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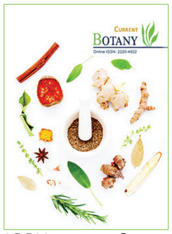
Research Article



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Response of six phytoplankton species in a high bicarbonate-containing culture medium spiked with gibberellic acid

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ABSTRACT

In the ocean and other aquatic bodies, phytoplankton plays a major role in fixing inorganic carbon in organic form. Anthropogenic input enhances the atmospheric carbon concentration, which leads to the dissolution of high amounts of carbon in water. In the present study, the response of five selected diatom species, *Nitzschia longissima*, *Ditylum brightwellii*, *Asterionellopsis glacialis*, *Coscinodiscus radiatus*, *Skeletonema costatum*, and one dinoflagellate species, *Protoperidinium*, were studied. The culture vessels spiked with gibberellic acid showed higher uptake relative to the control. Centric diatoms dominated over pinnate diatoms with respect to cell number in a high CO_2 environment. Relative abundance of *S. costatum* was found to be 30-55% in the culture medium with gibberellic acid and 30-46% in the control among all the phytoplankton species. In a high CO_2 environment, species specific positive response of phytoplankton may enhance the activity of the biological pump and hence turn the aquatic bodies into a sink for CO_2.

KEYWORDS: Phytoplankton, CO_2, Gibberellic acid, Bicarbonate concentration

INTRODUCTION

Ocean acidification (OA) is one of the most alarming issues regarding present-day climate change and is associated with rising atmospheric CO_2. Concentration of CO_2 in the atmosphere was about 270 ppm before the industrial revolution, but the present-day concentration reaches approximately 400 ppm and is expected to reach 800-1000 ppm by the end of this century (IPCC, 2014). Oceans are estimated to undergo significant changes due to the rising atmospheric CO_2 levels. The diffusion of atmospheric CO_2 in the ocean and the subsequent formation of carbonic acid have already resulted in a 30% increase in $[H^+]$ concentration in seawater with a net decrease of 0.1 pH unit and will continue to lower pH by an additional 0.2-0.3 pH units by the end of the century. This lowering in ocean pH is referred to as ocean acidification. The ocean acts as a sink of CO_2 and once dissolved in seawater, CO_2 reacts with water to form carbonic acid (H_2CO_3). However, ocean stores CO_2 as dissolved inorganic carbon (DIC), which remains in the form of dissolved CO_2 and H_2CO_3 (1%) while the rest is in the form of HCO_3 (90%) and CO_3^{2-} (9%) (Brewer, 1997; Wolf-Gladrow *et al.*, 1999; Rost *et al.*, 2008). pH changes have profound influences on the growth and interspecific competition of common algal species in natural waters (Ogbonda *et al.*, 2007; Liu & Vyverman, 2015). Effects of pH on algae can be observed in two ways: it may directly impact the enzyme activities in algal cells, affecting their growth (Tan *et al.*, 2018); in another way, pH changes are the direct result of changes in CO_2 levels in the water, which is crucial for algal photosynthesis and ultimately influences their growth rate. It is generally believed that cyanobacteria have a greater affinity for CO_2 in water than green algae, and cyanobacteria usually dominate in high-pH environments (Shapiro, 1984). A lower pH within an alkaline range of 8.0-9.5 could reduce the dominance of cyanobacteria to some extent and increase the biomass of some green algal species (Liu & Vyverman, 2015). An improved understanding of how the phytoplankton community will respond to a high CO_2 environment in the future is required to gain insight into the biological pump and the ocean's ability to act as a long-term sink for atmospheric CO_2. Phytoplankton plays a pivotal role in marine biogeochemical cycles by participating in nutrient cycling, organic matter decomposition and hence maintain carbon flow in the aquatic environment. Phytoplankton fixes CO_2 and supplies 90% of the total organic carbon in the ocean. Depending on the other aquatic growth factors both diatoms and cyanobacteria respond to the high CO_2 environment differently. It is reported that elevated pCO$_2$

