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ORIGINAL ARTICLE

Nutrient Removal Vis-à-Vis Change in Partial Pressure of CO_2 During Post-Monsoon Season in a Tropical Lentic and Lotic Aquatic Body: A Comparative Study

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Abstract
The rate of nutrient removal and changes in pCO_2 (water) were compared between a lentic aquaculture pond [East Kolkata Wetlands (EKW), India] and a lotic estuarine system [Diamond Harbor (DH) in Hugli Estuary, India] during the post-monsoon season (experiencing a similar tropical climate) by means of ex situ microcosm experiment. Though the DH waters were found to be substantial source of CO_2 towards atmosphere and EKW waters to be sink for CO_2 (according to the initial concentration of CO_2), the eight consecutive days microcosm experiment revealed that the nutrient removal and pCO_2 reduction efficiency were significantly higher in DH (ΔpCO_2—90%) compared to EKW (ΔpCO_2—78%). Among the five nutrients studied [dissolved nitrate-nitrogen (NO_3–N), dissolved ammonium nitrogen (NH_4–N), silicate, phosphate and iron], dissolved NO_3–N followed by NH_4–N was the most utilized in both EKW and DH. Except silicate, the other nutrients reduced to 78–91% in EKW and 84–99% in DH samples of their initial concentrations. Chlorophyll-*a* concentration steadily depleted in EKW (~ 68–26 mg m^{-3}) during the experiment indicating intense zooplankton grazing, whereas in DH it increased rapidly (~ 3.4–23 mg m^{-3}) with decreasing pCO_2 (water). The present observations further indicated that regular flushing of EKW aquaculture ponds is required to avoid stagnation of water column which would enhance the zooplankton grazing and hamper the primary production of an otherwise sink of CO_2. In DH, controlled freshwater discharge from Farakka and reduction of untreated organic waste might allow the existing phytoplankton community to enhance their photosynthetic activity.

Keywords Nutrient removal · PCO_2 (water) · Lentic ecosystem · Lotic ecosystem · East Kolkata Wetlands · Hugli Estuary

1 Introduction

Atmospheric concentration of radiatively active greenhouse gases like carbon dioxide (CO_2) has increased substantially throughout the last century and it is considered to be one of the driving factors behind phenomena like climate change and global warming (IPCC 2013). Ever since the importance of CO_2 in the atmosphere is realized, several researches were conducted to identify the CO_2 emission as well sink potential of various natural ecosystems (Selvam et al. 2014). Both lentic and lotic inland water bodies like lakes, ponds, rivers, and streams are considered to be a significant source of CO_2 towards the atmosphere emitting ~ 2.1 Pg C $year^{-1}$ (Raymond et al. 2013). Estuaries have been also recognized to be large sources of CO_2 (Borges and Abril 2011) emission at the rate of ~ 0.50 Pg C $year^{-1}$ (Laruelle et al. 2010). Among the various biogeochemical activities that take place in the water column, autotrophic primary production and

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bentho-pelagic respiration along with re-mineralization of organic substances to CO_2 by biological decomposition are the most crucial processes which regulate the net biological pump in any aquatic body (Aufdenkampe et al. 2011). Phytoplankton, in this regard, is the smallest unit of autotrophs which are capable of fixing dissolved CO_2 leading to increase in pH along with reduction of inorganic carbon and hence regulating the carbonate chemistry of the water column in favor of the climate, i.e., by stimulating CO_2 absorption from the atmosphere (Álvarez et al. 1999).

Nutrients play a fundamental role in regulating the performance and activities of the phytoplankton species assemblage of any natural aquatic body. Nutrients are one of the most crucial abiotic components from the perspective of biological pump as these can characterize the nature and magnitude of both aquatic primary production and respiration (Cole et al. 2000; Biddanda et al. 2001). Though nutrients are one of the most essential components required for primary production, it has long been realized that intensification of nitrogen and phosphorus inputs in aquatic ecosystems due to widespread anthropogenic activities lead to ill effects like eutrophication (Vitousek et al. 1997). Allochthonous input of nutrients often makes an aquatic system highly productive and leads to net autotrophy, i.e., the system acts as a net sink for CO_2 (Duarte and Agusti 1998). However, supply of nutrients beyond a certain threshold in aquatic ecosystems having highly enriched organic substrate leads to super-saturation of CO_2 and the system acts as a net source of CO_2 (Marotta et al. 2012). Several exhaustive studies were carried out to delineate the efficiency of biological carbon pump in the field of oceanography, especially in open sea waters (De La Rocha and Passow 2012; Passow and Carlson 2012) owing to their CO_2 sink potential. However, the same approach in case of the inland waters is rarely reported. In this study, we have examined the nutrient utilization rate along with the change in partial pressure of CO_2 in the surface waters [pCO_2 (water)] of two different types of inland water bodies: one being an aquaculture pond situated in a wetland (lentic ecosystem) and the other being a perennial open urban estuary (lotic ecosystem). Excessive nutrient loading in both these types of ecosystems due to increased population growth (which in turn led to enhanced waste water discharge and agricultural practices) might have several negative impacts on the magnitude of primary production, timing of bloom, composition of the phytoplankton community and so forth (Wilkerson et al. 2015). Estuaries are very crucial sites as they act as the bridging zone between a river and oceans and all the anthropogenic loads that fall in the rivers are buffered in these estuarine regions before they enter the sea. Several estuaries are gradually becoming prone to nutrient enrichment and cultural eutrophication (Painting et al. 2007; Wilkerson et al. 2015) due to excessive sewage discharge and fertilizer runoff (Fisher et al. 2006). Similarly, aquaculture ponds are also susceptible to excessive nutrient loading. In several studies, it is observed that only small quantities of nutrients are actually utilized for fish production in an aquaculture pond, while the rest remains in the sediment or gets discharged to other adjacent water bodies (Xia 2013).

In all types of inland water bodies, the role of nutrients behind primary production is well recognized and perhaps well studied also; however, the direct effect of nutrient loading to carbon source/sink functions is yet to be understood properly. There are studies where increase in carbon uptake rate is observed with enhancement in nutrient load leading to high primary production (Downing et al. 1993), whereas there are also examples where high primary production is held accountable for net source nature due to severe mineralization of organic matter (Zheng et al. 2009). These contrasting results testify the significance and the necessity of conducting studies related to nutrient uptake and utilization vis-à-vis pCO_2 (water) variability in inland aquatic systems whether lentic or lotic. We hypothesized that, among various bio-physical attributes the intrinsic nutrient uptake rate of the respective water column (especially within the euphotic depth) could be one of the most significant regulating factors regarding pelagic productivity. In other words, we hypothesized that different types of aquatic column with different magnitudes of nutrient loading would exhibit varying pCO_2 (water) variability under similar climatic conditions. Based on the framed hypothesis, we analyzed the nutrient uptake rate and pCO_2 (water) variability in the surface waters of an aquaculture pond and an urban estuary situated very close to each other and experiencing similar tropical climate. The primary objectives of the study were to (1) compare the magnitude of nutrient loading and pCO_2 (water), (2) compare the rate of change of nutrient concentration and pCO_2 (water) with time and (3) characterize the difference in primary production: net carbon flux (if, any) between the two types of ecosystem. In this study, no additional nutrient loading has been performed on the microcosm setups. The prime intention of the study was to examine the rate at which the pre-existing nutrient levels are getting exhausted and vis-à-vis the change in pCO_2 (water) of the respective samples. Few in situ studies related to nutrient dynamics and pCO2 (water) dynamics in Hugli Estuary (Akhand et al. 2016; Mukhopadhyay et al. 2002, 2006) and EKW (Kundu et al. 2008; Adhikari et al. 2017) are previously reported; however, in situ microcosm studies are rarely reported.

