excessive nutrient inputs often lead to harmful algal blooms, including red tides, which can severely disrupt aquatic ecosystems [4]. Phytoplankton diversity in aquatic ecosystems is strongly influenced by physicochemical properties of water, which regulate their composition, abundance, and distribution [1]. Due to their high sensitivity to environmental fluctuations, phytoplankton serve as reliable bioindicators of water quality and ecological health [13, 25]. Moreover, they play a crucial role in reflecting ecological interactions within aquatic systems [31]. The spatial and temporal dynamics of phytoplankton communities are governed by variations in environmental factors, while seasonal changes significantly shape their diversity and community structure [20].

In estuarine ecosystems such as the Sundarbans, seasonal variability exerts a pronounced influence on phytoplankton dynamics. Monsoonal precipitation and increased runoff elevate turbidity levels, thereby reducing light penetration and limiting photosynthetic activity, which in turn affects phytoplankton productivity and community composition. The region experiences a tropical monsoonal climate, with summer (pre-monsoon) extending from mid-March to mid-June, monsoon from mid-June to mid-October, and winter (post-monsoon) from mid-November to February. The average annual maximum temperature reaches approximately 35°C, while annual rainfall averages around 1920 mm. Relative humidity remains consistently high, averaging about 82% throughout the year. Additionally, the Sundarbans harbour rich biodiversity, including 34 true mangrove species, which contribute to the ecological complexity and productivity of this unique estuarine environment [26].

The present study aims to evaluate the density and diversity of phytoplankton in the Sundarbans mangrove ecosystem and examine their relationship with varying physicochemical parameters. It also seeks to analyse seasonal fluctuations in phytoplankton density across selected sampling sites in the Indian Sundarbans.

Materials and Methods

Phytoplankton samples were collected with standard phytoplankton net and conducted laboratory analysis to identify major phytoplankton groups, including Bacillariophyceae, Chlorophyceae, Cyanophyceae and Euglenophyceae via standard taxonomic keys. Determination of the density of these organisms was carried out by using Sedgwick-Rafter counting technique.

Water quality Parameters

Water sample were collected from four different study areas and analysed their various physicochemical parameters including water temperature, pH, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). Temperature of water sample from study area was measured by Thermometer of Deschem. pH of water sample was measured by standard pH meter of Systronics. BOD and COD are assessed according to the guideline of standard method of The American Public Health Association [5].

Study Area

For this study, four sampling stations were selected along with the Ganga River in the Sundarbans. All are situated on the north-western to central edge of the Indian Sundarbans.

1. **Godkhali:** It is located near the confluence of tidal creeks. The site shows moderate human activity and its water reflects mixed freshwater and tidal inflow.
2. **Gosaba:** It is densely inhabited area with notable agricultural and human activities. Its water reflects both tidal and freshwater influences.
3. **Canning:** Canning is key town along with Malta river, linked to the Sundarbans delta. It is influenced by river flow, tidal changes, fishing and transport.
4. **Jharkhali:** This placed lies within inner Sundarbans by dance mangrove. The water quality remains unaffected by urban or industrial disturbance and reflecting near natural ecological environment.

Duration of study

The present investigation was conducted over a one-year period from November, 2023 to October, 2024. Sampling was carried out on a monthly basis to observed seasonal variations in water quality and phytoplankton diversity. Whole year was classified into three main seasons for analysis, such as pre-monsoon period, which includes from March to June; monsoon period, which includes from July to October and post-monsoon period, which includes from November to February. Seasonal variations were used to assess the relationship between physicochemical parameter and phytoplankton community.

Statical analysis

Statical analysis including mean, standard deviation and standard error, correlation, regression, one-way ANOVA and two-way ANOVA were done by Microsoft Excel and SPSS vs 16 software.

Result and Discussion

Analysis of dynamism of temperature of water body from selected sampling area

Temperature of water has exhibited a clear variation at all sampling stations. Higher temperature was shown in pre-monsoon period followed by monsoon and post-monsoon periods respectively at every selected area of Sundarbans (Table 1-4; Fig. 1a). Among the sampling stations Canning recorded the comparatively higher temperature in all the season of year, such as pre-monsoon, monsoon and post-monsoon period (Table 3; Fig. 1a); where as Jharkhali consistently exhibited low temperature throughout the year (Table 4; Fig. 1a) from other three places. Annual range of variation of temperature was from 19.9±0.91^{0}C to 26.2±1.2 ^{0}C. The temperatures across Godkhali, Gosaba, Canning and Jharkhali remain incredibly close to one another within the same season. The monsoon season showed the lowest fluctuations of standard errors (ranging from ± 0.49 to ± 0.54) in comparison with other season of year, meaning water temperature are highly stable compared to pre-monsoon and post-monsoon (Table 1-4; Fig. 1a). Mean water temperature peaks especially in March to June because the pre-monsoon season has strong sunlight, longer day and very few cloud [10].

Analysis of dynamism of pH of water from selected sampling area

Surface water pH across the four sampling sites showed a clear seasonal pattern. pH of water exhibited gradual decreasing order from pre-monsoon period to post-monsoon period from each selected area (Table 1-4; Fig. 1b). Highest pH of water was recorded from Canning (8±0.06) in pre-monsoon season (Table 3) and lowest pH of water exhibited from Godkhali (7.1±0.04) and Gosaba (7.1±0.04) in post-monsoon period (Table 1, 2; Fig. 1b). That means nature of water was changing from alkaline to acidic from March to January, though the range of variation is very low. The probable reason might be in monsoonal runoff introduces organic load and terrestrial humic substance into water increasing free CO_2 levels and lowering alkalinity [6]. Maximum and minimum change of seasonal pH was recorded from Canning (from 7.2±0.04 to 8±0.06) and Godkhali (from 7.1±0.04 to 7.5±0.14) respectively (Table 1-4; Fig. 1b).