can increase photosynthesis rate and cyanobacterial blooms (Shetye *et al.*, 2013; Eggers *et al.*, 2014). It is assumed that, in optimum temperature and available nutrient environment, primary productivity can be enhanced. Increased rate of CO_2 fixation due to high primary production can result in high bicarbonate acquisition by phytoplankton. The idea is that, increasing seawater pCO_2 facilitates the diffusive uptake of CO_2, thereby reducing the energy demand for active carbon acquisition (Giordano *et al.*, 2005; Reinfelder, 2011). The energy that is saved by reducing the operation of this so-called "carbon concentrating mechanism (CCM)" may be diverted into the acquisition of other resources, ultimately leading to faster growth. Studies made on diatom physiology are in agreement with this concept, though the result varies with the species variation (Rost *et al.*, 2003; Hopkinson *et al.*, 2011; Trimborn *et al.*, 2013; Gao & Campbell, 2014). On the other hand, species-specific CO_2 compensation point might play a major role in controlling different rates of CO_2 acquisition by phytoplankton and growth response of major phytoplankton groups (Tortell, 2000). Tortell *et al.* (2002) found that alteration in dissolved CO_2 did not modify total primary productivity and biomass, but high CO_2 treatment facilitated dominance of diatoms over the prymnnesiophyte *Phaeocystis* (colonial) in the equatorial Pacific, and vice versa at low CO_2, without any noticeable change in CO_2 uptake. In coastal seas and estuaries of North-Eastern India, diatoms and dinoflagellates dominate over cyanobacterial species in all seasons (Biswas *et al.*, 2004; Chowdhury *et al.*, 2012). Increased growth of bloom-forming diatom species can result in high bicarbonate uptake, consequently turning coastal seas and estuaries a CO_2 sink (Chowdhury, 2020). So, increased growth rate of diatom species via high carbon uptake and assimilation can be proved as a useful suggestion for a better carbon sink in estuaries and coastal seas. Studies showed variations in response of marine photosynthetic autotroph communities towards elevated pCO_2 which suggests response towards rising CO_2 and lowering pH is species specific (Price *et al.*, 2011). So it is also important to observe the changes in dominant phytoplankton species in high CO_2 and low pH environment to predict the effect of global climate change in term of Ocean acidification by keeping it into the mind that, a small but significant stimulation of primary production in oceanic environment in response to elevated CO_2 concentration (Hein & Sand-Jensen, 1997) during Short-term experiments was witnessed. Introduction of plant growth- promoting factors, like gibberellic acid, can promote phytoplankton growth in the aquatic medium. Gibberellic acid is a simple gibberellin, a pentacyclic diterpene acid, which promotes growth and is known for use in cultural studies. Adding gibberellic acid to the culture medium can have different responses. GA3 (200 mg/L) increased the growth *of P. tricornutum*, resulting in 52% more dry biomass compared to the control and a yield of 0.6 mg/L of eicosapentaenoic acid (EPA) from the culture. A yield of 0.18 mg/L fucoxanthin was obtained for *P. tricornutum* cultivated with GA3 (2 mg/L) supplementation (Fierli *et al.*, 2022). The plant hormone, gibberellic acid (GA), stimulated growth of a marine diatom, *Cyclotella cryptica* (Reimann *et al.*, 1963). Four concentrations of GA ($5 \times 20 \times 25 \times$ and 35×10^{-6} g/mL) were added to axenic cultures of *C. cryptica*. By measuring cell densities, cell counts, and turbidity, it was confirmed that GA at 20×10^{-6} g/mL was the most effective dose for growth stimulation. There was an increase in the total number of cells produced and a shorter lag phase of growth at this concentration. Coulter counter measurements of cell size, as well as ocular micrometer measurements, indicated there was no significant variation in cell volumes of GA grown cells over that of the controls (Adair & Miller, 1984). This study reports the use of gibberellic acid as growth promoting factor towards a natural mixed phytoplankton population. GA3 caused an increase in chlorophyll content in unicellular algae *Chlamydomonas* and *Anacystis* (Kadioglu, 1992), *Microcystis aeruginosa* (Pan *et al.*, 2008) and *Chlorella vulgaris* (Falkowska *et al.*, 2011). Gibberellic acid application can be a suitable and inexpensive way to increase algal biomass (Mansouri & Talebizadeh, 2017).