2 Materials and Methods

2.1 Study Area

Kolkata is the oldest and one of the most densely populated metropolitan cities of India (Population Census 2011) situated in the bank of River Hugli (Fig. 1). To the east of the city lies the 'East Kolkata Wetlands' (hereafter referred to as EKW) which comprises a huge garbage dumping site of Kolkata Municipal Area, followed by a series of agricultural fields interspersed with ~ 300 aquaculture ponds, inter-connected through major and secondary canals, several rice fields and 43 villages with ~ 60,000 population (Saha et al. 2015). Estimated 1.1 million m^3 wastewater generated in the city of Kolkata per day ends up in a major canal which flows 30 km through the EKW and finally drains in the Kulti-Bidyadhari River system which in turn drains into the Bay of Bengal (Edwards 2008). EKW is popularly known as the 'kidney of Kolkata' as the entire wetland system acts as a filter by utilizing the wastewater in the field of agriculture and fisheries and purifying the water mass before draining in Bay of Bengal (Kundu et al. 2008). EKW is a unique example of natural waste recycling region as it offers a cheap, efficient and eco-friendly sewer and solid waste treatment for the city of Kolkata deploying minimal use of technology and engineering (Raychaudhuri et al. 2008) and at the same provides about 150 tons of fresh vegetables daily, ~ 10,500 tons of table fish per year providing livelihoods to about 50,000 people (Chaudhuri et al. 2012). This EKW nurtures the world's largest sewage fed aquaculture system encompassing an area of about 12 km^2 (Aich et al. 2012). The depths of the aquaculture ponds vary from 1 m to 1.5 m. Several studies have been conducted in EKW from the perspective of fisheries, phytoplankton abundance, environmental pollution, etc.; however, attempts of quantifying pCO_2 (water) and nutrient dynamics of the aquaculture ponds are rarely reported.

The other aquatic system selected for the present study is the Hugli Estuary that flows by the city of Kolkata and considered as a well-mixed mesotidal–macrotidal estuary (De et al. 2011). Water samples were collected from Diamond Harbour (hereafter referred to as DH) situated in the upper estuarine part of the Hugli river. Hugli happens to be a 260 km long tributary of River Ganges and it receives a perennial freshwater discharge from the Farakka barrage which makes this region to act as an open estuary throughout the year (Akhand et al. 2016). It is an extremely important estuary as it acts as the artery that favors the navigability of big ships to Kolkata and upstream as well as it provides substantial quantity of freshwater to the Indian part of Sundarban

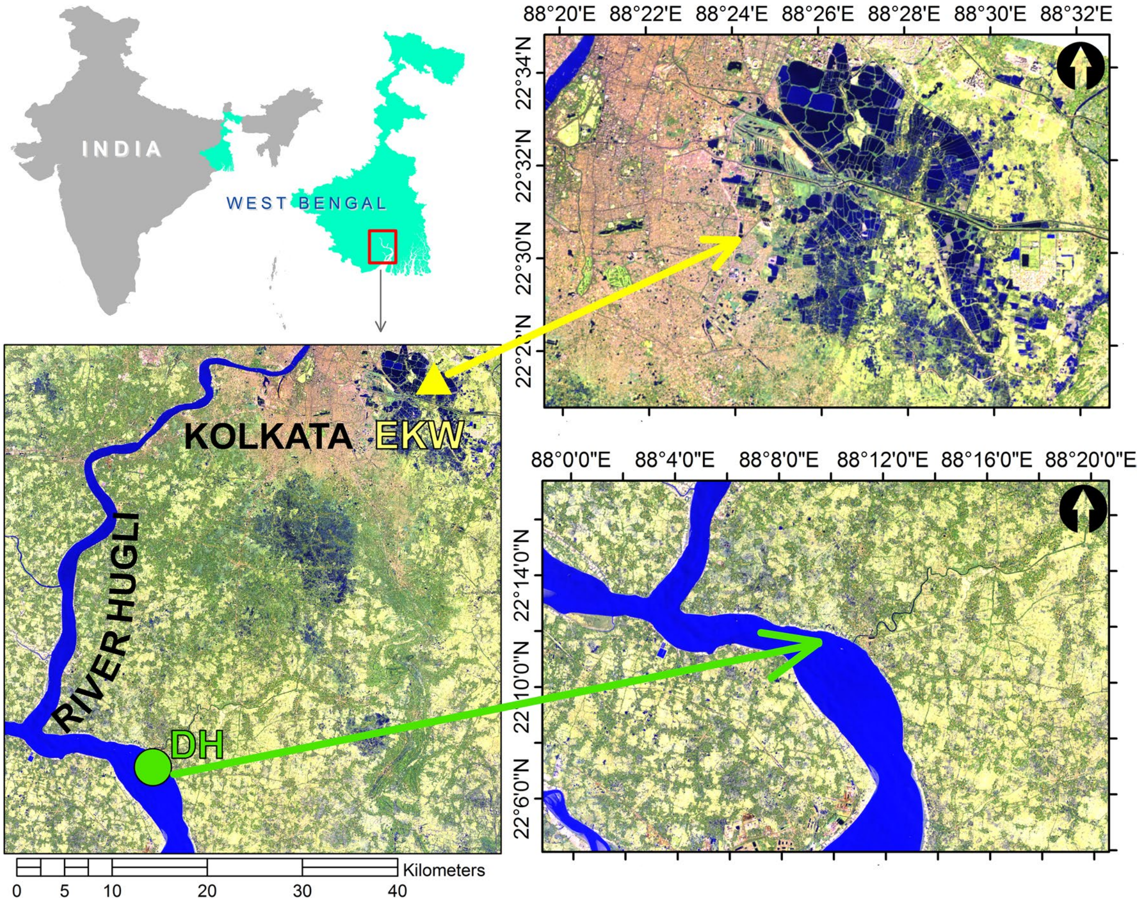

Fig. 1 The study area map showing the East Kolkata Wetlands (EKW) situated beside Kolkata metropolis and Diamond Harbour (DH) in the Hugli Estuary

mangroves (the largest mangrove forest of the world) (Biswas et al. 2007). However, ever since the construction of Farakka Barrage (300 km upstream from the sea mouth of Hulgi River) the estuary has been experiencing severe stress due to frequent dredging, discharge of sewage and port activities, especially around Haldia and Kolkata metropolis (Biswas et al. 2004). Aquaculture ponds of EKW and the Hugli estuarine phase near DH are absolutely two different types of inland aquatic systems experiencing the same typical tropical climatic features. February to May marks the pre-monsoon season followed by the monsoon season which extends from June to September. Almost 70–80% of the rainfall takes place during this phase of summer monsoon (Mukhopadhyay et al. 2006) and the weather remains extremely humid during the pre-monsoon and monsoon months. The month of October to January marks the post-monsoon season of which December and January are considered to be the winter months being characterized by lower temperature ranges and humidity.

2.2 Sampling Strategy

The present study was deliberately carried out in the post-monsoon season as optimum conditions in terms of light availability favoring photosynthesis are known to prevail in this region during this time of the year. Surface water samples were collected from DH and EKW on the 15th January, 2017 at 9:00 am by two separate team of researcher. Two 300 l reservoirs made up of opaque polyvinyl chloride were placed in the roof top of the School of Oceanographic Studies, Jadavpur University's laboratory. The height of the reservoirs was 1 m. Both the reservoirs were filled up with waters collected from DH and EKW, respectively, to create a near reality situation. Eight microcosm chambers (each being a 6-litre transparent sealed polycarbonate bottle without any headspace) were filled with the same surface waters of DH and another eight were filled with surface waters of EKW. These chambers were incubated the same day and kept floating 0.25 m below the surface in the respective reservoirs under natural day–night cycle following Biswas et al. (2015). This setup was deliberately chosen for the two types of water samples in order to allow both the types of water samples to experience same climatic condition throughout the experiment. One bottle was kept as a control for both DH and EKW by poisoning the microcosm chamber with 105 µg mercuric chloride ($HgCl_2$) per ml of sample (Kattner 1999). A battery operated mechanized rotor (120 rpm) was used in the DH sample's microcosm chambers twice a day (in 10 am morning and 8 pm evening for 5 min each) in order to ensure that there is no biomass settlement at the bottom as the DH surface waters never experience such conditions in reality. Whereas, no such arrangements were made for EKW sets as EKW is a lentic ecosystem of shallow depth and experiences no hydrodynamic shear or turbulence. The microcosms of both DH and EKW were sampled everyday for eight consecutive days from the eight floating microcosm chambers. Though the experiment was conducted for 12 days; however, in this study we have reported the data of 8 days only, as most of the nutrients were almost exhausted by the end of eighth day. We deliberately wanted to avoid the data during a nutrient starved phase for both the systems. Hence, an optimum of 8 day period was chosen for the present study. The initial data of all the parameters were measured within 6 h of collecting the water samples from DH and EKW. The setup of microcosm chambers in the roof top was completed on 15th January, 2017 and from the next day onwards samples were collected daily at 9:00 am and analyzed on that very day. The instantaneous readings by deploying probes were also taken every day at 9:00 am.

