Journal of Environmental Biology
p-ISSN: 0254-8704 • e-ISSN: 2394-0379 • CODEN: JEBIDP

JEB®

Original Research Paper
Volume 45 Issue 6 November 2024 pp. 654-665
DOI: http://doi.org/10.22438/jeb/45/6/MRN-5369

J. Environ. Biol., 2024
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Journal website : www.jeb.co.in ★ E-mail : editor@jeb.co.in

Dynamics of phytoplankton community in relation to environmental variables in tropical mangrove estuary, Sundarbans, India

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Received: 10 May 2024 **Revised:** 13 June 2024 **Accepted:** 18 July 2024

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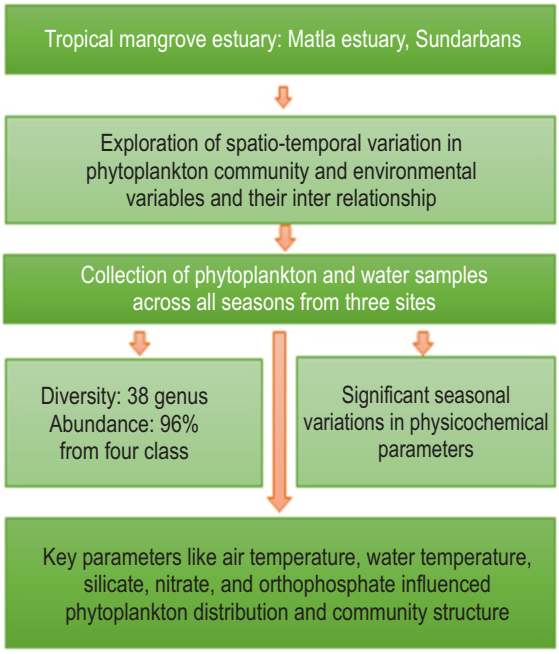
Abstract

Aim: To explore the spatio-temporal variation of phytoplankton diversity and community structure, in response to associated environmental variables in Matla estuary, Sundarbans, India.

Methodology: Monthly sampling was carried out from August 2022 to July 2023 at three locations within the estuary. Plankton was identified and its dynamics were studied in relation to the environment variables.

Results: A total of 38 genera of phytoplankton, belonging to 8 classes, were identified. Spatial diversity was high in the upper reaches of the estuary, while temporal diversity peaked during the monsoon season. The majority of the abundance (96%) was contributed by four classes: Coscinodiscophyceae (35%), Mediophyceae (27%), Bacillariophyceae (25%) and Dinophyceae (9%). Bacillariophyceae exhibited higher species richness, while Coscinodiscophyceae dominated in terms of density. Cluster analysis and non-metric multidimensional scaling revealed four separate groups with varying spatio-temporal attributes. Analysis of variance (ANOVA) post-hoc tests highlighted significant variations in environmental parameters across seasons. Various phytoplankton groups were positively correlated with the physio-chemical parameters such as temperature, alkalinity, free CO_2, NO_3, NO_2, silicate, temperature, orthophosphate and chlorophyll-a. Biota-environment stepwise analysis (BIO-ENV) underscored the importance of air temperature and free CO_2 (ρ= 0.4929) as key factors shaping phytoplankton distribution and community structure. Canonical Correspondence Analysis (CCA) further showed the significant influence of parameters such as temperature, silicate, nitrite and orthophosphate on the phytoplankton community.

Interpretation: Finding of this study enriches our comprehension of estuarine ecosystem dynamics, and this information may serve as a baseline study and thereby aid in framing management measures for long-term conservation and management of both biotic and abiotic components within estuaries.



Key words: Environmental variables, Estuary, Mangrove, Phytoplankton, Sundarbans

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How to cite: Bhutia, R.N., K. Abhilashwodeyar, D. Devadas, U.K. Mandal, G.B. Sreekanth, A.T. Landge, A.K. Jaiswar, G. Deshmukhe and D. Burman: Dynamics of phytoplankton community in relation to environmental variables in tropical mangrove estuary, Sundarbans, India. *J. Environ. Biol.*, **45,** 654-665 (2024).

Introduction

Mangrove estuaries are recognized as crucial and highly productive coastal ecosystems that play an essential role in supporting fisheries in tropical regions (Saifullah *et al.,* 2016). They are situated at the interface of land and sea and are under the influence of different geophysical and biochemical perturbation (Alongi, 2008). These estuaries demonstrate variations in biological production from plankton with respect to salinity gradients and hence, are considered as biologically and environmentally highly active zones along any coastal belts (Kibirige and Perissinotto, 2003). They form an important ecosystem for the primary producers, as they act as a cradle ground for supplying nutrients from both sea and land drainages (Ketchum, 1967). Mangrove habitats within estuarine ecosystems, are commonly described as nutrient traps, capturing essential nutrients that contribute to high primary productivity, consequently fostering increased levels of secondary production (Badarudeen *et al.,* 1996). This nutrient rich ecosystem due to the abundance and dynamics of phytoplankton can indicate various stresses at estuarine environment (Manna *et al.,* 2010).

The complex interaction of living and non-living components within the mangrove estuarine ecosystem plays a key role in upholding robust productivity and biological balance. This dynamic relationship is essential for supporting aquatic ecosystem food webs, operating through both grazing and detrital food chains (Claudino *et al.,* 2015; Peng *et al.,* 2017). The conventional perspective on biotic communities within mangrove ecosystems has been that their dynamics are influenced primarily by the substantial production of mangrove litter (Odum and Heald, 1975). However, in recent studies, it has come to light that the significance of phytoplankton may have been undervalued within the framework of 'detritus-based food web' (Saifullah *et al.,* 2019). Phytoplankton, are ubiquitous and microscopic in nature, found in various aquatic environments playing a crucial role in maintaining the ecological balance of these systems (Inyang *et al.,* 2023). They serve as the cornerstone of primary production in mangrove ecosystems, playing a vital role in supporting aquatic life (Gogoi *et al.,* 2021).