Analysis of BOD from selected sampling area

Biological Oxygen Demand measures the organic water pollution by tracking how much oxygen microorganism consume while breaking down organic matters [27]. Average BOD was maximum in monsoon season followed by pre-monsoon and post-monsoon period respectively from each sampling area (Table 1-4; Fig. 1c). BOD is maximum in the rainy season because runoff brings large amounts of organic matter and several pollutants into water bodies. This increases microbial decomposition, which utilizes more dissolved oxygen, leading to higher BOD. Maximum BOD was recorded from Canning (25.7±0.78 mg/L) in monsoon season and minimum was reported from Godkhali (15.7±0.3 mg/L) during November to February. Among the four sampling areas annual range of variation of BOD is highest in Canning (from 16.2±0.48 mg/L to 25.7±0.78 mg/L) and lowest in Godkhali (from 15.7±0.3 mg/L to 24±0.62 mg/L) (Table 1, 3; Fig. 1c).

Table 1: Physicochemical factors and phytoplanktonic density of Godkhali with corresponding level of significance ($P<0.05$) of Two-way ANOVA

Season	Water Temperature (^{0}C)	Water pH	BOD (mg/L)	COD (mg/L)	Phytoplankton (Org/L)	P-value (Two-way ANOVA)
Pre-monsoon	26.1±1.18	7.5±0.14	19.4±0.88	42.4±2.85	366±3.22	0.001×10^{-13}
Monsoon	25.3±0.49	7.2±0.04	24±0.62	40.4±2.09	282.33±4.41	0.004×10^{-12}
Post-monsoon	20.5±1.05	7.1±0.04	15.7±0.3	30.1±1.18	454.33±3.48	0.003×10^{-9}

Table 2: Physicochemical factors and phytoplanktonic density of Gosaba with corresponding level of significance ($P<0.05$) of Two-way ANOVA

Season	Water Temperature (^{0}C)	Water pH	BOD (mg/L)	COD (mg/L)	Phytoplankton (Org/L)	P-value (Two-way ANOVA)
Pre-monsoon	25.6±1.23	7.8±0.06	19.1±1.11	44.7±3.08	409.67±4.33	0.004×10^{-13}
Monsoon	24.9±0.5	7.2±0.11	24.5±0.65	42.8±1.93	338.67±1.85	0.007×10^{-4}
Post-monsoon	20.2±1.0	7.1±0.04	16±0.35	32.7±1.34	494.67±3.48	0.009×10^{-16}

Table 3: Physicochemical factors and phytoplanktonic density of Canning with corresponding level of significance ($P<0.05$) of Two-way ANOVA

Season	Water Temperature (^{0}C)	Water pH	BOD (mg/L)	COD (mg/L)	Phytoplankton (Org/L)	P-value (Two-way ANOVA)
Pre-monsoon	26.2±1.2	8±0.06	20.1±0.96	48.2±3.49	509±2.0	0.001×10^{-14}
Monsoon	25.5±0.54	7.4±0.04	25.7±0.78	45.5±1.82	398.67±0.67	0.001×10^{-15}
Post-monsoon	20.8±1.07	7.2±0.04	16.2±0.48	37.4±0.8	586±3.05	0.001×10^{-17}

Table 4: Physicochemical factors and phytoplanktonic density of Jharkhali with corresponding level of significance ($P<0.05$) of Two-way ANOVA

Season	Water Temperature (^{0}C)	Water pH	BOD (mg/L)	COD (mg/L)	Phytoplankton (Org/L)	P-value (Two-way ANOVA)
Pre-monsoon	25.5±1.18	7.7±0.13	19.6±0.97	45.5±2.67	425±3.21	0.001×10^{-14}
Monsoon	24.8±0.53	7.3±0.04	24.9±0.57	43±2.61	339.33±0.33	0.007×10^{-14}
Post-monsoon	19.9±0.91	7.2±0.04	15.8±0.27	35.3±1.14	507.33±3.18	0.001×10^{-16}

Analysis of COD from selected sampling area

Chemical Oxygen Demand measures the total amount of oxygen required to chemically oxidize both biodegradable and non-biodegradable organic matter in water. The maximum mean values were recorded during pre-monsoon season followed by monsoon and post-monsoon season respectively from each study area (Table 1-4; Fig. 1d). Highest COD value was recorded from Canning (48.2±3.49 mg/L) in pre-monsoon season (Table 3; Fig. 1d) and lowest COD was reported from Godkhali (30.1±1.18 mg/L) in post-monsoon season (Table 1; Fig. 1d). During monsoon, the values decreased moderately, varying between 40.4±2.09 mg/L (from Godkhali) to 45.5±1.82 mg/L (from Canning). The lowest values were recorded during post-monsoon, ranging from 30.1±1.18 mg/L (from Godkhali) to 37.4±0.8 mg/L (from Canning). Among the stations Canning consistently exhibited the highest values followed by Jharkhali and Gosaba, whereas Godkhali showed lowest value through the study period (Table 1-4; Fig. 1d). High COD promotes intense microbial decomposition, which consume dissolved oxygen and can create hazardous environment for aquatic fauna [2].