2.3 Analytical Protocol

Salinity/conductivity was measured using a Multikit (WTW Multi 340 i Set; Merck, Germany) fitted with the probe WTW Tetracon 325. pH and water temperature were measured with a micro-pH meter having a precision of 0.001 and 0.1 °C, respectively. pH was measured using the Orion PerpHecT ROSS Combination pH Micro-Electrode fitted with a data logger [Thermo Scientific, USA]. The glass electrodes for pH measurements were calibrated daily on the NBS scale using technical buffers of pH 4.01 (Part no: 1.09475.0500; Merck), pH 7.00 (Part no: 1.09477.0500; Merck) and pH 9.00 (Part no: 1.09476.0500; Merck) at a controlled temperature of 25 °C. Dissolved oxygen (DO) was measured using a digital DO meter (FiveGo Series, Mettler Toledo) having a precision of 0.01 mg l^{-1}. Turbidity was measured with a turbidity meter (TN-100; Eutech Instruments, precision 0.1 NTU) and underwater photosynthetically active radiation (PAR) was determined with standard sensors (UWQ 8247, Li-Cor, USA, precision 0.1 µ mol m^{-2} s^{-1}) and a data logger (Li-250A, Li-Cor, USA). The incoming solar radiation falling on the water surface was measured with the help of a Lux meter (LX-105, Leutron). Total alkalinity (TAlk) was determined using an automated titrator (905 Titrando, Metrohm, Switzerland).Chlorophyll-*a* (Chl-*a*) (precision 0.01 mg m^{-3}) and all the nutrients [namely dissolved nitrate–nitrogen (NO_3–N), nitrite–nitrogen (NO_2–N), ammonium-nitrogen (NH_4–N), phosphate, silicate and iron] (precision 0.01 µM) were measured following standard spectrophotometric procedures (Parsons et al. 1992). The pCO_2 (water) and dissolved inorganic carbon (DIC) were computed using the data of measured salinity, water temperature, T Alk, pH, phosphate and silicate using CO2SYS.EXE programme (Lewis and Wallace 1998). The dissociation constants K_1 and K_2 were used according to Peng et al. (1987) on the NBS scale and the correction for sulphate as proposed by Khoo et al. (1977) for the samples of DH. However, for the EKW samples the dissociation constants K_1 and K_2 were used according to Millero (1979), especially advised to use for freshwater.

Each day, separate light and dark bottles were kept floating at the depth of the microcosm chambers filled up with waters taken from one microcosm chamber for that particular day's analysis and these bottles were incubated at 9:00 am in the morning and their changes in DO concentration were measured after being incubated for 24 h cycle, i.e., the next day at 9:00 am. The gross primary production (GPP, from the difference between light bottle DO and dark bottle DO), community respiration (CR, from the difference between dark bottle DO and initial DO) and the net primary production (NPP, from the equation NPP = GPP − CR) were computed for eight consecutive days.

Apart from primary production, trophic state index (TSI) is also considered very useful parameter to categorize the trophic condition of any aquatic system. Carlson (1977) coined the term TSI to be used for freshwater lake systems according to the formulae:

$$\mathrm{TSI} = 10\left(6 - \frac{2.04 - 0.68\ln(\mathrm{Chl}\text{ - }a)}{\ln 2}\right) \tag{1}$$

where Chl-*a* stands for chlorophyll-*a* concentration (mg m^{-3}). TSI can vary from 0 to 100 and each major division like 10, 20, 30, etc. denotes a doubling of algal biomass (Carlson 1977).TSI in this study was calculated for EKW samples. Similar to Carlson's TSI, Vollenweider et al. (1998) formulated a trophic index (TRIX) for estuarine systems and marine coastal waters according to the equation:

$$\mathrm{TRIX} = \frac{\log((\mathrm{Chl}\text{ - }a) \times D\%O \times \mathrm{IN} \times \mathrm{IP}) + 1.5}{1.2} \tag{2}$$

where chl-*a* stands for chlorophyll-*a* concentration (mg m^{-3}), $D\%O$ denotes the absolute deviation value of the saturation percentage of dissolved oxygen, $|100 - \mathrm{DO_{sat}}|$. IN and IP stand for inorganic nitrogen and phosphorus concentration (mg m^{-3}). The DO saturation was calculated according to the formula proposed by Benson and Krause (1984). The TRIX can vary from 0 to 10 covering a wide spectrum from oligotrophy to eutrophy (Vollenweider et al. 1998); however, it can be simplified as: high (2–4), good (4–5), bad (5–6) and poor (6–8) according to (Penna et al. 2004).

3 Results

3.1 Initial Conditions of EKW and DH Waters

The surface temperature of water in the two aquatic systems was almost same (Table 1). EKW waters hardly had any salinity (the conductivity was recorded to be 854 µS cm^{-1}), whereas the DH waters had a salinity of 3.4. DO was slightly higher in EKW (6.5 mg l^{-1}) compared to DH (4.25 mg l^{-1}). Experiencing identical climatic conditions, the solar intensity striking the water surface was same in both DH and EKW; however, turbidity of the water column was slightly higher in EKW (76.5 NTU) compared to DH (61.2 NTU). Consequently, lower PAR was observed in EKW (2.4 µmol m^{-2} s^{-1}) than DH (3.5 µmol m^{-2} s^{-1}). The difference in pH between DH (8.802) and EKW (8.869) was substantial. Due to this difference in pH, despite having similar T Alk and DIC values, the pCO_2 (water) was quite low in EKW (239 µatm) compared to DH (1683 µatm). The nutrient concentrations were 3–8 times higher in DH than EKW; however, the only exception was silicate (Table 1). Like pH and pCO_2 (water), the chl-*a* concentration also displayed significant difference with as high as 68.8 mg m^{-3} in EKW and only 3.4 mg m^{-3} in DH.

3.2 Temporal Variation of Physico-Chemical Parameters During the Microcosm Experiment

The microcosm experiment was continued for eight consecutive days. Since the entire experiment was done in the same season, the ambient temperature and hence the water temperature along with the solar intensity remained the same throughout the experiment. No reportable change in either the conductivity of EKW samples or salinity of the DH samples was observed. DO showed an increasing trend in both

Table 1 Initial physico-chemical conditions before the beginning of the microcosm experiment in the EKW and DH surface waters

Parameters	EKW	DH
Water temperature (°C)	23.1	23.1
Salinity	0.0	3.4
Dissolved Oxygen (mg l^{-1})	6.5	4.25
Photosynthetically active radiation (µmol m^{-2} s^{-1})	2.4	3.5
Solar intensity (k lux)	33.1	33.1
Turbidity (NTU)	76.5	61.2
pH	8.869	8.082
Total Alkalinity (µmol kg^{-1})	2936	3224
Dissolved inorganic carbon (µmol kg^{-1})	2847	3161
pCO_2(water) (µatm)	239	1683
Fe (µM)	20.1	77.2
Phosphate (µM)	5.9	15.5
Nitrate(µM)	5.6	46.8
Ammonium (µM)	12.2	44.4
Silicate (µM)	67.7	49.1
Chl-*a* (mg m^{-3})	68.8	3.4
TSI	72.1	–
TRIX	–	8.96

EKW and DH samples (Fig. 2). In case of EKW, a sharp increase in DO was observed in the second day; however, on the whole the net increase in DO at the end of eighth day was higher in DH (2.4 mg l^{-1}) compared to EKW (2.1 mg l^{-1}). pH also showed an overall increasing trend in both EKW and DH samples; however, in EKW pH decreased second to fourth day followed by an increase again. Like DO, the net increase in pH was much higher in DH (0.719) than EKW (0.291). A sharp increase in pH of DH samples was observed between fourth and fifth day and thereafter it did not vary to a great extent. The DIC and TAlk curves were almost identical. Both TAlk and DIC showed a depleting trend through the 8 days (Fig. 2). In case of EKW, a sharp decline in the TAlk and DIC was observed in the very second day, followed by a gradual depletion, however, in DH a comparatively steady depletion was observed to take place throughout the eight days. The net depletion in TAlk and DIC after 8 days was significantly high in EKW (1588 and 1587 µmol kg^{-1}) compared to DH (1063 and 1309 µmol kg^{-1}).