Approximately, 90% marine ecosystem production is contributed by phytoplankton (Kartik *et al.,* 2012). Additionally, they serve as indicators for trophic status and environmental stresses (Roshith *et al.,* 2018). The productivity of phytoplankton and zooplankton in mangrove ecosystems reflect the ecosystem health and fertility, influencing the occurrence of consumer organisms and forms a vital link in the food chain (Saifullah *et al.,* 2019). However, alterations in hydrographical conditions, along with seasonal rainfall, plays a pivotal role in governing the change in community of phytoplankton in the estuarine system (Biswas *et al.,* 2010). The abundance of phytoplankton community exhibits significant variation, attributed to their dynamic nature (Rahman *et al.,* 2013). The succession of phytoplankton and the characteristics of species may vary significantly in response to the ever-changing environmental conditions in estuaries (da Costa Santana *et al.,* 2018). Approximately, 39.2% of the global mangrove cover is found in the South and South-east Asia (Leal and Spalding, 2024). Among them Sundarbans, is the world's largest deltaic mangrove ecosystem formed at the estuarine zone of Ganga and Brahmaputra basin, in India and Bangladesh (Bhattacharjee *et al.,* 2013). In contrast to other mangroves associated estuaries in India, Hooghly-Matla Estuarine System is highly complex and dynamic aquatic environment. Hooghly experiences continuous freshwater input from the Ganga-Bhagirathi system via Farakka barrage, causing spatio-temporal variations in salinity, nutrients and turbidity, while the Matla estuary lacks freshwater supply due to siltation in Bidyadhari channel (Roshith *et al.,* 2018).

Despite of previous studies (Choudhury and Pal, 2011; Roshith *et al.,* 2018; Rath *et al.,* 2021; Gogoi *et al.,* 2021; Roy *et al.,* 2022) on phytoplankton, zooplanktons, interaction studies of plankton with respect to environment, and productivity along different part of this large Hooghly-Matla estuarine system, specific and focused study on spatio-temporal dynamics of phytoplankton in Matla estuary is scanty. Understanding the climate change scenario and various vulnerabilities on coastal shallow ecosystems of huge fisheries and livelihood importance, reliable information on plankton dynamics and their annual interaction with environment is of prime importance for any coastal aquatic environmental management. In this line, the study was attempted to decipher the spatio-temporal trends of community structure and abundance phytoplankton in response to water quality parameters to gain a more comprehensive grasp of ecological status of Matla estuary.

Materials and Methods

Study area: Matla Estuary, a mangrove estuary located in Indian part of Sundarbans (21°N-22°9'N; 88°15'E-89°E), spans over 200 km^2 area. It is macro tidal in nature with swift tidal current. The estuary has become permanently disconnected with its parent freshwater river. It is characterized by high salinity regime throughout the year and abundant in rich mangrove vegetation, providing numerous critical ecological services. However, currently it is under considerable stress due to both natural and human-induced factors. The geographical layout of the study area is provided in Fig. 1.

Sampling methodology: In total, 36 sampling sessions were undertaken at three sites, with one sampling per month from August 2022 to July 2023. The selection of the sampling sites was based on the estuarine gradient. The first sampling site (S1) was located on the upper region while the second (S2) and third sites (S3) were in the middle and lower region of the estuary.

Collection and analysis of phytoplankton sample: The phytoplankton samples were collected by filtering 50 l of sub-surface water at 0.5 m depth, using 20-µm mesh plankton net during morning hours (8-10 am). The filtered samples were preserved in 4% buffered formalin. Quantitative analysis was

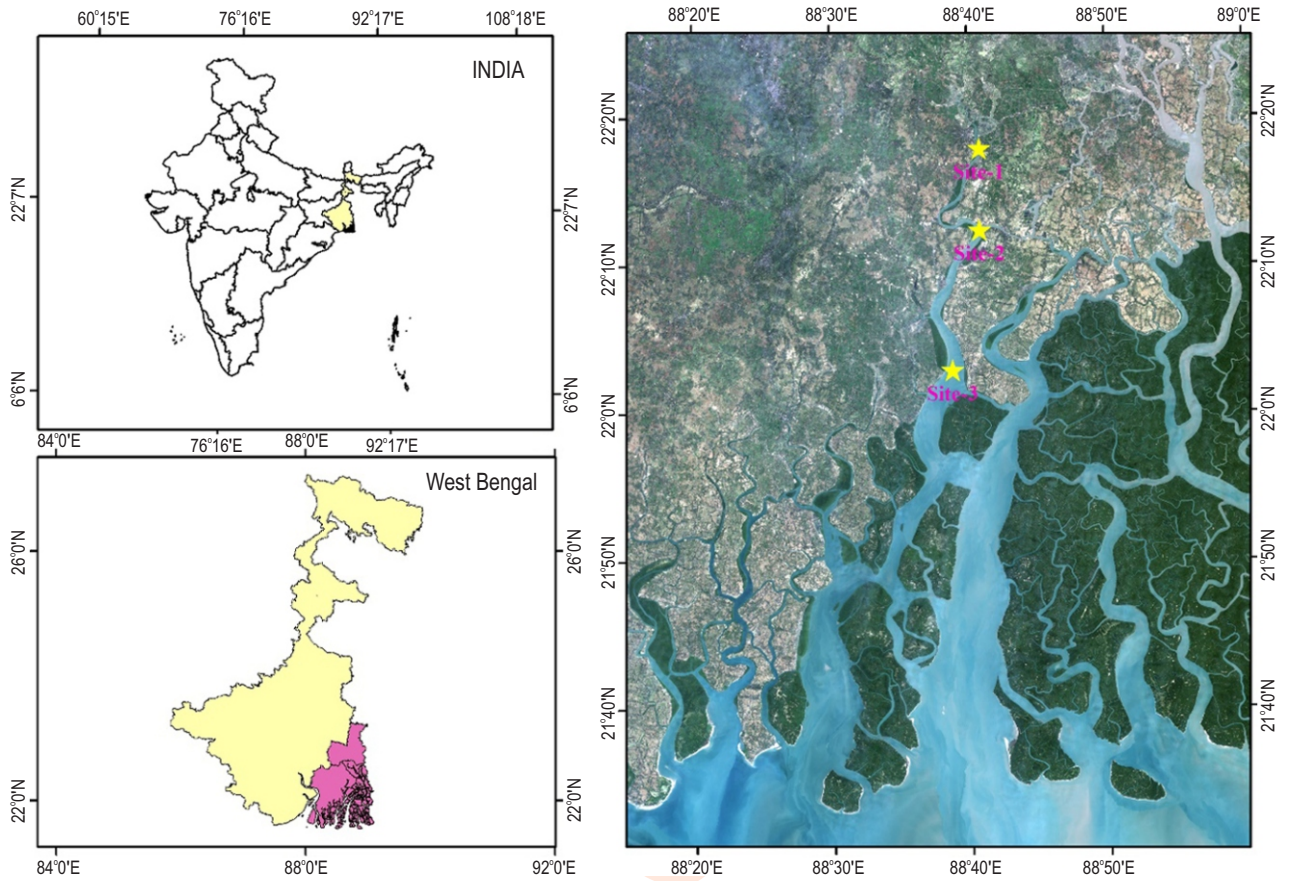

Fig. 1: Map of Matla estuary depicting sampling sites (S1, S2 and S3).

done following drop count method given by Trivedi and Goel (1984). Phytoplankton were identified under a microscope (Carl Zeiss: Primo Star) following the standard taxonomic identification keys (Subrahmanyan, 1946; Santhanam *et al.,* 1987; Verlecar and S.R. Desai, 2004).