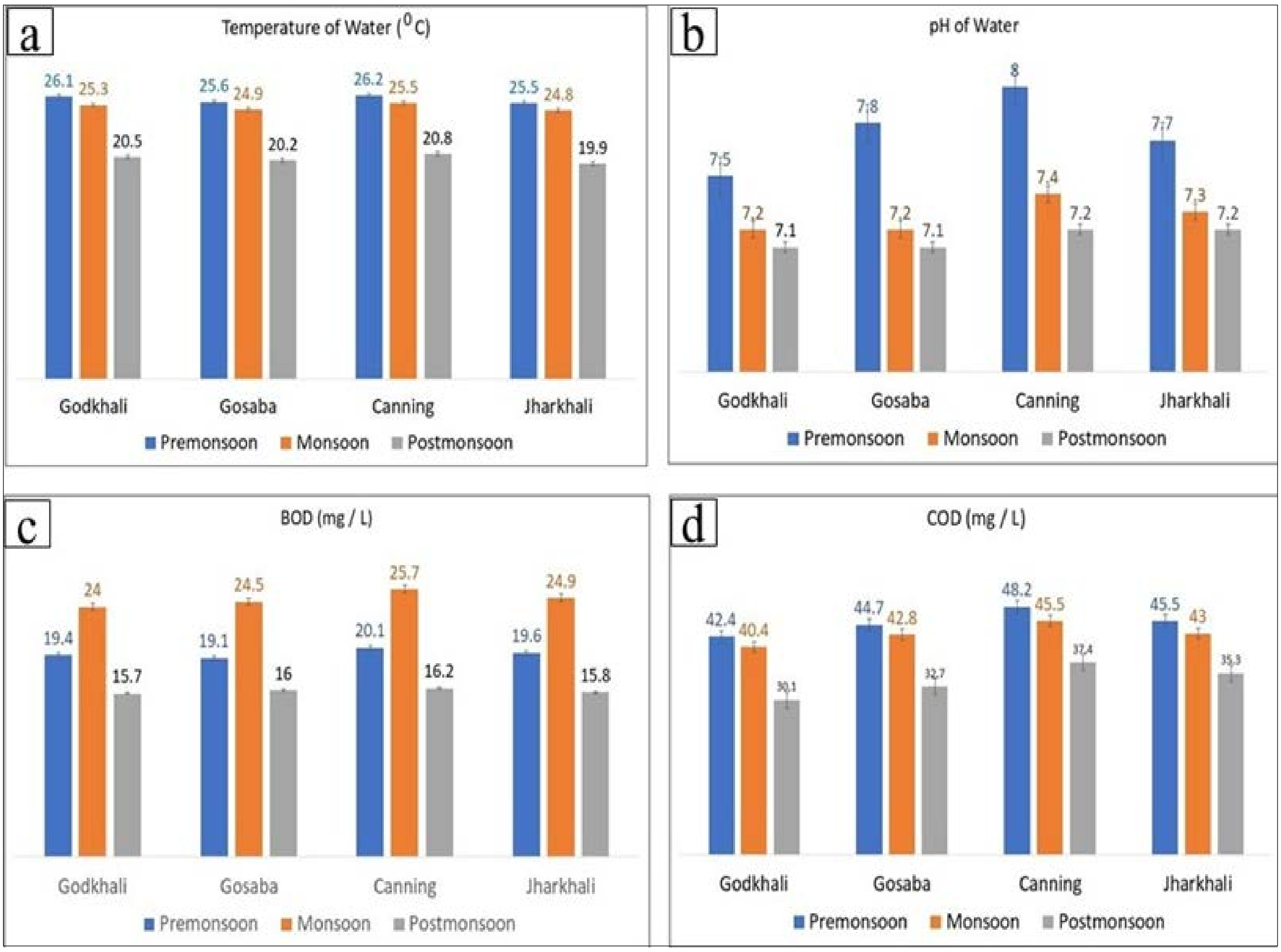

Fig 1: Seasonal physicochemical variation from study areas of Sundarbans: a: Godkhali; b: Gosaba. c: Canning; d: Jharkhali

Phytoplanktonic density and diversity from selected sampling area

In this study density of phytoplankton is maximum in post-monsoon period followed by pre-monsoon and monsoon period from every sampling site. Among the stations Canning consistently exhibited the highest density of phytoplankton followed by Jharkhali and Gosaba, whereas Godkhali showed lowest value through the study period. Maximum and minimum seasonal fluctuation of phytoplanktonic density was reported from Canning (from 398.67±0.67 Org/L to 586±3.05 Org/L) and Gosaba (from 338.67±1.85 Org/L to 494.67±3.48 Org/L) respectively (Table 1-4; Fig. 2). Phytoplanktonic density is minimum in the rainy season due to dilution of water and reduced light penetration caused by turbidity. High water flow and mixing also wash away phytoplankton, lowering their population density [32].

Majorly four different classes of phytoplankton were observed from each station, such as Chlorophyceae, Bacillariophyceae, Cyanophyceae and Euglenophyceae. Maximum Bacillariophyceae was observed from each sampling area except Godkhali, where Chlorophycere shown maximum (47%) (Fig. 3). Phytoplankton belonging to Euglenophyceae exhibited least density from every study zone throughout study tenure (Fig. 3). Density of Chlorophyceae, Bacillariophyceae, Cyanophyceae and Euglenophyceae was recorded maximum in post-monsoon season followed by pre-monsoon and monsoon period respectively from every study site.