METHODOLOGY

Natural phytoplankton were isolated from waters of the Sundarban mangroves (21°32´- 22°40´ N and 88°05´-89° E), North East Coast of India. Collected phytoplankton were grown and maintained in f/2 medium at 18 °C and 3200 lux of illumination. The algal species in f/2 medium were spiked with gibberellic acid amount of 14 mg in each culture vessel of set 2 and set 1 without adding gibberellic acid. The culture vessels of both sets were spiked with Sodium bicarbonate to have final concentration of 500 μM, 1000 μM, 2000 μM, 3000 μM, 4000 μM. Every day, changes in phytoplankton number and their size, changes in pH, were measured under a phase contrast microscope in triplicate for 6 days and values reported here was the meaning of the experimental data. Nutrient concentration in the medium was not limited during the course of the experiment. Initial and final Chlorophyll a concentration of each vessel was measured by following the standard method (Parsons *et al.*, 1992).

1 mL of samples from each flask was taken in a Sedgwick Rafter counting chamber for enumeration.

RESULT

Changes in Culture Medium pH

Changes in culture medium pH were observed, and pH was increased with the increase in phytoplankton population while pH in the control medium was changed from the initial value of 8.3 to 8.345, but it was increased from 8.3 to 8.5 in the culture medium with gibberellic acid. pH in the culture vessels was lower (0.01 to 0.19% per day) in the control relative to the culture medium with gibberellic acid, which showed 0.02 to 1.56% increase per day.

Uptake of Bicarbonate by Phytoplankton in Response to its Increasing Concentration in the Presence and Absence of Gibberellic Acid in the Culture Medium

The bicarbonate concentration was 1.186 mmol kg^{-1} in the ambient medium from where the phytoplankton sample was collected. In the control vessels of in-vitro culture same concentration was added.

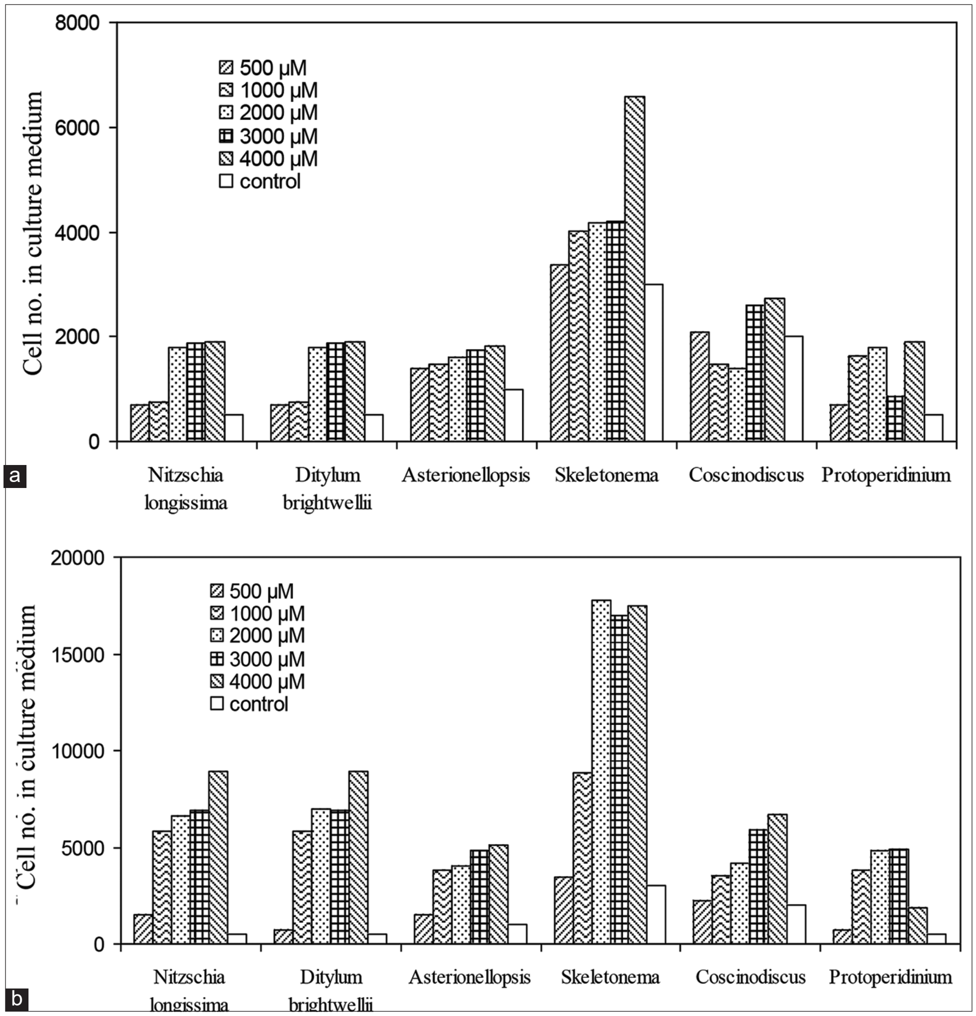

Figure 1: Total cell number of different species in culture meidum a) without gibberellic acid and b) with gibberellic acid on 6th day of experiment