3.3 Temporal Variation in pCO_2 (Water) Along with Nutrient and Chlorophyll Concentration During the Microcosm Experiment

pCO_2 (water) steadily decreased throughout the 8 days of experiment in both EKW and DH; however, the decrease was substantially high in DH samples. By the end of fifth day, the pCO_2 (water) magnitudes dropped from 1683 to 251 µatm (Fig. 3). The net decrease in pCO_2 (water) at the end of eighth day was 186 µatm only in case of EKW samples, whereas, in case of DH the decrease was as high as 1516 µatm. The change in chl-*a* concentration during the eighth day experiment showed contrasting trend in EKW and DH samples. In EKW, the chl-*a* concentration increased in the second day followed by a drastic reduction till the fourth day and by the 8 days it decreased from 68.8 to 26.0 mg m^{-3}. In DH samples, chl-*a* concentration decreased slightly in the second day followed by an increase till the sixth day followed by a decrease again by the eighth day (Fig. 3). The

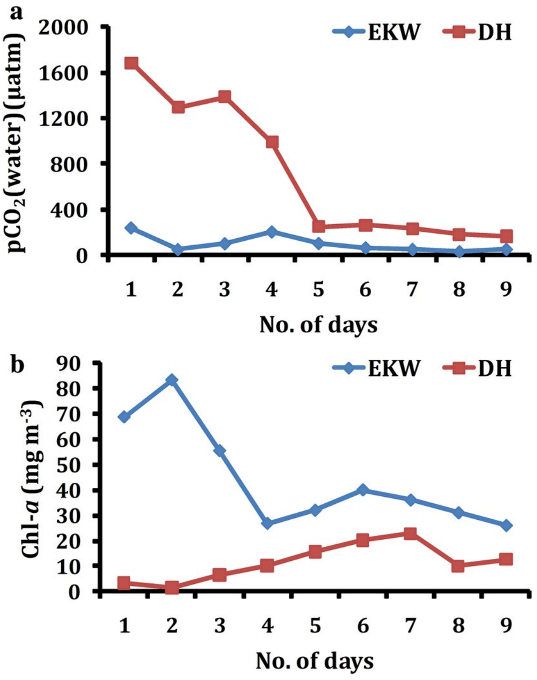

Fig. 3 The daily variation of (**a**) pCO_2 (water) and (**b**) chl-*a* in both EKW and DH during the 8 days microcosm experiment

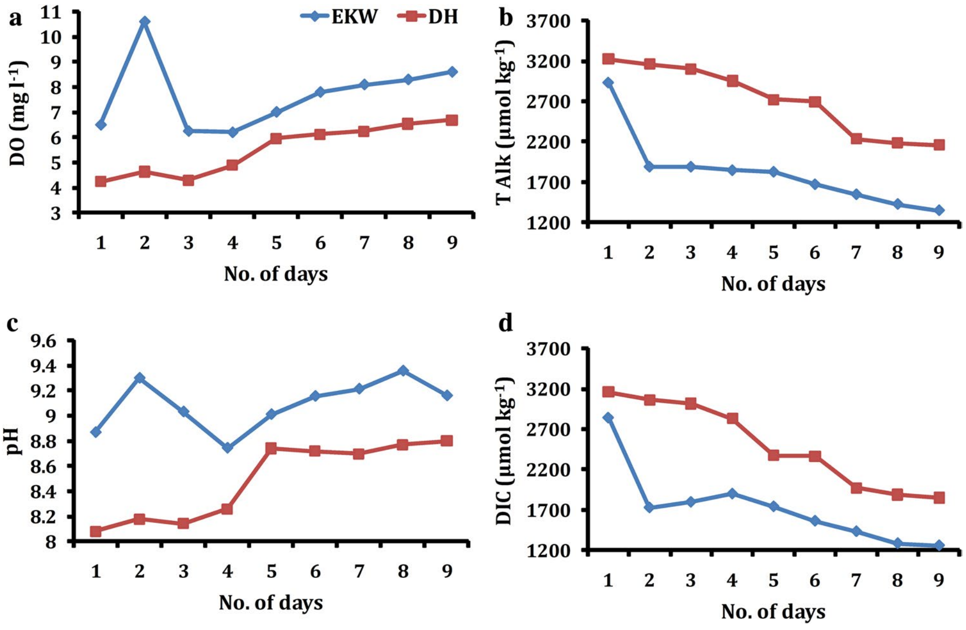

Fig. 2 The daily variation of (**a**) DO, (**b**) T Alk, (**c**) pH and (**d**) DIC in both EKW and DH during the 8 day microcosm experiment

chl-*a* concentration in DH samples increased from 3.4 to 12.7 mg m^{-3} by the end of eighth day. Mirroring the change in chl-*a* concentration, TSI magnitudes declined steadily from 72.1 to 62.5 throughout the study period in EKW, whereas TRIX magnitudes decreased from 8.96 to 7.15 by the end of eighth day.

pCO_2 (water) showed strong negative correlation with pH in both DH and EKW (Fig. 4); however, the goodness of fit of the correlation was much high in DH ($R^2 = 0.97$) compared to EKW ($R^2 = 0.84$). Similar negative correlation was also observed between DO and pCO_2 (water) with R^2 value as high as 0.95 in DH and R^2 of 0.49 was observed in EKW (depicting comparatively weaker correlation w.r.t. DH). A positive correlation between T Alk and pCO_2 (water) was observed in both EKW and DH. Chl-*a* showed a strong negative correlation with pCO_2 (water) in DH; however, there was no significant correlation between these two parameters in EKW. The scatter plot of nutrient data with respect to Chl-*a* showed a higher positive correlation in case of EKW whereas no such correlation was observed in case of DH (Fig. 5). The scatter plot between the nutrients and pCO_2 (water) exhibited significant correlation with NO_3–N only in case of EKW, whereas in case of DH, pCO_2 (water) showed significant correlation with NO_3–N, Fe and PO_4^{3-} (Fig. 6).

Apart from silicate, all other studied nutrients showed decreasing trend in both EKW and DH samples during the 8 day microcosm experiment (Fig. 7). The initial dissolved NO_3–N concentration in DH was 46.8 µM which reduced to 8.1 µM in the very second day and reached 0.60 µM by the eighth day. However, in EKW the initial concentration was 5.2 µM which gradually reduced to 0.5 µM by the eighth day. Alike NO_3–N, phosphate also showed depleting trend in DH and EKW; however, in EKW its concentration was found to increase in the second day followed by a gradual decrease. The initial phosphate concentration was comparatively higher in DH (15.5 µM) than EKW (5.9 µM); however, by the end of eighth day its concentration attained 1.4 µM in both DH and EKW samples. Dissolved NH_4–N also showed a net reduction in concentration; however, the DH samples exhibited fluctuations in its concentration between the third and seventh day. A net 10 µM decrease in the dissolved NH_4–N concentration was observed in EKW from an initial value of 12.2 µM, whereas in DH a net decrease of 37 µM was observed from an initial value of 44.4 µM. Fe curve also showed a similar curve like that of NO_3–N in case of both EKW and DH. Silicate concentration showed a significant depletion in EKW (from an initial concentration of 67.7–29.8 µM by eighth day); however, in DH there was hardly any variation in silicate concentration except an initial reduction in the second day.

4 Discussion

Several previous studies have enumerated the distribution and abundance of the phytoplankton standing stock in the two selected sites of the present study. Choudhury and Pal (2011) observed a total of 58 taxa in the phytoplankton community of the DH waters comprising mainly the divisions of Cyanophyta, Chlorophyta and Bacillariophyta. However, during the present study period, i.e., post-monsoon season (especially winter months), an extremely high dominance of diatoms was observed (98.3%) with *Nitzschia delicatissima* being the most dominant species followed by *Thalassionema nitzschoides*, *Gyrosigma beaufortianum*, *Pleurosigma salinarum*, *Bacillaria paxillifer*, *Odontella aurita*