Influence of physicochemical factors on phytoplanktonic density

Growth and diversity of phytoplankton is strongly regulated by different physicochemical parameters of environment, such as light intensity, salinity, temperature, pH, nutrient availability, BOD, COD etc; those directly or indirectly influenced the metabolic activity and population dynamics of phytoplankton.

In this study mainly four physical factors i.e. temperature of water, pH of water, BOD and COD are considered regarding the phytoplanktonic density from four different sampling areas of Sundarbans- Godkhali, Gosaba, Canning and Jharkhali. Two-way ANOVA clearly states that the variation of phytoplanktonic density is significantly affected ($P<0.05$)) by the cumulative interactions of four concerned physical factors.

As per correlation analysis among the concerned physicochemical factors it is clearly observed that they are positively correlated with each other (Table 5) and specially temperature of water has shown highly significant ($p<0.01$) positive correlation with COD from each sample area. COD of Canning and Jharkhali is exhibited significant positive correlation ($p<0.05$) with pH of water (Table 5c, 5d).

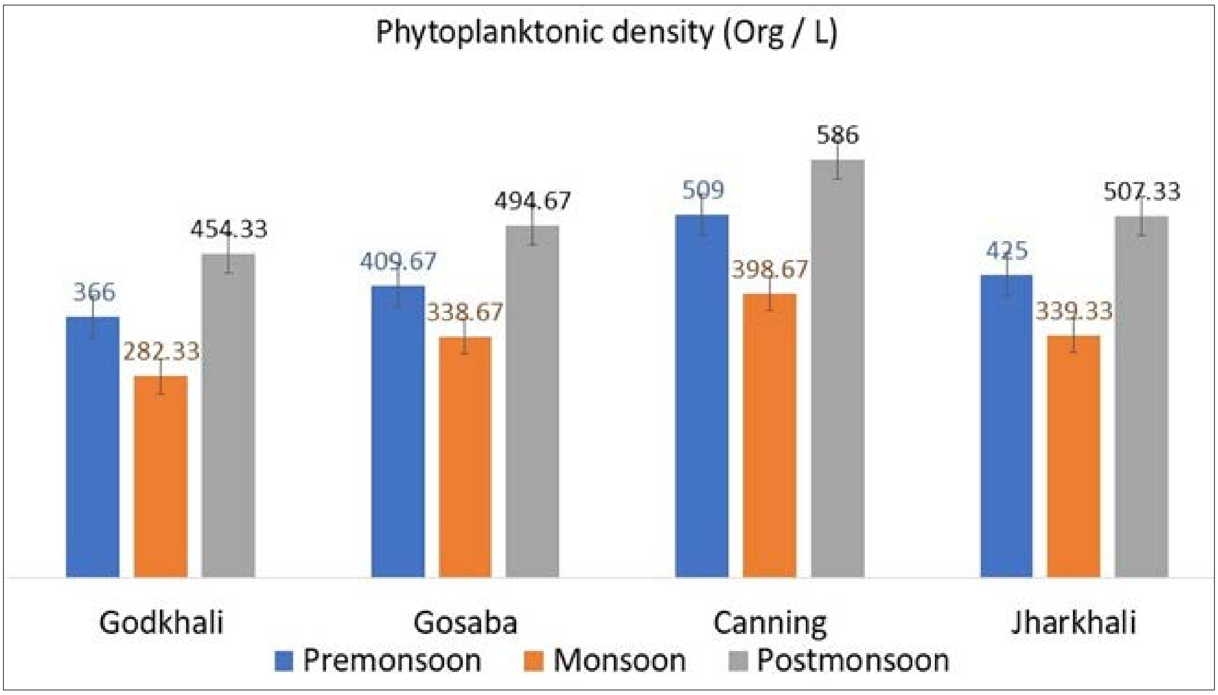

Fig 2: Seasonal phytoplanktonic density from sampling areas of Sundarbans

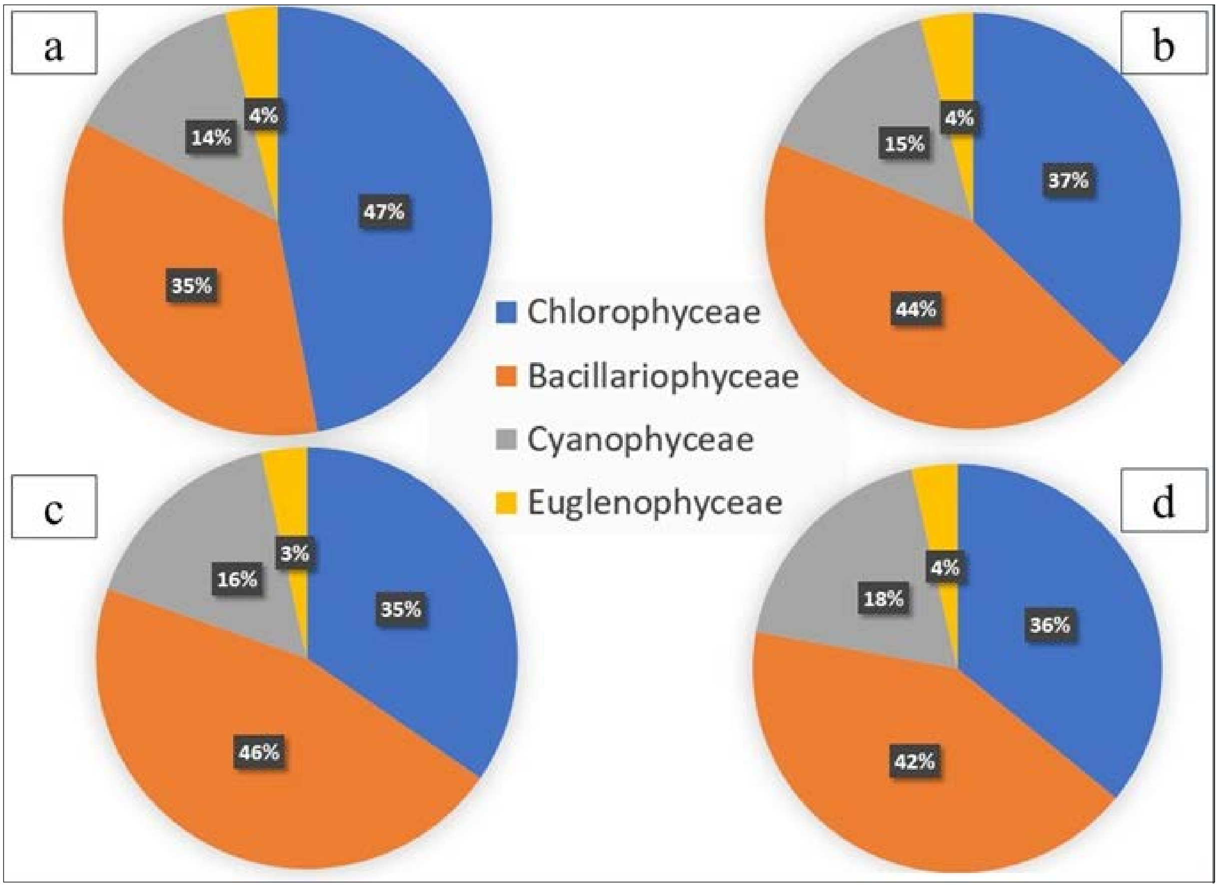

Fig 3: Comparative diversity of phytoplankton from study area of Sundarbans: a: Godkhali; b: Gosaba. c: Canning; d: Jharkhali

Phytoplanktonic density has shown negative correlation with each of the physicochemical factor, especially BOD value of every sample has exhibited highly statistically significant negative correlation ($p<0.01$) with the density of phytoplankton (Table 5). This might be due to unique estuarine and mangrove ecosystem of Sundarbans. High turbidity, fluctuating salinity and high BOD and COD reduce penetration of light in water and availability of oxygen, limiting photosynthesis; which results in lower phytoplanktonic growth despite of presence of heavy nutrients [7, 12]. Our observation is totally opposite with some of the previous reports [8, 32] and supported with the reports of Reynold [29] and APHA [5].