Response of Selected Species Towards Increasing Bicarbonate Spiked in the Culture Medium

Five selected diatom species, *Nitzschia longissima*, *Ditylum brightwellii*, *Asterionellopsis glacialis*, *Coscinodiscus radiatus*, *Skeletonema costatum*, and one dinoflagellate species, *Protoperidinium*, occurring in the sample collected from the Saptamuhki estuary were considered to study their response towards increasing bicarbonate concentration relative to the ambient medium with and without gibberellic acid during in-vitro culture, and the results are given in figures 1 to 5. Results of the experiment were taken into consideration till the 6th day after the experiment was initiated, as the population of all species reached to the maximum number on the 6th day. The specific growth rate of all species was higher in the culture medium with gibberellic acid than the control. Chain-forming small centric diatom, *S. costatum*, showed the maximum growth relative to other species (Figure 1). The first vessel contained 500 μM excess bicarbonate than the control. Phytoplankton growth rate was 0.11-0.16 d^{-1} and 0.25-0.43 d^{-1} in control and the gibberellic acid-treated medium, respectively. The experiment was repeated using 1000 μM, 2000 μM, 3000 μM, 4000 μM excess carbonate than the ambient medium and in all cases phytoplankton growth

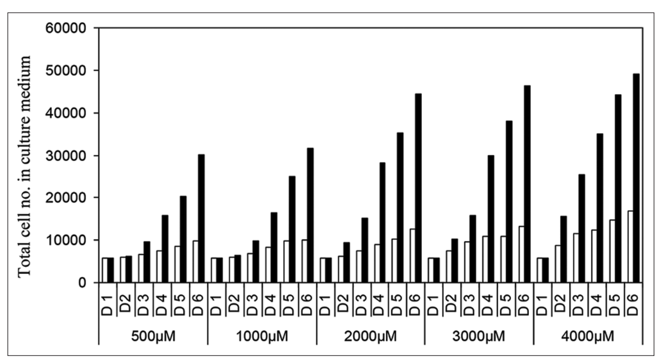

Figure 2: Total cell number in different culture vessels with (black bars) and without (white bars) gibberellic acid

rate was found significantly increased in the medium with gibberellic acid than the control with excess HCO_3^- (0.12-0.52 d^{-1} versus 0.03-0.2 d^{-1}, 0.22-0.61 d^{-1} vs 0.13-0.2 d^{-1}, 0.28-0.49 d^{-1} vs 0.01-0.24 d^{-1}, 0.24-0.58 d^{-1} vs 0.07-0.26 d^{-1}). Total phytoplankton count showed a maximum number in 200 ml culture medium with 4000 μM bicarbonate on the 6th day of the experiment and was found to be 49,100 cells in the medium with gibberellic acid vs 16,800 cells in the control with no excess bicarbonate. Among the six selected species, the relative abundance of *S. costatum* was found to be 30-55% in the culture medium with gibberellic acid and 30-46% in the control.

DISCUSSION

A study by Thangaraj and Sun (2020), *S. dohrnii* in a high carbon environment (2216 μM in 25 °C) showed a high growth rate

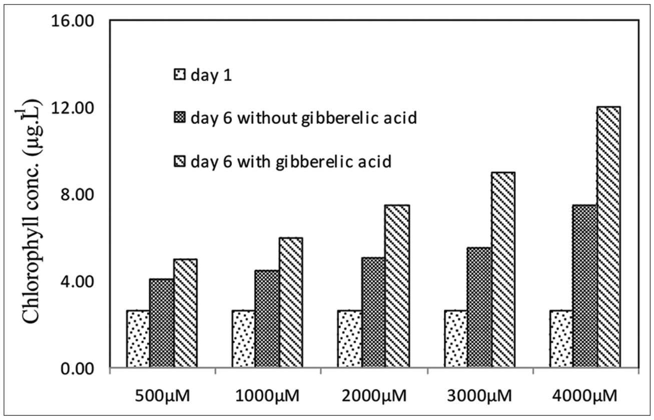

Figure 3: Chlorophyll concentration in different culture vessels on the final day of culture