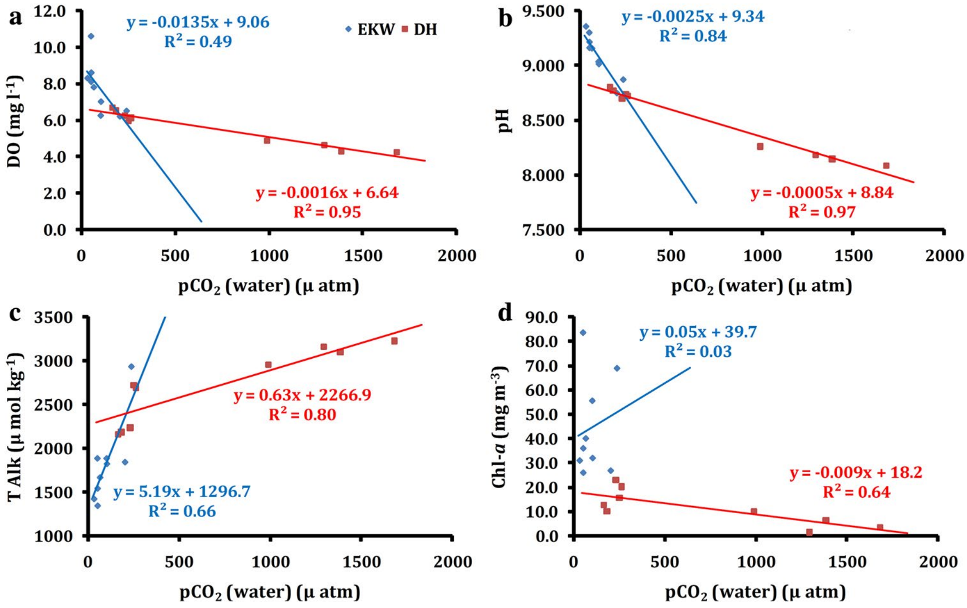

Fig. 4 The scatter plot of pCO_2 (water) vs (**a**) DO, (**b**) pH, (**c**) T Alk and (**d**) chl-*a* in both EKW and DH during the 8 days microcosm experiment

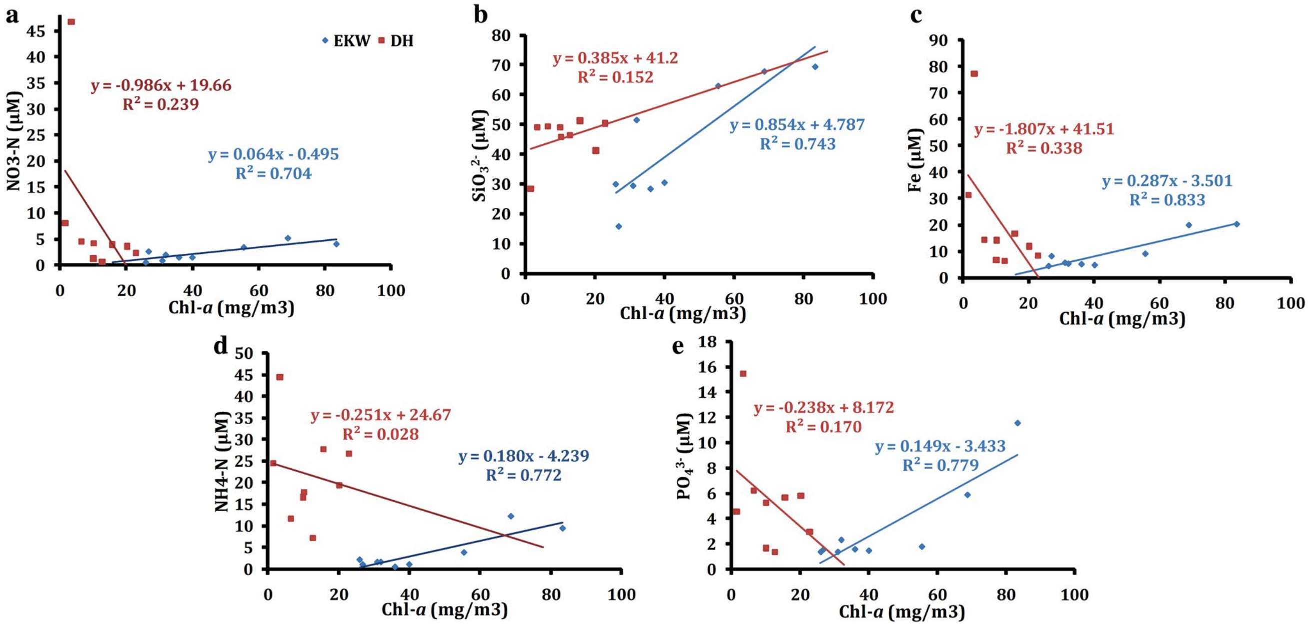

Fig. 5 The scatter plot of chl-*a* vs (**a**) NO_3–N, (**b**) silicate and (**c**) iron, (**d**) NH_4–N, (**e**) phosphate in both EKW and DH during the 8 days microcosm experiment

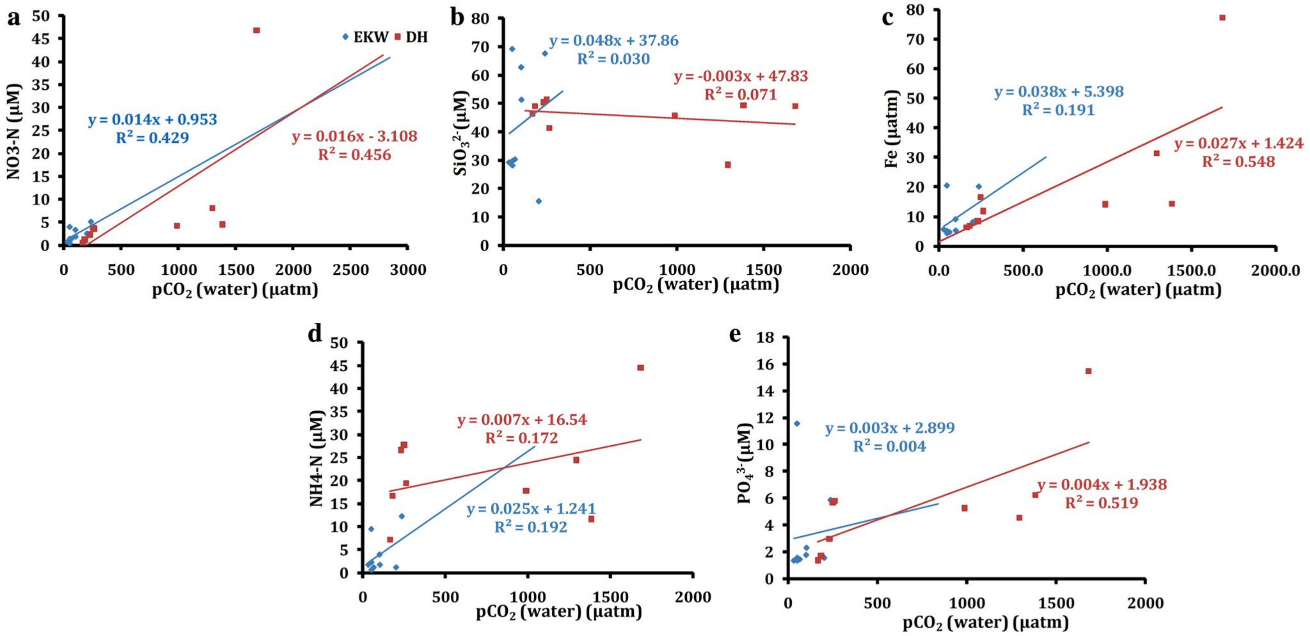

Fig. 6 The scatter plot of pCO_2 (water) vs **a** NO_3–N, **b** silicate and **c** iron, **d** NH_4–N, **e** phosphate in both EKW and DH during the 8 day microcosm experiment

and *Paralia sulcata* (Choudhury and Pal 2011). *Microcystis aeruginosa* and *Pediastrum tetras* were found to be the only representatives of Cyanophyceae and Chlorophyceae family, respectively. On the contrary in EKW aquaculture pond waters, a total of 114 taxa of phytoplankton were identified which are mostly dominated by Chlorophytes throughout the year followed by Cyanoprokaryota which was found to be the second most dominant group during the post-monsoon season (winter months) (Roy and Pal 2015). Among Cyanoprokaryota phylum, *Chroococcus* sp., *Merismopedia*