Table 5: Correlation of phytoplanktonic density with physicochemical factors: a: Godkhali; b: Gosaba. c: Canning; d: Jharkhali

a	Water Temp (^{0}C)	Water pH	(BOD) (mg/L)	(COD) (mg/L)	Phytoplankton (Org/L)
Water Temp (^{0}C)	1				
Water pH	0.782	1			
(BOD) (mg/L)	0.753	0.179	1		
(COD) (mg/L)	1.000**	0.795	0.740	1	
Phytoplankton (Org/L)	-0.802	-0.255	-0.997**	-0.790	1

b	Water Temp (^{0}C)	Water pH	(BOD) (mg/L)	(COD) (mg/L)	Phytoplankton (Org/L)
Water Temp (^{0}C)	1				
Water pH	0.700	1			
(BOD) (mg/L)	0.698	-0.023	1		
(COD) (mg/L)	1.000**	0.720	0.678	1	
Phytoplankton (Org/L)	-0.830*	-0.183	-0.979**	-0.814*	1

c	Water Temp (^{0}C)	Water pH	(BOD) (mg/L)	(COD) (mg/L)	Phytoplankton (Org/L)
Water Temp (^{0}C)	1				
Water pH	0.774	1			
(BOD) (mg/L)	0.734	0.139	1		
(COD) (mg/L)	0.992**	0.846*	0.646	1	
Phytoplankton (Org/L)	-0.735	-0.140	-1.000**	-0.646	1

d	Water Temp (^{0}C)	Water pH	(BOD) (mg/L)	(COD) (mg/L)	Phytoplankton (Org/L)
Water Temp (^{0}C)	1				
Water pH	0.737	1			
(BOD) (mg/L)	0.743	0.095	1		
(COD) (mg/L)	0.993**	0.814*	0.656	1	
Phytoplankton (Org/L)	-0.796	-0.178	-0.997**	-0.716	1

** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level,

One-way ANOVA and regression analysis has also proven the outcome of correlation studies. Regression curve showing how much phytoplanktonic density is significantly depended on the concerned physicochemical factors by R^2 value and linear regression equation. Linear regression analysis has explained clearly that, the annual variation of phytoplanktonic density is significantly (P value <0.05) depending upon the value of BOD followed by temperature of water from each sample site of Sundarbans (Fig. 4-7). Phytoplanktonic density from selected areas is not depended on pH of water as per regression analysis (Fig. 4b, 5b, 6b, 7b) throughout the whole tenure of survey, as pH of