(1.23 ± 0.15 d^{-1}) in the medium. The experiments conducted by Bach *et al.* (2019) with pCO_2 in the culture mesocosm ranged from 375 to 1406 μatm, had one of the highest carbon contributing genera, *Skeletonema*. In their study, without any growth stimulant, in a high CO_2 environment, the diatom community showed a long lag phase and attained a growth peak on day 17 of the study, as evident by the chlorophyll concentration in the medium. In all CO_2 concentrations in the mesocosm, *Skeletonema* showed a highest cell density in 5 to 10 days of study. Causes of diatom responses to high CO_2 are difficult to uncover in experimental set-ups as there might be inter-related phenomena in phytoplankton growth culture (Bach *et al.*, 2017). A laboratory study by Wu *et al.* (2014) in high CO_2 experiments with *Thalassiosira* sp. and *Coscinodiscus* sp. found that high CO_2 uptake enhances growth rates of larger diatoms with respect to cell volume. Based on the Positive correlation between cell size and diffusion gradients, evidence account for the beneficial effect of a high amount of CO_2, in carbon acquisition for bigger-celled diatoms like *Coscinodiscus* (Pasciak & Gavis, 1974; Wolf-Gladrow & Riebesell, 1997; Flynn *et al.*, 2012; Shen & Hopkinson, 2015). This observation is physiologically well substantiated. But study by Bach *et al.* (2019) showed small species like *Skeletonema* and *Chaetoceros* also responded well in high CO_2 environment which has the similarity with present study. Kim *et al.* (2006)

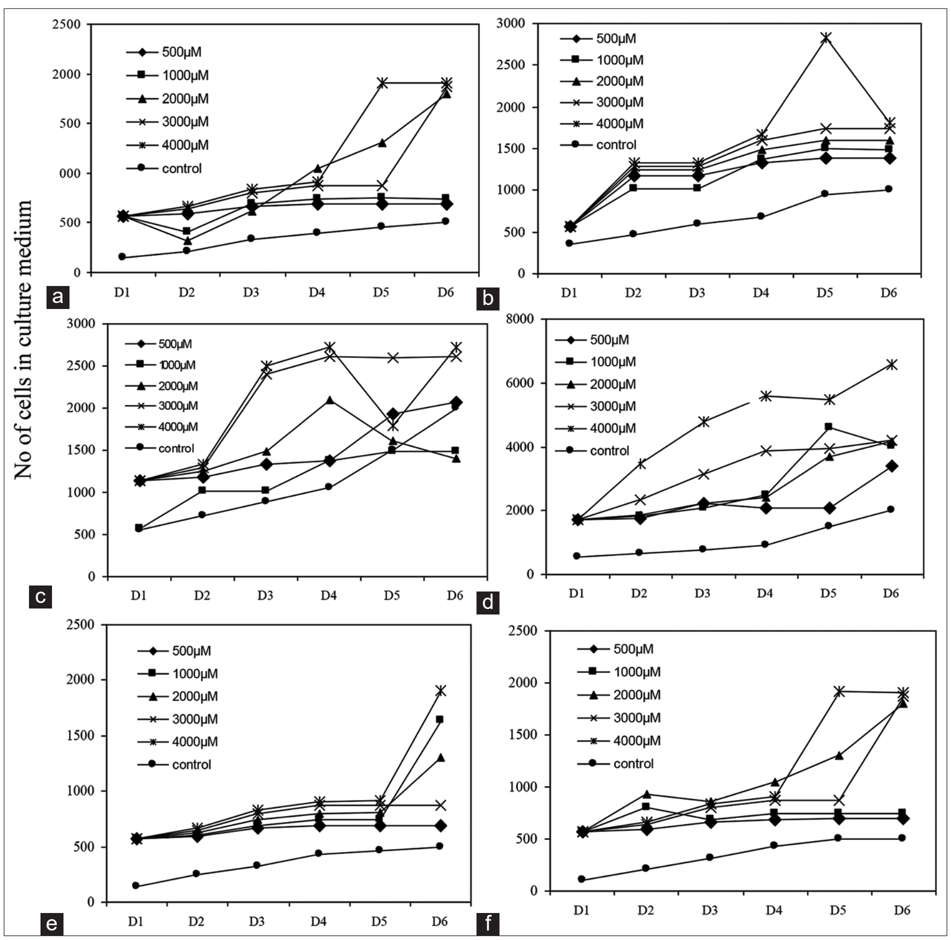

Figure 4: Growth of a) *Dytilum brightwellii*, b) *Asterionellopsis*, c) *Coscinodiscus*, d) *Skeletonema* cf *costatum*, e) *Protoperidinium*, f) *Nitzschia logissima* in the culture vessels without gibberellic acid