Collection of water samples and analysis: The sub-surface water samples were collected monthly from all the sites and parameters viz. pH, temperature, salinity, dissolved oxygen, free CO_2, total alkalinity and transparency were measured *in-situ*. Parameters like pH, temperature and salinity were measured with a digital pH meter (HANNAHI98107), mercuric thermometer and refractometer, respectively. Transparency was measured employing Secchi disc (Strickland and Parsons, 1972). Dissolved oxygen, free CO_2 and alkalinity were estimated following the standard titrimetric methods (APHA, 2017). Further, sub-surface water samples were collected in a one litre amber coloured HDPE polyethylene bottle for further analysis of water nutrients (APHA, 2017) and Chlorophyll-a (Hall and Coombs, 1982).

Statistical analyses: The data collected were segregated into categories representing the upper, middle, and lower reaches, in three distinct seasons (pre-monsoon (March-June); monsoon (July-October); and post-monsoon (November-February). The physio-chemical parameters of water from different seasons were subjected to One-way ANOVA followed by a post hoc test (Duncan's) employing SPSSv.21. Pearson's correlations of environmental variables and phytoplankton abundance were examined in R-software version 4.2.3. Further, to evaluate the key parameters influencing phytoplankton community, Canonical Correspondence Analysis (CCA) was performed. The diversity indices were estimated from spatio-temporal data of numerical abundance, using PRIMER v7 software (Clarke *et al.,* 2014).

The k-dominance curve, Bray–Curtis similarity measures, SIMPROF test and NMDS was done in PRIMER v7 software. Additionally, to decipher the significant difference in groups extracted by SIMPROF test, Analysis of Similarity (ANOSIM) was performed. To explore the similarity and dissimilarity amongst the group, Similarity percentage (SIMPER) test was also performed. The biota-environment stepwise analysis (BIOENV) technique (Clarke and Ainsworth, 1993) using R software version 4.2.3 (R Core Team, 2023) was carried out to decipher the physio-chemical parameters affecting the

community of phytoplankton.

Results and Discussion

Data pertaining seasonal variations in the environmental variables are given Table 1. The assemblage of phytoplankton is affected due to slight modification in the physico-chemical, biological parameters and anthropogenic exposure (Shahi *et al.,* 2015). Seasonally, One-way ANOVA showed statistically significant differences ($p<0.05$) for the environmental variables such as water and air temperature, alkalinity, dissolved oxygen, free CO_2, salinity, transparency, silicate, nitrate, nitrite, ammonia and chlorophyll-a. The air and water temperature during the post-monsoon season varied significantly ($p< 0.05$) with temperature in monsoon and pre-monsoon season with a record of highest values (air temp: 30.30±1.44°C; water temp: 28.38±1.21°C) during pre-monsoon and lowest (air temp: 23.75±3.39°C; water temp: 22.58±3.48°C) during post-monsoon season. An ascending trajectory of temperature from post-monsoon to monsoon season attributing to the intensity of sunlight was reported by Gogoi *et al.* (2019).

The dissolved oxygen level showed a marked difference across the season where it was observed to be highest in the monsoon (5.5±0.90 mg l^{-1}) and lowest during pre-monsoon (2.33±1.67 mg l^{-1}) season. Similar findings were observed by Akter *et al.* (2024) in Manori creek, Mumbai. However, in contrary Mukherjee *et al.* (2013) reported highest dissolved oxygen during post-monsoon from Matla estuary. According to Levinton (2001), enhanced temperature, salinity and biological activity during pre-monsoon resulted in low concentration of dissolved oxygen. Basu *et al.* (2021) studied the physicochemical parameters of Hooghly estuary in the Sundarbans, adjacent to Matla estuary, and reported dissolved oxygen levels ranging from 1.3 to 4.3 mg l^{-1}. They noted an extreme case of hypoxic conditions, with dissolved oxygen levels falling below 2 mg l^{-1}, during dry seasons (pre and post-monsoon). The researchers attributed these low dissolved oxygen levels to increased temperatures, elevated organic matter, and a higher rate of community respiration relative to autotrophic activities. Similar reasons might have contributed to low concentration of dissolved oxygen (2.33 mg l^{-1}) during pre-monsoon season in the Matla estuary. Factors like freshwater discharge, breakdown of bicarbonates, decomposition of organic matters and CO_2 removal from water through photosynthesis contribute to fluctuation in pH level (Rajasegar, 2003; Kumary *et al.,* 2007).

However, pH value did not reveal a significant difference ($p < 0.05$) across the season where only a small range of variation (7.75±0.20-7.93±0.16) was observed. The distribution of salinity, in the Matla estuary is associated with annual rainfall pattern in its catchment area and tidal saline water from the Bay of Bengal (Mukherjee *et al.,* 2013). Salinity showed significant difference ($p<0.05$) only during monsoon and its level was observed to be on a higher side (10.92±3.99 - 22.08±3.55 psu) in the Matla estuary. The minimum (10.92±3.99 psu) and maximum (22.08±3.55 psu) salinity values were observed during monsoon and pre-monsoon season, respectively. These distribution pattern of salinity (high salinity regime) might be due to no connection with the parent fresh water river and supply of freshwater only through surface runoff during monsoon. The alkalinity value ranged from 131.5±8.87 to 155.33±11.23 mg l^{-1} with a trend of seasonal variation where low alkalinity was observed during pre-monsoon in comparison to monsoon and post-monsoon season.