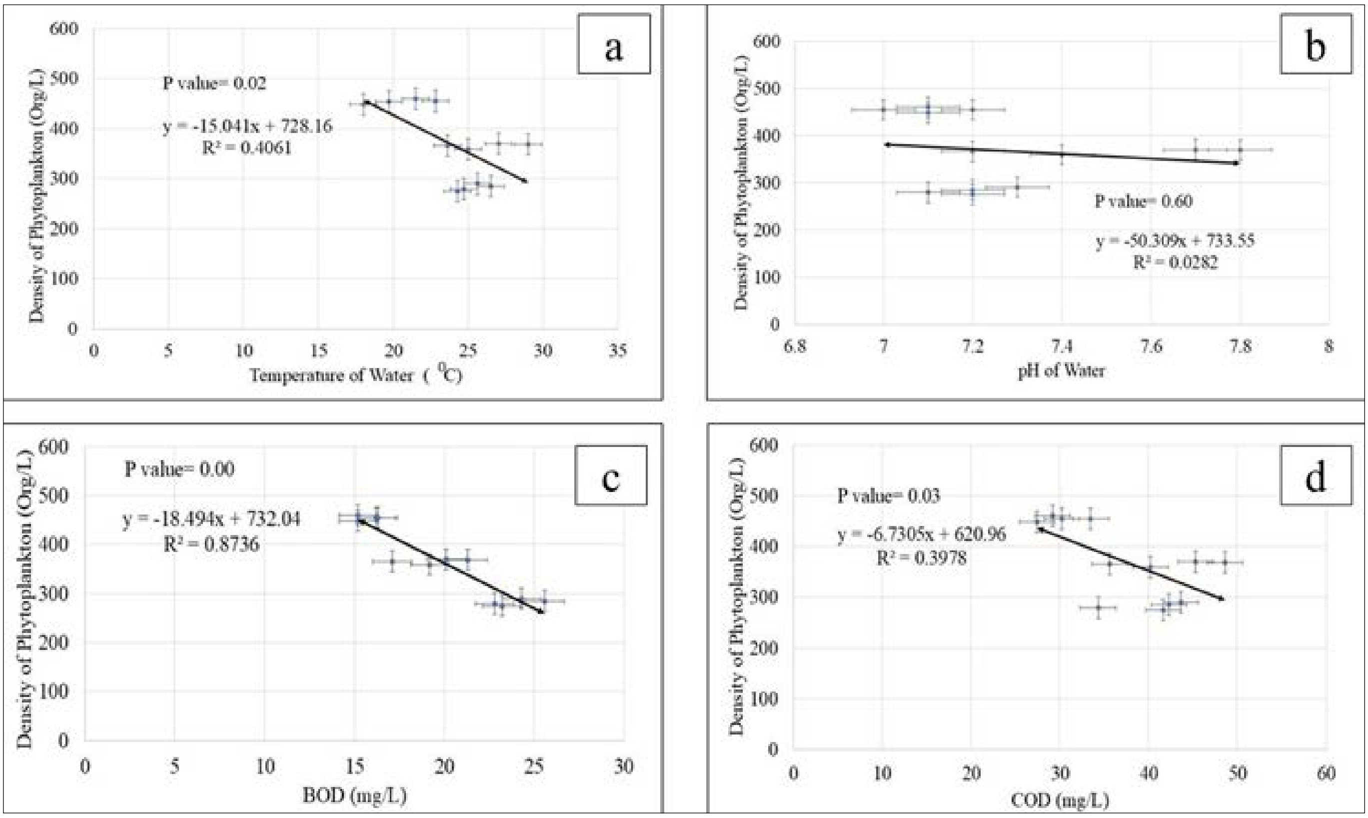

Fig 4: Regression curve showing R^2 value and linear regression equation at Godkhali: a: Phytoplanktonic density with water temperature; b: Phytoplanktonic density with water pH; c: Phytoplanktonic density with BOD; d: Phytoplanktonic density with COD