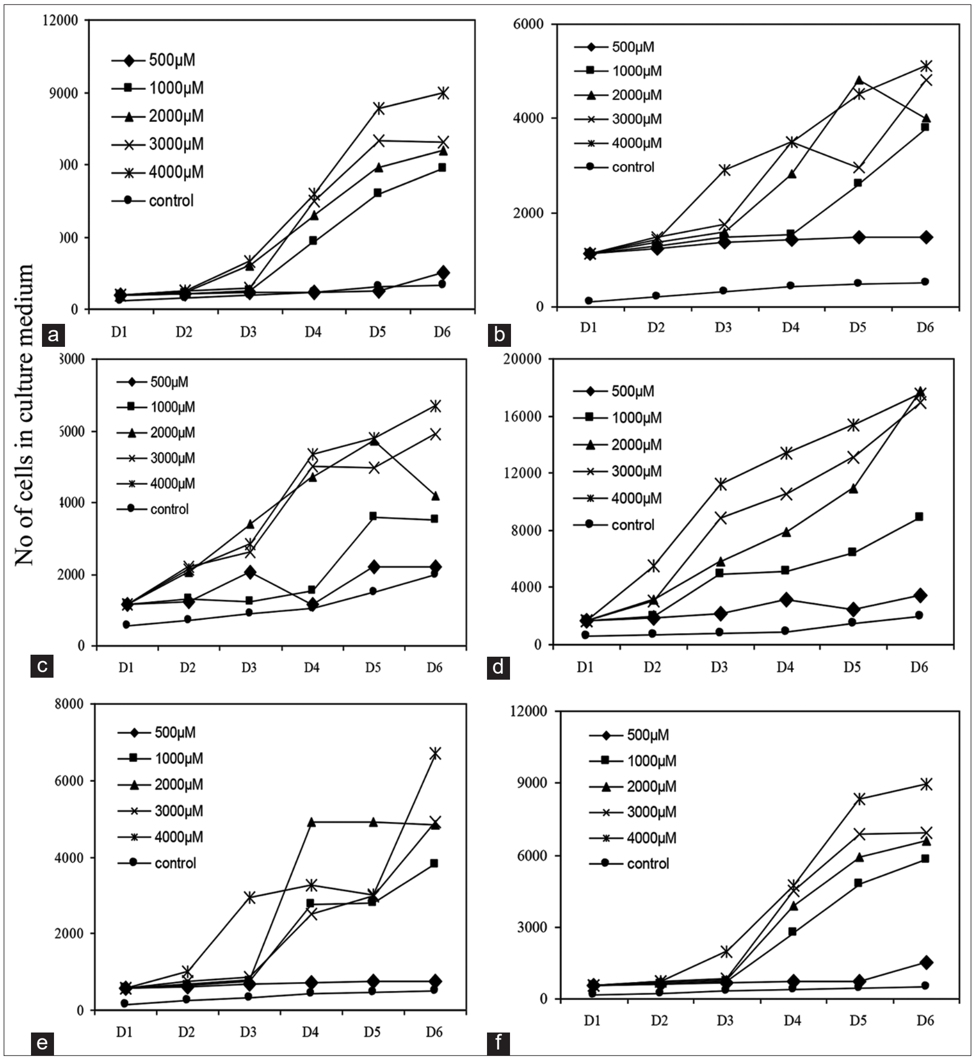

Figure 5: Growth of a) *Dytilum brightwellii*, b) *Asterionellopsis*, c) *Coscinodiscus*, d) *Skeletonema* cf *costatum*, e) *Protoperidinium*, f) *Nitzschia logissima* in the culture vessels with gibberellic acid