The peak level of alkalinity during monsoon and post-monsoon could be linked to the runoff from agriculture fields and decomposing organic matters. Chaudhuri *et al.* (2012) documented a moderately enhanced concentration of alkalinity throughout the study period from Jharkhali region of Matla estuary. The transparency of water was low during monsoon

Table 1: Seasonal variations in physico-chemical properties

Parameters	Post-monsoon	Pre-monsoon	Monsoon
Water temperature (°C)	22.58±3.48^{a}	28.38±1.21^{b}	27.75±0.58^{b}
Air temperature (°C)	23.75±3.39^{a}	30.29±1.44^{b}	29.62±0.68^{b}
Alkalinity	155.33±11.23^{b}	131.50±8.87^{a}	150.17±4.78^{b}
Dissolved oxygen (mg l^{-1})	4±1.48^{ab}	2.33±1.67^{b}	5.5±0.90^{a}
pH	7.89 ±0.16^{a}	7.93± 0.16^{a}	7.75 ±0.20^{a}
Salinity (psu)	18.83±4.97^{b}	22.08±3.55^{b}	10.92±3.99^{a}
Free CO_2 (mg l^{-1})	4±1.48^{a}	2.33±1.67^{b}	5.55±0.90^{c}
Transparency (cm)	51.25±4.81^{b}	55.08±5.32^{b}	30.0833±6.92^{a}
Silicate (mg l^{-1})	3.26±0.87^{a}	4.47±0.62^{b}	5.64±0.53^{c}
Orthophosphate (mg l^{-1})	1.23±0.43^{a}	1.65±0.60^{a}	1.5175±0.35^{a}
Nitrate (mg l^{-1})	11.37±2.52^{a}	9.83±2.21^{a}	17.88±2.44^{b}
Nitrite (mg l^{-1})	6.67±1.29^{b}	4.2733±1.32^{a}	6.84±0.64^{b}
Ammonia (mg l^{-1})	1.71±0.49^{b}	1.2817±0.54^{a}	1.02±0.12^{a}
Chlorophyll-a (mg m^{-3})	4.50±0.56^{a}	6.76±0.82^{b}	9.42±1.72^{c}

Values are mean ± S.D.

(30.08±6.92 cm) in comparison to other seasons. The limited transparency in water during monsoon may be due to ingress of slit laden runoffs from the adjacent catchment area which corroborates with the findings of Gogai *et al.* (2019) and Aktar *et al.* (2024). Free CO_2, silicate and chlorophyll-a were significantly different in all three seasons. Free CO_2 level was maximum (5.55±0.90 mg l^{-1}) in monsoon and minimum (2.33±1.67 mg l^{-1}) in pre-monsoon. The silicate level was more during monsoon, because of the influx of freshwater discharge (Govindasamy and Arulpriya, 2011) and lesser during post-monsoon due to uptake by diatoms (Ramakrishnan *et al.,* 1999). Similar trend was observed in the present research and it was complemented by the similar results of George *et al.* (2012); Bharathi et al. (2018); Manohar *et al.* (2020) and Akter *et al.* (2024).

The Chlorophyll-a concentration also showed a similar trend with a maximum value during monsoon and minimum in post-monsoon season. Nitrate value was substantially more during monsoon season (17.88±2.44 mg l^{-1}) and it showed a marked variations with other two seasons. The lower concentration of nitrate might be due to utilization by the phytoplanktons. In contrast to the report of this study, Mukherjee *et al.* (2013) reported decreased level of NO_3 during monsoon in the Matla estuary. The seasonal variations of nitrite are due to oxidation of ammonia, excreta of biotic components and conversion of nitrate (Sridhar *et al.,* 2006; Manohar *et al.,* 2020). In this study, the nitrite value was low (4.27±1.32 mg l^{-1}) during pre-monsoon season revealing significant difference ($p<0.05$) from its value during monsoon (6.84±0.64 mg l^{-1}) and post-monsoon (6.67±1.29 mg l^{-1}) season. The ammoniacal nitrogen varied from minimum (1.03±0.12 mg l^{-1}) in monsoon to maximum (1.71±0.49 mg l^{-1}) in post-monsoon.

The enhanced level of ammonia is contributed by the excretion of biotic components and sewage runoffs (Thasneem *et al.,* 2018; Naik *et al.,* 2020). In the present study, 38 genera of phytoplankton, grouped into 8 classes were identified. Among the 8 classes identified, class-wise genera representation was as follows: Bacillariophyceae (15), Mediophyceae (10), Dinophyceae (5), Coscinodiscophyceae (4), Cyanophyceae (1), Xanthophyceae (1), Zygnematophyceae (1) and Chlorophyceae (1). Manna *et al.* (2010) reported 46 species of six classes from the Matla estuary. The numbers of taxa documented were lesser compared to previous study, indicating shrinking diversity of phytoplankton. According to Sinha *et al.* (2015), the western region of Sundarbans is hypo-saline due to its constant connection with a freshwater river. In contrast, the central part, where Matla estuary is located, is hypersaline because it lacks a freshwater connection. Their study revealed a significant inverse relationship between phytoplankton abundance and salinity, indicating the increase in salinity in the Matla estuary, posing a threat to certain phytoplankton species, and these could be the reason for reduced diversity observed in this study. The spatial-temporal variations in class-wise percentage contribution of phytoplankton are given in Fig. 2. In the present study, 96% of the abundance was contributed by four major classes in the following order: Coscinodiscophyceae (35%), Mediophyceae (27%), Bacillariophyceae (25%) and Dinophyceae (9%).

Despite the fact that the maximum number of taxa or species richness belonged to class Bacillariophyceae, the highest density was depicted by the class Coscinodiscophyceae. These findings are in contradiction to that of Manna *et al.* (2010), as dominant class observed were Bacillariophyceae, followed by Dinophyceae and Chlorophyceae resulting from inclusion of taxa belonging to Coscinodiscophyceae and Mediophyceae in the class Bacillariophyceae. The overall numerical abundance of phytoplankton varied across different seasons and sites. At Site

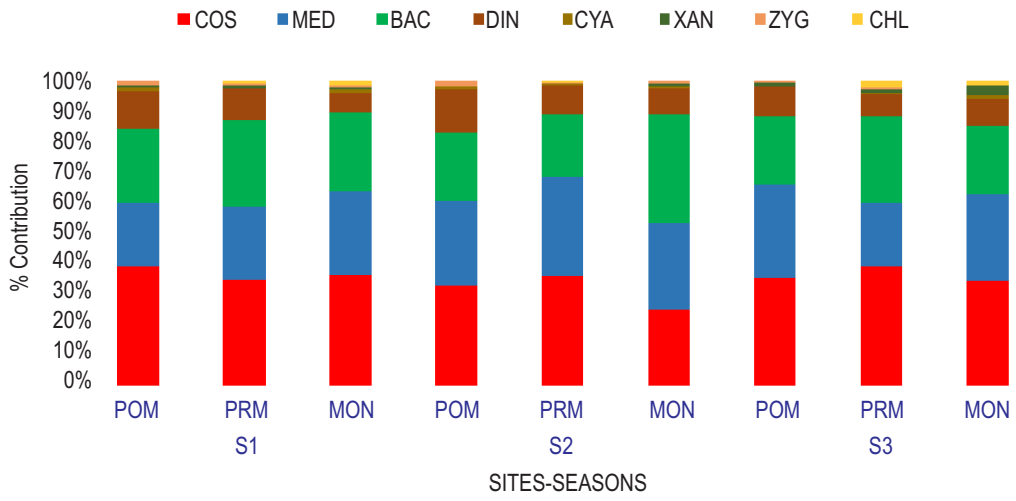

Fig. 2: Percentage contribution of different class of phytoplankton in Matla estuary.