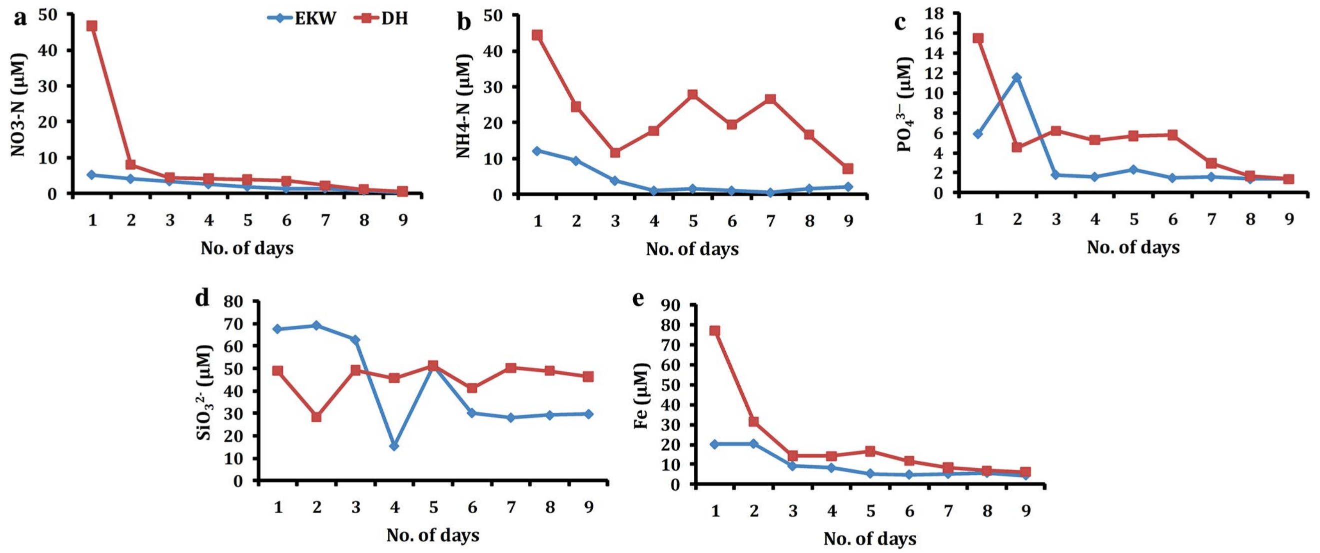

Fig. 7 The daily variation of **a** NO_3–N, **b** NH_4–N, **c** phosphate, **d** silicate and **e** iron in both EKW and DH during the 8 day microcosm experiment

sp., *Synechococcus* sp. and *Spirulina* sp. prevailed in the EKW waters throughout the years with maximum abundance observed during the winter (Roy and Pal 2015) whereas, among Chlorophyta phylum, *Closterium* sp., *Tetraedron* sp., *Cosmarium* sp and *Euglena* sp., etc. were found abundant (Kundu et al. 2008). Though Bacillariophycean members were observed to exist throughout the year, however, their abundance was much smaller compared to Cyanoprokaryota and Chlorophyta (Roy and Pal 2015).

The first and foremost evident fact that came out by analyzing the present observations was that the surface water of EKW was under saturated with respect to CO_2. Not only under the in situ condition (i.e., while collecting the samples) but also during the entire microcosm study, it acted as a sink for CO_2. Whereas, the DH samples under the in-situ condition were substantially supersaturated with CO_2 and till the fourth day of the microcosm experiment it remained so, establishing itself as a source of CO_2. Akhand et al. (2016) while analyzing the in-situ pCO_2 (water) dynamics in the Hugli Estuary observed DH as a source throughout the year. However, the new aspect that we got to learn by means of this study was that the DH surface waters were found to be capable of becoming a sink for CO_2 fifth day onwards and till the eighth day it acted the same. Scrutinizing the data set of both DH and EKW, it was seen that the overall chl-*a* concentration in DH was far low than EKW leading to lesser primary production, which in turn could attribute to the high pCO_2 (water) in DH (Mukhopadhyay et al. 2006) and vice versa in EKW. Mukhopadhyay et al. (2002) and Mukhopadhyay et al. (2006) consistently observed in their study that GPP in DH was always lower than community respiration despite having substantially high nutrient concentration (in this study we also observed that initial nutrient load of DH was much higher than EKW). Mukhopadhyay et al. (2006) attributed factors like lesser light availability (due to increased suspended particulate matter), hydrodynamic factors like extreme turbulent motion and shear leading to the cellular rupture of diatoms and dinoflagellates which inhibit the growth rates of phytoplankton. In this study, we observed that chl-*a* concentration significantly increased from the third day. Moreover, the decrease in TRIX magnitude from extremely poor condition (according to the classification of Penna et al. 2004) to much better condition was observed by the end of eighth day. In the microcosm setup, there was no steady source of sewage or industrial effluent as usually experienced by Hugli Estuary and, moreover, the turbulence caused by the rotator was minimal. However, earlier studies of Sinha et al. (1998) and Sarkar et al. (2004) observed huge organic matter input by means of domestic sewage. Hence, it can be inferred that if the sewage inflow to the Hugli Estuary can be restricted and the river discharge from the Farakka Barrage can be effectively optimized so as to increase the residence time of freshwater and lower the extreme turbulence, the in situ productivity of the DH waters might get enhanced.

A completely reverse scenario was observed in case of EKW. Though the pCO_2 (water) decreased on the whole throughout the study, the net rate of decrease was much lower than DH and most essentially the chl-*a* concentration also depleted rapidly, instead of increasing. This depicted that though the phytoplankton strength in EKW was found much stronger than DH, they might be comparatively short lived than the phytoplankton of EKW. The very low depth of the aquaculture ponds along with static conditions makes the environment suitable for photosynthesis (by increasing the euphotic depth). Hence, the aquaculture ponds can undergo quick purification process by means of natural recycling of sewage and organic wastes and abundant quantity of algal photosynthetic activities (Raychaudhuri et al. 2008). Moreover, higher pH is known to make nutrients more readily available for phytoplankton (Wurts and Durborow 1992). Despite the favorable conditions, the depletion in chl-*a* magnitudes could be also due to intense zooplankton grazing (Carpenter et al. 1985). Saha et al. (2016) observed a sharp enhancement of zooplankton community in EKW during the winter months of post-monsoon season leading to rapid grazing and consequently a steady decline in the phytoplankton load. Thus, it can be inferred that zooplankton in EKW plays a key role in balancing the carbon dynamics of the ecosystem. Dutta et al. (2006) observed that the enzyme activity of zooplankton population works best around or below 30 °C and higher temperature is detrimental to them. The steady decline in chl-*a* concentration in the microcosm chambers of EKW testified that zooplanktons of EKW were well active around the temperature of 23 °C (as observed in the present study). The decline in TSI magnitudes from 72.1 (initial) to 62.5 (by the end of eighth day) also testified the fact that this zooplankton grazing could effectively convert the system from a hyper-eutrophic state to a moderate eutrophic state (Shankar 2006). However, the EKW ponds having extremely shallow depth have a tenacity of temperature build up (Saha et al. 2016); hence, it is advisable to flushup ponds with fresh sewage feed so as to avoid the enhancement in temperature. Under elevated temperatures and sluggish environment, once the Chlorophytes and Cyanoprokaryota were being already grazed by zooplankton, the growth of toxin producing cyanobacterial population could be triggered (Jumars et al. 1989), which in turn could be detrimental for the entire aquatic body.

Analyzing the percentage reduction in pCO_2 (water) vis-à-vis the percentage reduction in nutrient concentration of both EKW and DH, it was clearly observed that the net reduction efficiency of nutrient as well as CO_2 removal was lower in EKW compared to DH (Table 2). One of the prime reasons could be intensive zooplankton grazing in EKW (as discussed above) leading to lesser abundance of chl-*a* to utilize the nutrients optimally. Another important factor could be the difference in the type of phytoplankton abundance between EKW and DH. Previous study already established that during post-monsoon season, DH waters are dominated by diatoms, whereas EKW waters by chlorophytes (Choudhury and Pal 2011; Roy and Pal 2015). Geider et al. (1986) observed that the chl-*a*: carbon ratio followed the hierarchy: chlorophytes > diatoms > dinoflagellates. This implied that a certain magnitude of chl-*a* within chlorophytes is capable of lesser magnitude of carbon uptake compared to diatoms or, in other words, the photosynthetic carbon uptake potential of chlorophytes is lesser than diatoms. Our results of nutrient reduction and pCO_2 (water) removal from the respective aquatic systems passed through the observations of Geider et al. (1986). Among the five nutrients studied, dissolved NO_3–N followed by NH_4–N was found to be the most utilized nutrients in both EKW and DH. In DH, NO_3–N concentration was almost extinguished by the end of eighth day. This indicated an NO_3–N limitation as observed by several previous studies carried out in freshwater and estuarine systems (Hecky and Kilham 1988; Howarth 1988; Elser et al. 1990). Compared to NO_3-N, a lower utilization of phosphate in both EKW and DH could be attributed to the higher pH which in turn could assist phosphate release from organic substrate (Zhou et al. 2008) in EKW and due to release of freely diffusible rapidly soluble cellular materials of low-molecular-density (Fallon and Brock 1979) in DH, respectively. In this way, both the systems might get replenished with phosphate, hence leading to the apparent lesser utilization of phosphate compared to NO_3–N. Though DH had substantially higher nutrient utilization efficiency than EKW, the only exception was silicate. Silicate concentration hardly changed in DH waters and decreased by only 5% by the end of eighth day. This observation might seem contradicting as diatoms were abundant in DH waters and diatoms are efficient to assimilate the silicate ions the most among all the groups of phytoplankton. However, Kilham and Hecky (1988) observed that different diatom species