showed that increasing CO_2 stimulated the growth of the diatom *Skeletonema costatum* in coastal waters of southern Korea. Riebesell *et al.* (2007) demonstrated that increased CO_2 concentration enhanced the efficiency of the biological carbon pump during a diatom bloom in a coastal mesocosm experiment. In Antarctic sea ice diatom *Nitzschia* sp. ICE-H, high CO_2 concentration (1000 ppm) triggered reduced activities in both extracellular and intracellular carbonic anhydrase could suggest that the carbon concentrating mechanisms of *Nitzschia* sp. ICE-H may have a reduced effect in elevated CO_2 (Chang-Feng *et al.*, 2017). In the present study, in the control culture (without gibberellic acid) pinnate diatoms showed overall lower growth up to day 4 of the culture. At Day 5 and Day 6, 3 pinnate diatom species showed increase in cell numbers. The presence of gibberellic acid might be helping the *Nitzschia* sp. in growth and cell division in a high CO_2 environment in the current study. Cell number of Dinoflagellate *Protoeridinium* also increased at day 6 of the experiment. Some of the toxic dinoflagellate species do not show any considerable change in a high pCO_2 environment (Guanyong *et al.*, 2017), and dinoflagellate *Alexandrium tamarense* did not show any biomass increase in increased pCO_2 (i.e. 180-1200 μatm) (Eberlein *et al.*, 2014). Centric diatom, *Coscinodiscus*, cell numbers reached from 1200 to 2500 per litre from day 2 to day 3 in this experiment. Diatom *Asterionellopsis glacialis* grown under increasing CO_2 levels ranging from 320 to 3400 μatm underwent an increase in chain length, with rising CO_2 concentrations (Barcelos e Ramos *et al.*, 2014). Many of the estuarine diatom species change their cellular carbon allocation from cellular storage to increased exudation of dissolved organic carbon in increased dissolved CO_2 concentration (Chowdhury *et al.*, 2016). From these culture experiments, it can be understood, that elected species of estuarine centric diatom *Coscinodiscus* and *Skeletonema* have a shorter lag phase than the pinnate diatoms in control culture without any stimulants. In the culture vessels with gibberellic acid and with different bicarbonate concentrations, 6 selected species showed shorter lag phase than experimental vessels without gibberellic acid. An increase in cell numbers for selected species accelerated after day 2 of the experiment with the gibberellic acid. Uptake rate of bicarbonate concentration increased as a result of higher growth stimulated by gibberellic acid in set 2 culture vessels. In an experiment with *Trichodesmium erythraeum* and *Melosira sulcata*, a cyanobacterium and centric diatom species, the presence of gibberellic acid resulted in an accelerated rate of cell division, and the interval between successive divisions was reduced to 4-8 hours in the case of *T. erythraeum* and 7-14 hours in the case of *M. sulcata*, in the case of *T. erythraeum*, the optimum dose of gibberellic acid increased the initial population of 66 cells/10 mL to 672 cells in seven days, and for *M. sulcata* the optimum dose was 1.0 mg/L which increased the initial population of 55 cells/10 mL to 364 cells in six days (Ramamurthy & Seshadri, 1966). Chlorophyll concentration in the culture medium showed an increase in concentration and from 3 μg L^{-1} to 8 μg L^{-1} in the medium without gibberellic acid and 3 μg L^{-1} to 12 μg L^{-1} with gibberellic acid at the 6^{th} day of the experiment. Chlorophyll concentration increased in the gibberellic acid spiked medium, but did not reach a high peak, as *S. costatum*, the highest contributing genus, falls under the small size class, and chlorophyll content is low per cell. Chlorophyll concentrations reached much higher concentrations than previously reported values in the southern Ross Sea during the summer phytoplankton bloom in 2022-2023 (Portela *et al.*, 2025). But the result may not be the same in all cultural set-ups. Availability of light in the culture vessel may play an important role in determining chlorophyll concentration as changes in photo physiology of phytoplankton cells to changing light intensity can control Chl-a concentration per cell which may not necessarily correspond to increased phytoplankton biomass (Graff *et al.*, 2016) in natural condition.

The phytoplankton showed increased uptake with increasing bicarbonate concentration in the control medium, and the highest uptake was observed on the 6^{th} day of the experiment. The culture vessels spiked with gibberellic acid showed higher uptake relative to the control, and the difference was significant (ANOVA: F=4.17, P=0.075).