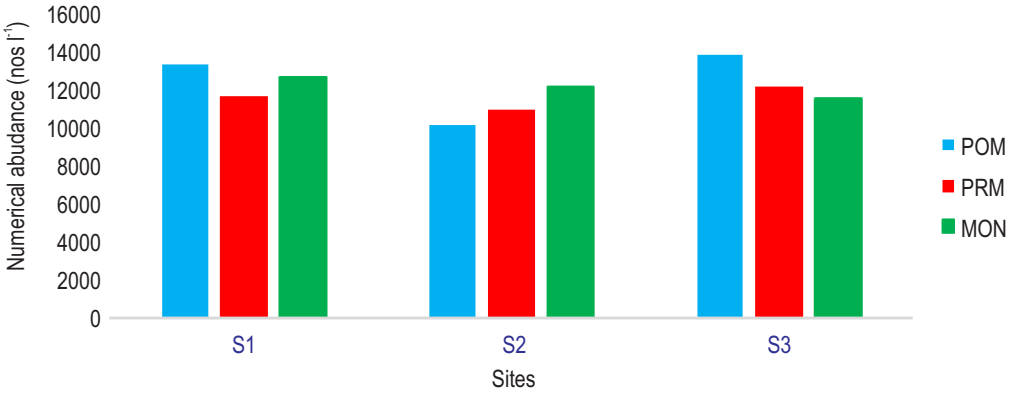

Fig. 3: Spatial and seasonal pattern of total abundance of phytoplankton in Matla estuary

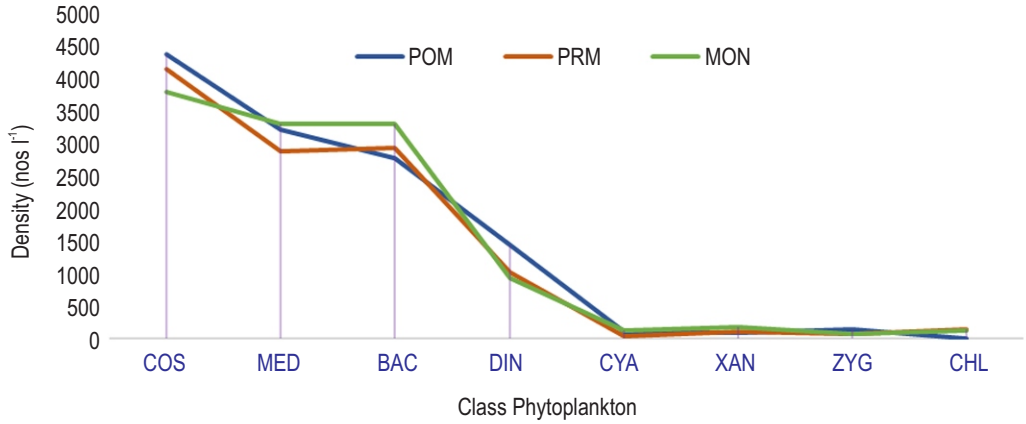

Fig. 4: Seasonal variation of phytoplankton density in Matla estuary.

S1, the abundance was 1.12 x 10^4 nos. l^{-1} during the pre-monsoon season and increased to 1.28 x 10^4 nos. l^{-1} in the post-monsoon. At Site S2, the abundance was 0.98 x 10^4 nos. l^{-1} during the post-monsoon and 1.17 x 10^4 nos. l^{-1} during the monsoon season. Meanwhile, at Site S3, the abundance was 1.11 x 10^4 nos. l^{-1} during the monsoon season and increased to 1.34 x 10^4 nos. l^{-1} in the post-monsoon period (Fig. 3). The findings of Manna *et al.* (2010) showed a similar pattern of variation which complements the findings of this study. Positive correlation between abundance of Coscinodiscophyceae and salinity was reported by Gogai *et al.* (2019). In the present study, a similar trend of increasing density of Coscinodiscophyceae with salinity was observed, with highest density during post-monsoon season ($4.33x10^3$ nos. l^{-1}) followed by pre-monsoon ($4.12x10^3$ nos. l^{-1}) and monsoon ($3.75x10^3$ nos. l^{-1}) seasons. Low abundance of phytoplankton during monsoon season may be due to sudden rainfall mediated changes in the physio-chemical parameters and the resulting influence on regeneration (Sahu *et al.,* 2012; Babu *et al.,* 2013). On the contrary, Sekh *et al.* (2016) documented a predominance of Coscinodiscophyceae during monsoon from the nearby river Bidya located in the northern part of Sundarbans. The mean density of Mediophyceae ($3.27x10^3$ nos. l^{-1}) and Bacillariophyceae ($3.28x10^3$ nos. l^{-1}) was maximum in monsoon, which may possibly be due to the allochthonous nutrients received from the land run-off and rivers (Gogai *et al.,* 2021). Dinophyceae was observed to be maximum ($1.42x10^3$ nos. l^{-1}) during post-monsoon season, and these observations are in line with the reports of Manna *et al.* (2010) with peak density of Dinophyceae during post-monsoon period, due to run-off driven nutrient enrichment (Fig. 4). The k-dominance curve of phytoplankton density in Matla estuary indicated that species abundance and diversity was at peak during post-monsoon, followed by pre-monsoon and monsoon seasons (Fig. 5). This contrasts with the reports of Gogai *et al.* (2021), who found maximum diversity and abundance during the pre-monsoon period.