Table 2 The percentage reduction of pCO_2 and nutrient in both the EKW and DH microcosm setups during various intervals

% Reduction	East Kolkata wetlands				Diamond Harbor			
	Day 0th–2nd	Day 2nd–5th	Day 5th–8th	Day 0th–8th	Day 0th–2nd	Day 2nd–5th	Day 5th–8th	Day 0th–8th
ΔpCO_2	57	−35	21	78	18	81	37	90
ΔFe	54	47	7	78	81	18	47	92
ΔPO_4^{3-}	70	18	7	77	60	−7	76	91
ΔNO_3^-	34	57	67	91	90	20	83	99
ΔNH_4^+	68	71	−100	82	74	−67	63	84
ΔSiO_3^-	7	52	2	56	−1	16	−12	5

Negative values indicate increase during the respective interval utilize silicate up to different extent and have differing life span. A set of short lived diatom species after consuming a substantial quantity of silicate might die and the consumed silicate again gets released to the system by means of dissolution of the dead diatom's frustules as well as from the zooplankton excreta which consumed such diatoms (Bidle and Azam 1999). Choudhury and Pal (2011) observed a 98.3% dominance of diatoms in DH during winter; hence, it is quite possible that the rate of replenishment of silicate ions from dead diatoms equals the rate of its consumption leading to no significant net silicate removal from the DH waters.

5 Conclusion

Analyzing the present observations, it can be inferred that DH waters were acting as a source and EKW waters were acting as sink for CO_2 under in situ conditions during the winter months (post-monsoon season); however, the microcosm chamber experiments showed that the nutrient utilization/reduction capacity of the DH waters were found to be higher than the EKW waters. The difference in the type of phytoplankton composition (which was described in earlier studies; not a direct outcome of the present study) can be one of the most probable reasons behind such difference in nutrient reduction in the two types of waters. In case of lentic aquaculture wetlands, higher capability of primary producers to assimilate the degraded organic materials by means of natural recycling may be responsible to develop higher sewage purification capacity. It can be deduced from the present microcosm experiment that stagnant waters of EKW are extremely prone to intense zooplankton grazing as the chl-*a* degraded rapidly despite having favorable conditions for photosynthesis both in terms of light and nutrient availability. The present microcosm study shows that prolonged stagnation of EKW aquaculture ponds could be detrimental to the entire aquatic ecosystem, as excessive zooplankton grazing could lead to a dearth of chl-*a* to such an extent that the primary productivity vis-à-vis the fisheries sector could get severely affected. Frequent flushing of the aquaculture ponds from the sewage canals would replenish chl-*a* as well as nutrients to maintain the productivity of the water column. On the other hand, DH waters which acted as a substantial source under in situ conditions exhibited promising nutrient reduction efficiency and most essentially under less disturbed environment and optimum light availability along with the absence of sewage input, the chl-*a* concentration was found to increase steadily during the experiment. It is true that microcosm like conditions cannot be artificially created throughout the Hugli Estuary. However, controlled flow of freshwater discharge from the Farakka Barrage and reduction of sewage disposal in the estuary can enhance the productivity of the water column.

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References

Adhikari S, Goswami AR, Mukhopadhyay SK (2017) Diversity of zooplankton in municipal wastewater-contaminated urban pond ecosystems of the lower Gangetic plains. Turk J Zool 41:464–475

Aich A, Chakraborty A, Sudarshan M, Chattopadhyay B, Mukhopadhyay SK (2012) Study of trace metals in Indian major carp species from wastewater-fed fishponds of East Calcutta Wetlands. Aquacult Res 43:53–65

Akhand A, Chanda A, Manna S, Das S, Hazra S, Roy R, Mostofa KMG (2016) A comparison of CO2 dynamics and air-water fluxes in a river-dominated estuary and a mangrove-dominated marine estuary. Geophys Res Lett. https://doi.org/10.1002/2016GL070716

Álvarez M, Fernández E, Pérez FF (1999) Air-sea CO2 fluxes in a coastal embayment affected by upwelling: physical versus biological control. Oceanol Acta 22:499–515

Aufdenkampe AK, Mayorga E, Raymond PA, Melack JM, Doney SC, Alin SR, Aalto RE, Yoo K (2011) Riverine coupling of biogeochemical cycles between land, oceans and atmosphere. Front Ecol Environ 9:53–60

Benson BB, Krause JR (1984) The concentration and isotopic fractionation of oxygen dissolved in freshwater and seawater in equilibrium with atmosphere. Limnol Oceanogr 29:620–632

Biddanda B, Ogdahl M, Cotner J (2001) Dominance of bacterial metabolism in oligotrophic relative to eutrophic waters. Limnol Oceanogr 46:730–739

Bidle KD, Azam F (1999) Accelerated dissolution of diatom silica by marine bacterial assemblages. Nature 397:508–512

Biswas H, Mukhopadhyay SK, De TK, Sen S, Jana TK (2004) Biogenic controls on the air-water carbon dioxide exchange in the Sundarban mangrove environment, northeast coast of Bay of Bengal, India. Limnol Oceanogr 49:95–101

Biswas H, Mukhopadhyay SK, Sen S, Jana TK (2007) Spatial and temporal patterns of methane dynamics in the tropical mangrove dominated estuary, NE coast of Bay of Bengal, India. J Mar Syst 68:55–64

Biswas H, Jie J, Li Y, Zhang G, Zhu ZY, Wu Y, Zhang GL, Li YW, Liu SM, Zhang J (2015) Response of a natural Phytoplankton community from the Qingdao coast (Yellow Sea, China) to variable CO_2 levels over a short-term incubation experiment. Curr Sci 108:1901–1909

Borges AV, Abril G (2011) Carbon dioxide and methane dynamics in estuaries. In: Wolanski E, Mclusky DS (eds) Treatise on estuarine and coastal science. Elsevier Academic Press, Waltham, pp 119–161

Carlson RE (1977) A trophic state index for lakes. Limnol Oceanogr 22:361–369

Carpenter SR, Kitchell JF, Hodgson JR (1985) Cascading trophic interactions and lake productivity. Bioscience 35:634–639

Chaudhuri SR, Mukherjee I, Ghosh D, Thakur AR (2012) East Kolkata Wetland: a multifunctional niche of international importance. Online J Biol Sci. https://doi.org/10.3844/ojbsci.2012.80.88

Choudhury AK, Pal R (2011) Variations in seasonal phytoplankton assemblages as a response to environmental changes in the surface waters of a hypo saline coastal station along the Bhagirathi-Hooghly estuary. Environ Monit Assess 179:531–553

Cole JJ, Pace ML, Carpenter SR, Kitchell JF (2000) Persistence of net heterotrophy in lakes during nutrient addition and food web manipulations. Limnol Oceanogr 45:1718–1730

De La Rocha CL, Passow U (2012) The biological pump. In: Holland HD, Turekian KK (eds) The oceans and marine geochemistry, vol 6. Treatise on geochemistry. Elsevier, Oxford, pp 1–29

De TK, De M, Das S, Chowdhury C, Ray R, Jana TK (2011) Phytoplankton abundance in relation to cultural eutrophication at the land-ocean boundary of Sunderbans, NE Coast of Bay of Bengal, India. J Environ Stud Sci 1:169–180

Downing JP, MeybeckM Orr JC, Twilley R, Scharpenseel H (1993) Land and water interface zones. Terrestrial biospheric carbon fluxes quantification of sinks and sources of CO_2. Springer, Dordrecht, pp 123–137