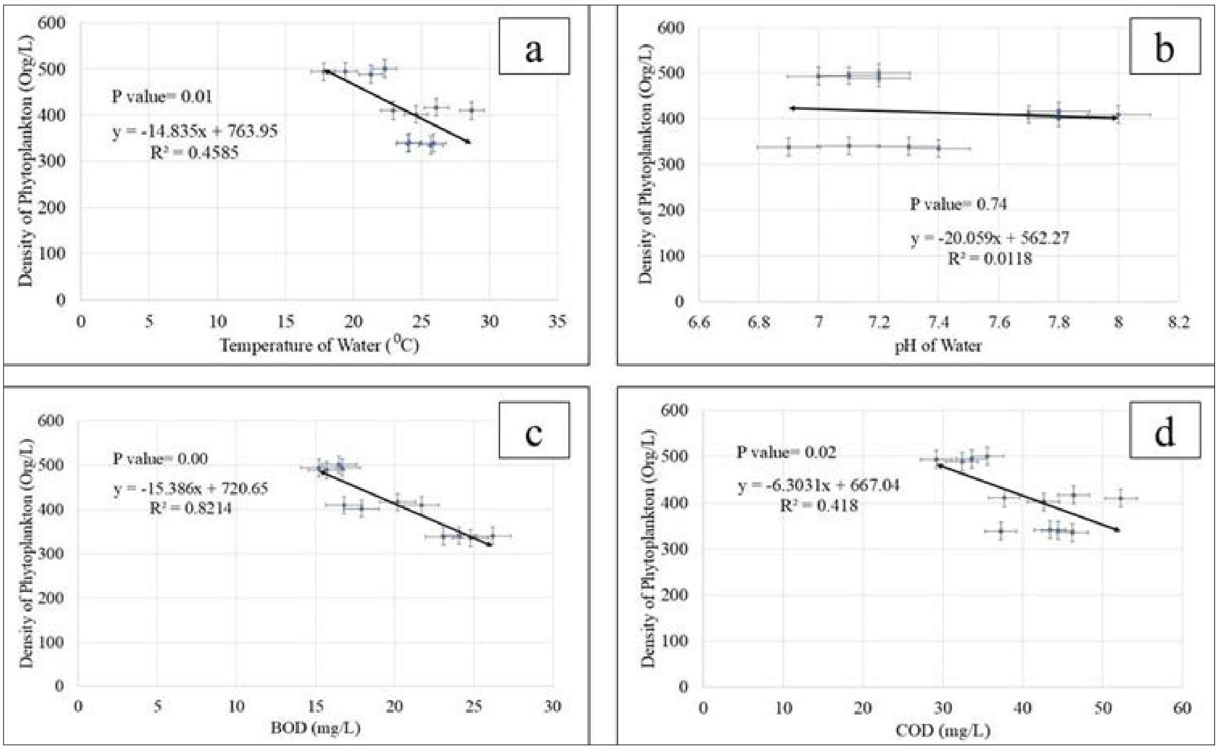

Fig 5: Regression curve showing R^2 value and linear regression equation at Gosaba: a: Phytoplanktonic density with water temperature; b: Phytoplanktonic density with water pH; c: Phytoplanktonic density with BOD; d: Phytoplanktonic density with COD

Water is very less non-significantly related with density of phytoplankton (Table 5). This might be due to pH remains relatively stable and fluctuation of pH of water is buffered by tidal sea water mixing in Sundarbans, and on the other hand phytoplankton can tolerate a broad pH range, which reduce the direct influence on phytoplanktonic growth [29, 32]. Density of phytoplankton is very less dependent on COD at Godkhali and Gosaba (Fig. 4d, 5d) and not depended (P value >0.05) at Canning and Jharkhali as per our regression analysis (Fig. 6d, 7d). As COD reflects organic and chemical load, its effect is often indirect and overshadowed by stronger controlling factors such as turbidity, light limitation and salinity fluctuation. Thus, regression analysis may exhibit a weak or no dependency of density of phytoplankton with COD at Sundarbans [7, 29, 32].

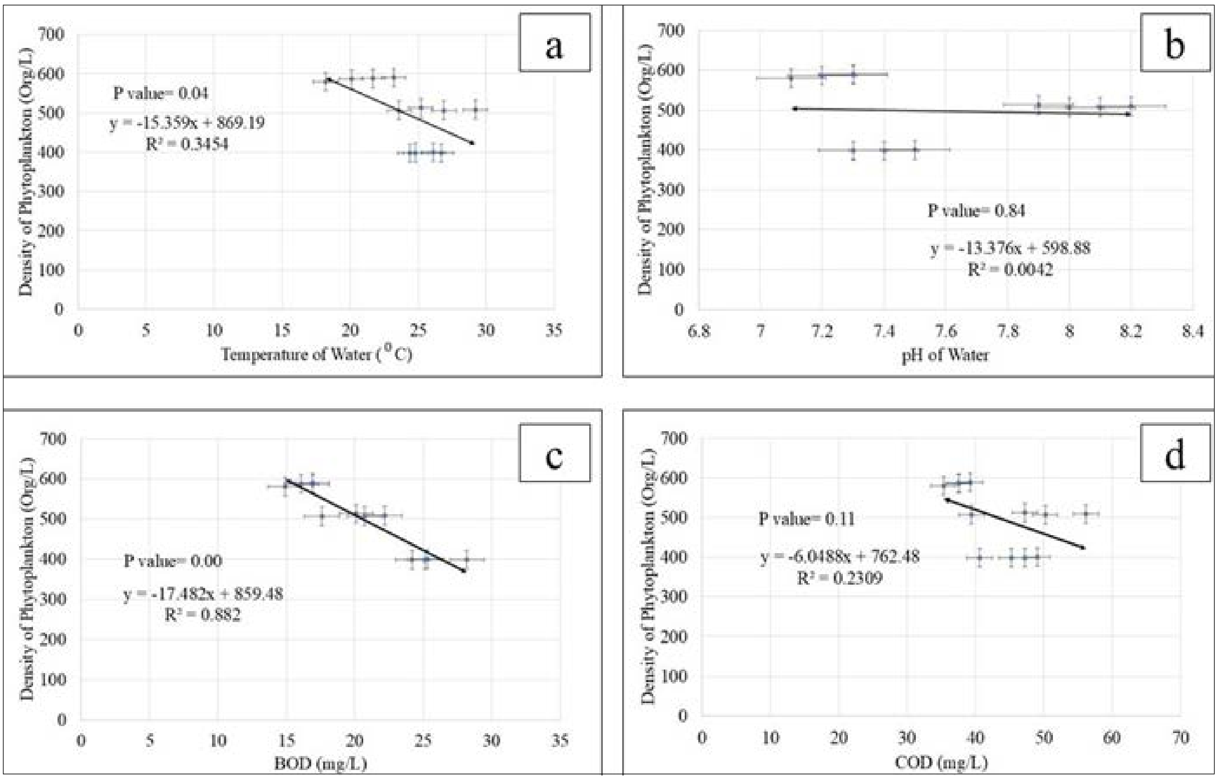

Fig 6: Regression curve showing R^2 value and linear regression equation at Canning: a: Phytoplanktonic density with water temperature; b: Phytoplanktonic density with water pH; c: Phytoplanktonic density with BOD; d: Phytoplanktonic density with COD