Table 2: Spatio-temporal variations of diversity indices

Biodiversity indices	Pre-monsoon			Monsoon			Post-monsoon		
	S-1	S-2	S-3	S-1	S-2	S-3	S-1	S-2	S-3
d'	4.76	4.64	4.77	5.62	5.44	4.9	5.29	4.79	4.66
j'	0.95	0.94	0.94	0.94	0.95	0.95	0.94	0.92	0.94
H'	3.26	3.20	3.23	3.41	3.41	3.30	3.35	3.19	3.26
1-λ	0.95	0.95	0.95	0.96	0.96	0.95	0.95	0.95	0.95

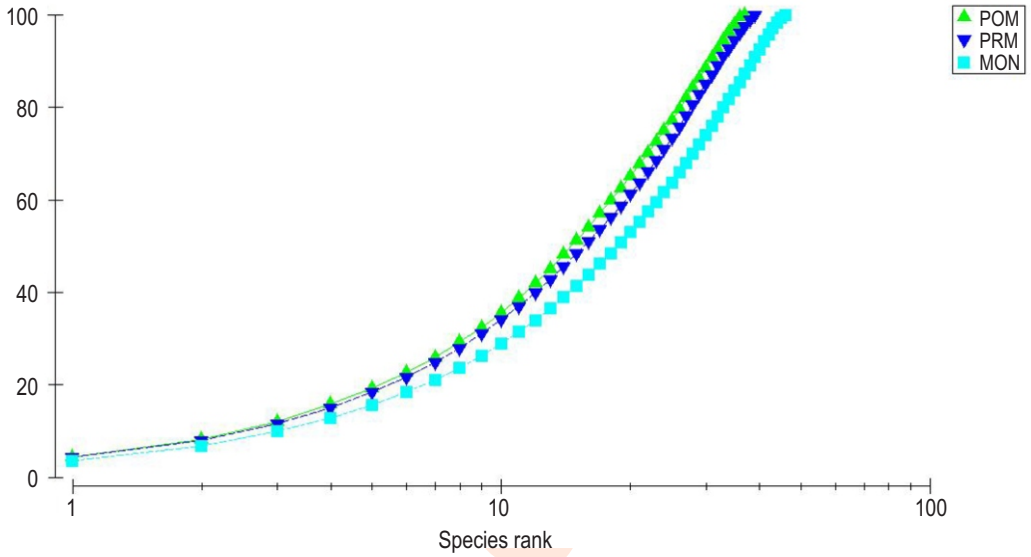

Fig. 5: k − dominance curve of phytoplankton.

Phytoplankton community of estuarine region of Sundarbans are characterized by high species richness and diversity (Biswas *et al.,* 2010). The diversity indices based on spatial and seasonal data of phytoplankton was worked out for Matla estuary and is given in Table 2. The SWDI value ranged between 3.16 to 3.41. The peak value was found at Site-1 and Site-2 during monsoon whereas, the lowest figured was noted at Site-2 during post-monsoon period. The higher concentration of total phosphate and silicate contribute towards species diversity and richness during monsoon (Hardikar *et al.,* 2022; Hasan *et al.,* 2022). In the present study also a maximum phytoplankton diversity and richness associated with highest concentration of silicate and phosphorous was reported during monsoon. Furthermore, these maximum values were observed at Site 1, which is near to the settlement area and agriculture land and thus, the house hold and agricultural runoff might have contributed to its enrichment. Simpson's dominance index was constant (0.95) across the season and sites, with an exception of value, 0.96 at Site-1 and Site-2 in monsoon which coincided with the highest value of H' at same sites and season. Pielou's evenness index was greater than 0.92 at all the sites and seasons, depicting an even distribution of species. The findings are in line with the study of Gogai *et al.* (2019) conducted in Kailash Khal, Sundarbans. Margalef's richness index value was highest at Site-1 during monsoon (5.62) and lowest at Site-2 during pre-monsoon season.

Bray−Curtis similarity matrix ($p \leq 0.05$) illustrated four distinct clusters. Site 1 and 2 during monsoon formed 1st cluster, Site 1 and 2 during pre-monsoon formed 2nd cluster, Site 3 during pre-monsoon and monsoon formed 3rd cluster and Site 1, 2 and 3 during post-monsoon formed 4th cluster (Fig. 6). NMDS (Fig. 7) also revealed trend similar to cluster analysis with overall 60% similarity across the sites and seasons. More than 80% similarity was observed in 3 clusters, except in the cluster of Site-1 and 2 during monsoon the similarity was 78.37%. Analysis of Similarities (ANOSIM) test validated significant difference amidst the four clusters (Global R: 0.556; p=0.7%).

Similar findings were reported by Akter *et al.* (2024) from Manori creek, Mumbai where 60% similarity was observed across the sites and seasons. SIMPER analysis was done to characterize the role of different genera of phytoplankton in the formation of diverse groups across the seasons. The results showed three separate groups viz. Gr. I (pre-monsoon), Gr. II (monsoon) and Gr. III (post-monsoon), with average similarity of 75.03%, 66.07% and 80.03% respectively. The maximum

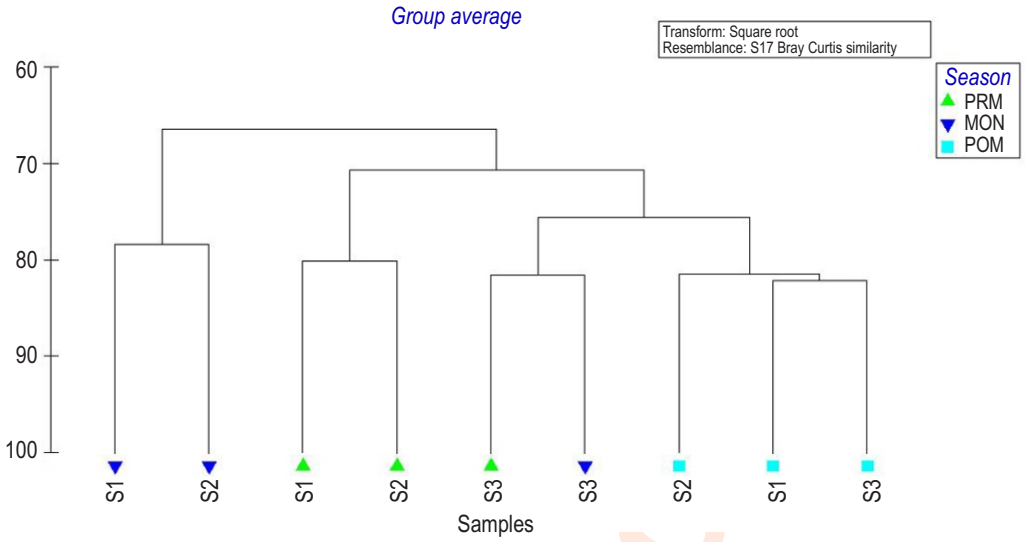

Fig. 6: Bray–Curtis similarity index- dendrogram: Phytoplankton abundance.