Duarte CM, Agusti S (1998) The CO_2 balance of unproductive aquatic ecosystems. Science 281:234–236

Dutta TK, Jana M, Pahari P, Bhattacharya T (2006) Effect of temperature, pH and salt on amylase in *Heliodiaptomus viduus* (Gurney) (Crustacea: Copepoda: Calanoida). Turk J Zool 30:187–195

Edwards P (2008) An increasingly secure future for wastewater-fed aquaculture in Kolkata, India? Aquacult Asia Mag 13:3–9

Elser JJ, Marzolf ER, Goldman CR (1990) Phosphorus and nitrogen limitation of phytoplankton growth in the freshwaters of North America: a review and critique of experimental enrichments. Can J Fish Aquat Sci 47:1468–1477

Fallon RD, Brock TD (1979) Decomposition of blue-green algal (cyanobacterial) blooms in Lake Mendota, Wisconsin. Appl Environ Microbiol 37:820–830

Fisher TR, Hagy J III, Boynton WR, Williams MR (2006) Cultural eutrophication in the Choptank and Patuxent estuaries of Chesapeake Bay. Limnol Oceanogr 51:435–447

Geider RJ, Platt T, Raven JA (1986) Size dependence of growth and photosynthesis in diatoms: a synthesis. Mar Ecol Prog Ser 30:93–104

Hecky RE, Kilham P (1988) Nutrient limitation of phytoplankton in freshwater and marine environments: a review of recent evidence on the effects of enrichment. Limnol Oceanogr 33:796–822

Howarth RW (1988) Nutrient limitation of net primary production in marine ecosystems. Ann Rev Ecol Syst 19:89–110

IPCC (2013) In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jumars PA, Penry DL, Baross JA, Perry MJ, Frost BW (1989) Closing the microbial loop: dissolved carbon pathway to heterotrophic bacteria from incomplete ingestion, digestion and absorption in animals. Deep Sea Res 36:483–495

Kattner G (1999) Storage of dissolved inorganic nutrients in seawater: poisoning with mercuric chloride. Mar Chem 67:61–66

Khoo KH, Ramette RW, Culberson CH, Bates RG (1977) Determination of hydrogen ion concentrations in seawater from 5 to 40 °C: standard potentials at salinities from 20 to 45‰. Anal Chem 49:29–34

Kilham P, Hecky RE (1988) Comparative ecology of marine and freshwater phytoplankton. Limnol Oceanogr 33:776–795

Kundu N, Pal M, Saha S (2008) East Kolkata Wetlands: a resource recovery system through productive activities. In Proceedings of Taal 2007: the 12th world lake conference, 868, pp 881

Laruelle GG, Dürr HH, Slomp CP, Borges AV (2010) Evaluation of sinks and sources of CO_2 in the global coastal ocean using a spatially-explicit typology of estuaries and continental shelves. Geophys Res Lett. https://doi.org/10.1029/2010GL043691

Lewis E, Wallace DWR (1998) Program developed for CO_2 system calculations, ORNL/CDIAC-105, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee

Marotta H, Duarte CM, Guimaraes-Souza BA, Enrich-Prast A (2012) Synergistic control of CO_2 emissions by fish and nutrients in a humic tropical lake. Oecologia 168:839–847

Millero FJ (1979) The thermodynamic of the carbonate system in seawater. Geochim Cosmochim Acta 43:1651–1661

Mukhopadhyay SK, Biswas H, De TK, Sen S, Jana TK (2002) Seasonal effects on the air–water carbon dioxide exchange in the Hooghly estuary, NE coast of Bay of Bengal, India. J Environ Monit 4:549–552

Mukhopadhyay SK, Biswas H, De TK, Jana TK (2006) Fluxes of nutrients from the tropical River Hooghly at the land-ocean boundary of Sundarbans, NE Coast of Bay of Bengal, India. J Mar Syst 62:9–21

Painting SJ, Devlin MJ, Malcolm SJ, Parker ER, Mills DK, Mill C, Tett P, Wither A, Burt J, Jones R, Winpenny K (2007) Assessing the impact of nutrient enrichment in estuaries: susceptibility to eutrophication. Mar Pollut Bull 55:74–90

Parsons TR, Maita Y, Lalli CM (1992) A manual of chemical and biological methods for sea water analysis. Pergamon, New York

Passow U, Carlson CA (2012) The biological pump in a high CO_2 world. Mar Ecol Prog Ser 470:249–271

Peng T-H, Takahashi T, Broecker WS, Olafsson J (1987) Seasonal variability of carbon dioxide, nutrients and oxygen in the northern North Atlantic surface water: observation and a model. Tellus 39:439–458

Penna N, Capellacci S, Ricci F (2004) The influence of the Po River discharge on phytoplankton bloom dynamics along the coastline of Pesaro (Italy) in the Adriatic Sea. Mar Pollut Bull 48:321–326

Population \Census (2011) http://www.censusindia.gov.in/2011-common/census_data_2001.html. Accessed 31 Mar 2011

Raychaudhuri S, Mishra M, Nandy P, Thakur AR (2008) Waste management: a case study of ongoing traditional practices at East Calcutta Wetland. Am J Agric Biol Sci 3:315–320

Raymond PA, Hartmann J, Lauerwald R, Sobek S, McDonald C, Hoover M, Butman D, Striegl R, Mayorga E, Humborg C, Kortelainen P (2013) Global carbon dioxide emissions from inland waters. Nature 503:355–359

Roy AS, Pal R (2015) Planktonic Cyanoprokaryota and Bacillariophyta of East Kolkata Wetlands ecosystem, a Ramsar Site of India with reference to diversity and taxonomic study. J Algal Buinass Utln 6:47–59

Saha S, Hazra GC, Saha B, Mandal B (2015) Assessment of heavy metals contamination in different crops grown in long-term sewage-irrigated areas of Kolkata, West Bengal, India. Environ Monit Assess 187:4087. https://doi.org/10.1007/s10661-014-4087-9

Saha S, Saha T, Basu P (2016) Planktons in dirty water: carbon cycling process of sewage fed fisheries in East Kolkata Wetland, India. Wetlands 3:415–429

Sarkar SK, Frančišković-Bilinski S, Bhattacharya A, Saha M, Bilinski H (2004) Levels of elements in the surficial estuarine sediments of the Hugli River, northeast India and their environmental implications. Environ Int 30:1089–1098

Selvam BP, Natchimuthu S, Arunachalam L, Bastviken D (2014) Methane and carbon dioxide emissions from inland waters in India-implications for large scale greenhouse gas balances. Glob Change Biol 20:3397–3407

Shankar PH (2006) Trophic State Index (TSI) in conservation of lake ecosystems. http://wgbis.ces.iisc.ernet.in/energy/lake2006/programme/programme/proceedings/lc9.htm. Accessed 20 Sept 2017

Sinha PC, Rao YR, Dube SK, Murthy CR (1998) A numerical model for residual circulation and pollutant transport in a tidal estuary (Hooghly) of NE Coast of India. Indian J Mar Sci 27:129–137

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277:494–499

Vollenweider RA, Giovanardi F, Montanari G, Rinaldi A (1998) Characterization of the trophic conditions of marine coastal waters, with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics 9:329–357

Wilkerson FP, Dugdale RC, Parker AE, Blaser SB, Pimenta A (2015) Nutrient uptake and primary productivity in an urban estuary: using rate measurements to evaluate phytoplankton response to different hydrological and nutrient conditions. Aquat Ecol 49:211–233

Wurts WA, Durborow RM (1992) Interactions of pH, carbon dioxide, alkalinity and hardness in fish ponds. Southern Regional Aquaculture Center, United States. Publication No. 464; pp 1–4

Xia B (2013) Study on the biological recycling of nutrients in polyculture ponds of grass carp (*Ctenopharyngodonidella*) and silver carp (*Hypophthalmichthys molitrix*). PhD Dissertation, Ocean University of China, Qingdao **(in Chinese with English Abstract)**

Zheng ZM, Dong SL, Tian XL, Wang F, Gao QF, Bai PF (2009) Sediment-water fluxes of nutrients and dissolved organic carbon in extensive sea cucumber culture ponds. Clean Soil Air Water 37:218–224

Zhou Y, Song C, Cao X, Li J, Chen G, Xia Z, Jiang P (2008) Phosphorus fractions and alkaline phosphatase activity in sediments of a large eutrophic Chinese lake (Lake Taihu). Hydrobiologia 599:119–125