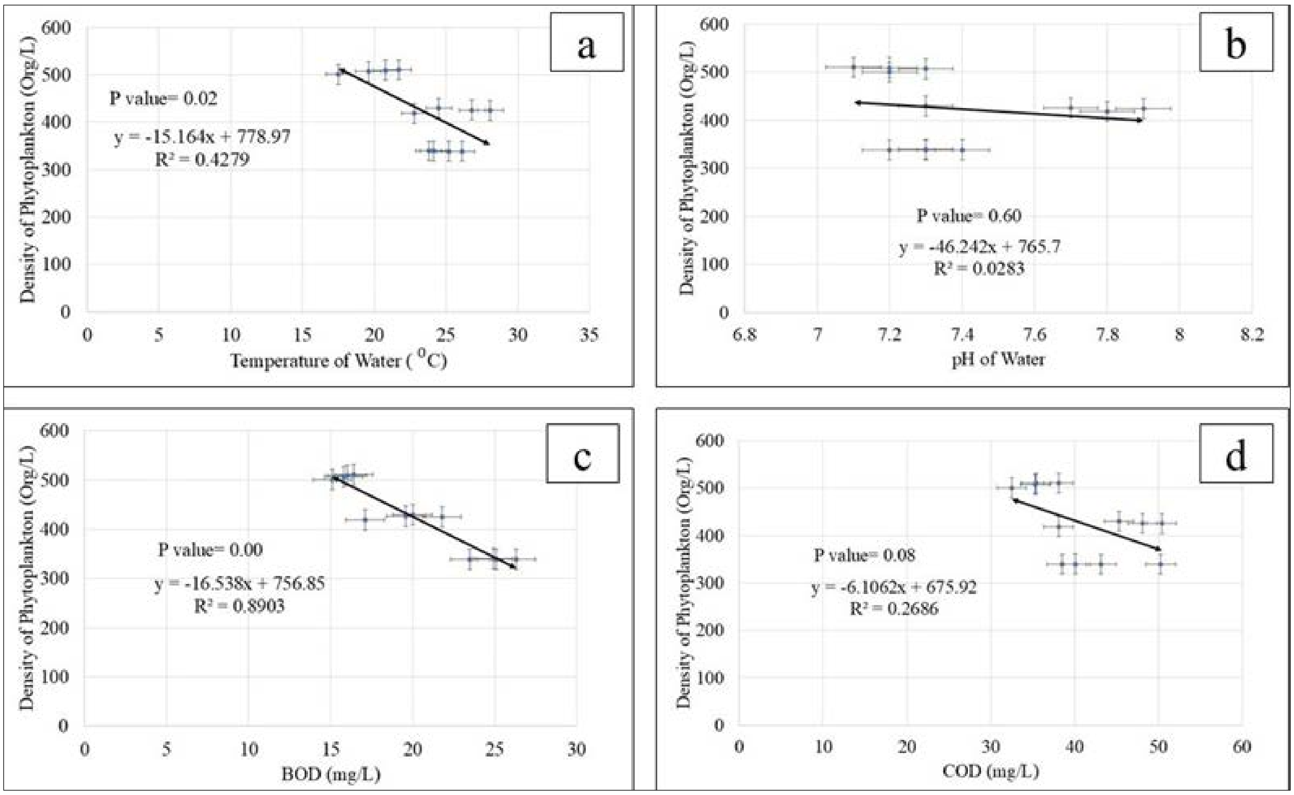

Fig 7 Regression curve showing R^2 value and linear regression equation at Jharkhali: a: Phytoplanktonic density with water temperature; b: Phytoplanktonic density with water pH; c: Phytoplanktonic density with BOD; d: Phytoplanktonic density with COD

But seasonal variation of phytoplanktonic density is significantly affected by physicochemical factors of water at Sundarbans. As per Two-way ANOVA, it clearly indicates that phytoplanktonic density in each season i.e. pre-monsoon, monsoon and post-monsoon period is significantly ($P<0.05$) affected by variation of water temperature, water pH, BOD and COD cumulatively of each sampling area (Table 1-4). Thus, the variation phytoplankton density is significantly controlled by the interaction of concerned physical parameters together in season wise as well as annually. From this study it is confirmed that the overall variation of phytoplanktonic density is not significantly influenced by individual physicochemical factor separately, except for BOD (Table 5; Fig. 4-7); rather they are significantly regulated by the cumulative interaction of those aquatic abiotic physical parameters.

Conclusion

From an ecological perspective, understanding these physicochemical interactions is crucial, as phytoplankton form the foundation of the aquatic food web and serve as sensitive indicators of environmental change [29]. The interplay among physicochemical factors determines primary productivity, carbon cycling, and overall ecosystem health in this fragile mangrove habitat [14]. The present study reveals that phytoplanktonic density in the Sundarbans is not governed by any single physicochemical parameter in isolation; rather, it is regulated through the synergistic interaction of multiple factors, particularly BOD, COD, pH, and temperature. These parameters collectively influence nutrient availability, metabolic activity, and environmental stability, thereby shaping phytoplankton dynamics [9, 32]. The ecological complexity of the Sundarbans mangrove ecosystem, which is characterized by tidal flux, salinity gradients, and organic loading, that further emphasizes the importance of such integrated controls over phytoplankton variability [3, 18].

Future research should focus on incorporating a broader range of environmental variables, including turbidity, light penetration, nutrient speciation, and hydrodynamic conditions, to develop a more comprehensive model of phytoplankton regulation. Advanced multivariate and modelling approaches will be required to understand the processes by which these interacting factors govern phytoplankton diversity, distribution and abundance. Such findings will make a substantial contribution to the Sundarbans ecosystem's long-term management and conservation strategies in the face of changing climate and anthropogenic stresses.

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