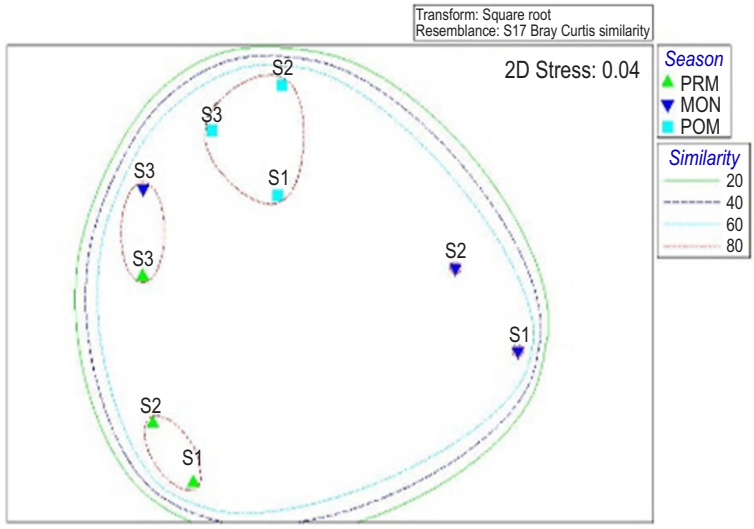

Fig. 7: NMDS for seasonal and spatial variation of phytoplankton assemblages.

similarity was observed in Gr. III (post-monsoon) and phytoplankton such as *Coscinodiscus* sp. (12.03%), *Thalassiosira* sp. (7.76%), *Fragilaria* sp. (5.32%), *Ceratium* sp. (5.01%), *Thalassionema* sp. (4.98%), *Cylindrotheca* sp. (4.69%), *Chaetoceros* sp. (4.25%), *Dinophysis* sp. (4.18%), *Protoperidinium* sp. (3.29) and *Triceratium* sp. (3.12%) contributed more towards the similarity of the species abundance. The percentage of average dissimilarity ranged from 30.41 to 34.55%, with the maximum between groups I and II and genera *Fragilaria* sp. (2.07%), *Thalassionema* sp. (1.69%), *Planktoniella* sp. (1.65%), *Ditylum* sp. (1.61%), *Protoperidinium* sp. (1.4%), *Thalassiothrix* sp. (1.38%), *Skeletonema* (1.34%) and *Melosira* sp. (1.31%) were the prominent contributors to form the group. These findings are in contrast to the reports of Akter *et al.* (2024) who observed the highest average similarity (73.72%) during the monsoon season and the maximum dissimilarity between the pre-monsoon and post-monsoon periods in the Manori Creek, Mumbai.

The phytoplankton growth and functioning are influenced by the abiotic parameters in an interconnected relationship. Numerous studies on inter-relationship of phytoplankton with the environmental variables in estuarine region of Sundarbans has

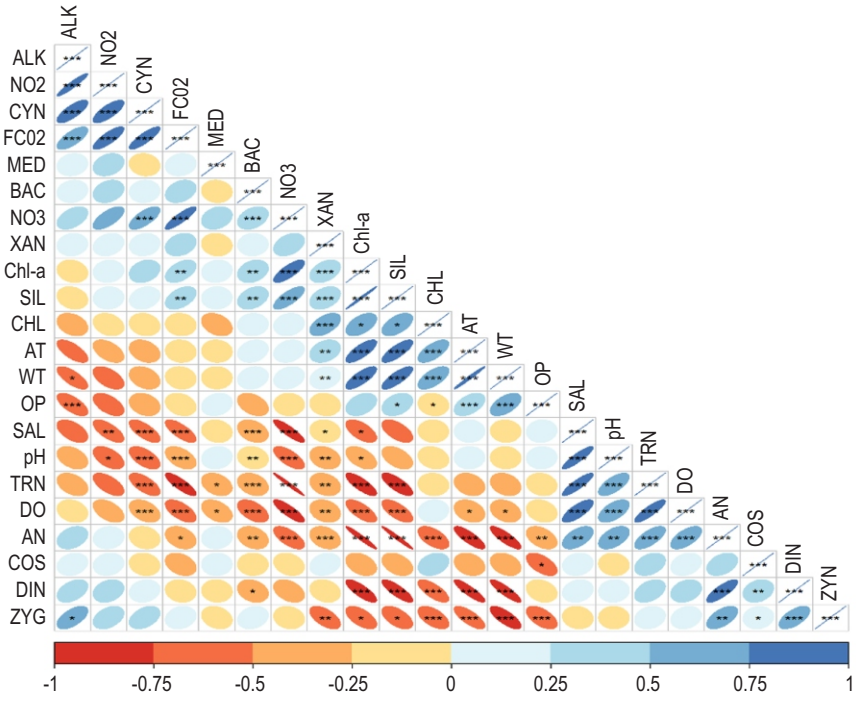

Fig. 8: Pearson's correlation matrix between physico-chemical parameters and phytoplankton abundance.

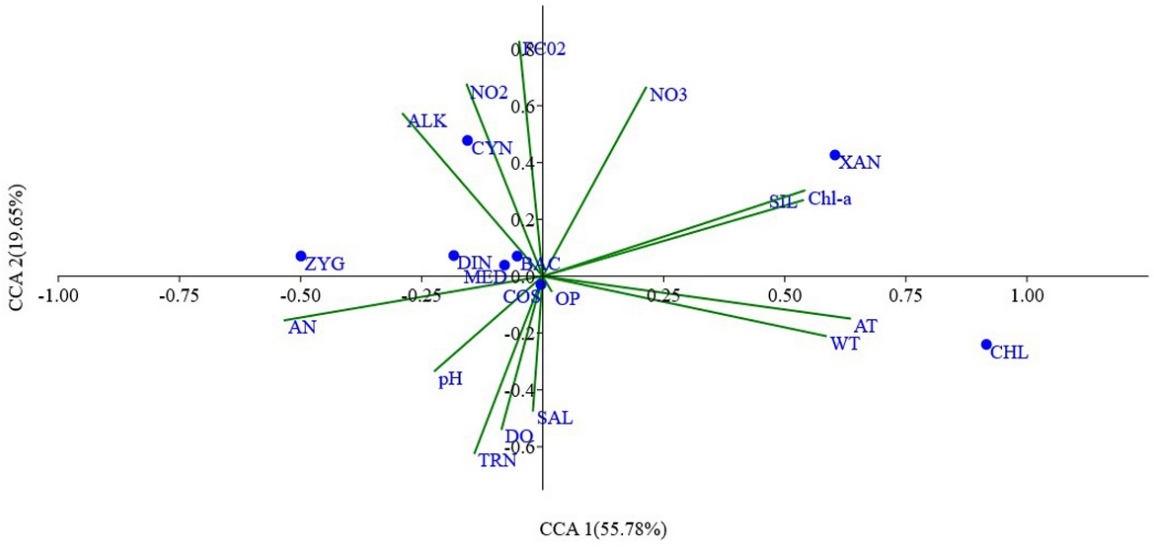

Fig. 9: CCA biplots depicting association of phytoplankton with environmental variables.

been documented earlier (Mitra *et al.,* 2012; Biswas *et al.,* 2010; Choudhury and Pal, 2011; Gogoi *et al.,* 2019). The Pearson' correlation between various class of phytoplankton and physico-chemical parameters is given in Fig. 8. Bacillariophyceae revealed a strong positive correlation with NO_3, Chl-a and silicate, which aligns with the findings of Gogai *et al.* (2021) from the Sundarbans eco-region. Dinophyceae showed a positive correlation to ammoniacal nitrogen, and the findings are contrary to the reports of Rath *et al.* (2021). The major parameters influencing the Coscinodiscophyceae were BOD, nitrite, DO and total phosphorous (Dienye *et al.,* 2023; Gogoi *et al.,* 2019; Gogoi *et al.,* 2021). However, in the present study Coscinodiscophyceae did

Table 3: BIO-ENV analysis

No. of variables	Environmental variables	Spearman co-rrelation
1	FCO_2	0.3900
2	AT, FCO_2	0.4929
3	ALK, FCO_2, Chl-a	0.4291
4	AT, FCO_2, NO_2, Chl-a	0.4239
5	AT, ALK, FCO_2, NO_3, Chl-a	0.4221
6	WT, FCO_2, TRN, NO_3, NO_2, Chl-a	0.3730
7	AT, ALK, FCO_2, SIL NO_3, NO_2, Chl-a	0.3686
8	AT, ALK, FCO_2, TRN, SIL, NO_3, NO_2, Chl-a	0.3645
9	WT, AT, ALK, FCO_2, TRN, OP, NO_3, NO_2, Chl-a	0.3174
10	WT, AT, DO, ALK, FCO_2, TRN,, SIL, NO_3, NO_2, Chl-a	0.3104

not exhibit a positive correlation with any environmental variables, except for a negative correlation with total phosphorous. CCA is used to assess the influence of physico-chemical parameters on phytoplankton distribution (Vajravelu *et al.,* 2018; Tran *et al.,* 2022; Akter *et al.,* 2024). CCA plot (Fig. 9) of the present study revealed that Eigen values and percentages of variance indicated a higher contribution from Axis 1 (55.78%) compared to Axis 2 (19.65%). Chlorophyceae and Xanthophyceae were positively linked with air and water temperature, silicate, nitrate, orthophosphate and chlorophyll-a along Axis 1. Conversely, Bacillariophyceae, Mediophyceae, Cyanophyceae, Dinophyceae and Zygnematophyceae demonstrated a negative correlation with salinity, free CO_2, dissolved oxygen, transparency, nitrite, pH, alkalinity and available nitrogen along the Axis 1. Coscinodiscophyceae had a negative association with both the Axis, while Xanthophyceae showed a positive correlation. Rath *et al.* (2021) reported a positive association of Chlorophyceae and Dinophyceae with temperature, NO_3 and NO_2, and negative with NH_4 in the Hooghly River estuary adjacent to Matla estuary.

BIO-ENV analysis identifies how various environmental factors combine to influence both the abundance and distribution patterns of phytoplankton communities. In the present study, parameters such as air and water temperature, free CO_2, nitrate, nitrite, silicate, alkalinity, transparency, orthophosphate, dissolved oxygen and chlorophyll-a were correlated with the phytoplankton abundance (Table 3). A strong correlation was noted between phytoplankton and parameters viz., air temperature and free CO_2 (ρ=0.4929). Akter *et al.* (2024) reported that parameters like air temperature, salinity, transparency, pH, nitrite, total phosphorus and silicate were key factors that influenced the phytoplankton community in Monori creek. The present findings are also in line with the previous reports in other estuaries where salinity, temperature and nutrient availability were the key factors determining the distribution of phytoplankton (Buyukates and Roelke, 2005; Riekenberg *et al.,* 2015).

In summary, the present study revealed the diversity and distribution of 38 phytoplankton genera across eight classes, influenced by seasonal variations in environmental factors. Key drivers like nutrients and temperature positively affected the algal community, while salinity and pH showed negative impacts, providing essential insights for estuarine ecosystem conservation and management.

Acknowledgments

The first author expresses sincere gratitude to the Director, ICAR-CSSRI and Head, ICAR-CSSRI, RRS, Canning, for the support and all the provisions made for the study. The first author also thank and acknowledges the fellowship received from the Indian Council of Agricultural Research (ICAR), New Delhi, during the initial study period of Ph.D. All the authors affiliated to ICAR – CIFE acknowledges the Director/Vice-Chancellor for all the support.

Authors' contribution: R.N. Bhutia: Conceptualisation, planning, sampling, execution of work, writing and manuscript preparation; **K. Abhilashwadoyer:** Data analysis, writing and editing manuscript; **D. Devadas:** Writing and correcting manuscript; **U.K. Mandal:** Planning of work, execution and overall guidance; **G.B. Sreekanth:** Work planning, manuscript correction and guidance; **A.T. Landge:** Guidance and correcting manuscript; **A.K. Jaiswar:** Manuscript correction and writing; **G. Deshmukhe:** Conceptualisation, work planning, data analysis and manuscript correction; **D. Burman:** Planning of work, execution and overall guidance.

Funding: The research was carried out with the financial support received from ICAR, New Delhi, to ICAR-CSSRI, RRS, Canning, West Bengal, India.

Research content: The research content of manuscript is original and has not been published elsewhere.

Ethical approval: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

Data availability: Data will be made available from

Online Copy

corresponding author upon reasonable request.

Consent to publish: All authors agree to publish the paper in *Journal of Environmental Biology.*

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