CONCLUSION

A natural phytoplankton community can fix CO_2 by uptaking bicarbonate ions from the water. The uptake rate of bicarbonate is species specific and controlled by different environmental factors. A high CO_2 environment in culture enhances the CO_2 uptake and growth. From this study, it can be concluded that, in optimum nutrient concentration, temperature, and salinity, high CO_2 concentration, along with gibberellic acid, facilitates bicarbonate uptake by estuarine diatoms, especially centric diatom species, resulting in rapid cell division and growth. So, if cell division and growth of large centric diatom species can be stimulated, the increase in species-specific bicarbonate uptake may lead to a lowering of CO_2 concentration and the effect of acidification.

REFERENCES

Adair, O. V., & Miller, M. W. (1982). Growth responses of the diatom, *Cyclotella cryptica* (Bacillariophyceae), to gibberellic acid. *Journal of Phycology, 18*(4), 587-589. https://doi.org/10.1111/j.1529-8817.1982.tb03225.x

Bach, L. T., Alvarez-Fernandez, S., Hornick, T., Stuhr, A., & Riebesell, U. (2017). Simulated ocean acidification reveals winners and losers in coastal phytoplankton. *PLoS One, 12*(11), e0188198. https://doi.org/10.1371/journal.pone.0188198

Bach, L. T., Hernández-Hernández, N., Taucher, J., Spisla, C., Sforna, C., Riebesell, U., & Arístegui, J. (2019). Effects of elevated CO_2 on a natural diatom community in the subtropical NE atlantic. *Frontiers in Marine Science, 6*, 75. https://doi.org/10.3389/fmars.2019.00075

Barcelos e Ramos, J., Schulz, K. G., Brownlee, C., Sett, S., & Azevedo, E. B. (2014). Effects of increasing seawater carbon dioxide concentrations on chain formation of the diatom *Asterionellopsis glacialis*. *PLoS One, 9*(3), e90749. https://doi.org/10.1371/journal.pone.0090749

Brewer, P. G. (1997). Ocean chemistry of the fossil fuel CO_2 signal: The haline signal of "business as usual". *Geophysical Research Letters, 24*(11), 1367-1369. https://doi.org/10.1029/97GL01179

Chang-Feng, Q., Fang-Ming, L., Zhou, Z., Yi-Bin, W., Xue-Gang, L., Hua-Mao, Y., Ning, L., Mei-Ling, A., Xi-Xi, W., Ying-Ying, H., Lu-Lu, L., & Jin-Lai, M. (2017). Effects of ocean acidification on the physiological performance and carbon production of the Antarctic sea ice diatom *Nitzschia* sp. ICE-H. *Marine Pollution Bulletin, 120*(1-2), 184-191. https://doi.org/10.1016/j.marpolbul.2017.05.018

Chowdhury, C. (2020). Comparison of phytoplankton community structure in two tropical estuaries of East Coast of India. *Current Botany, 11*, 159-170. https://doi.org/10.25081/cb.2020.v11.6382

Chowdhury, C., Majumder, N., & Jana, T. K. (2016). Seasonal distribution and correlates of transparent exopolymer particles (TEP) in the waters surrounding mangroves in the Sundarbans. *Journal of Sea Research, 112*, 65-74. https://doi.org/10.1016/j.seares.2016.01.004

Chowdhury, C., Majumder, N., Ray, R., & Jana, T. K. (2012). Inter-annual variation in some genera of diatom and zooplankton abundance in the mangrove ecosystem. *Biodiversity and Conservation, 21*, 2029-2043. https://doi.org/10.1007/s10531-012-0295-1

Eberlein, T., Van de Waal, D. B., & Rost, B. (2014). Differential effects of ocean acidification on carbon acquisition in two bloom-forming dinoflagellate species. *Physiologia Plantarum, 151*(4), 468-479. https://doi.org/10.1111/ppl.12137

Eggers, S. L., Lewandowska, A. M., Barcelos e Ramos, J., Blanco-Ameijeiras, S., Gallo, F., & Matthiessen, B. (2014). Community composition has greater impact on the functioning of marine phytoplankton communities than ocean acidification. *Global Change Biology, 20*, 713-723. https://doi.org/10.1111/gcb.12421

Falkowska, M., Pietryczuk, A., Piotrowska, A., Bajguz, A., Grygoruk, A., & Czerpak, R. (2011). The effect of gibberellic acid (GA_3) on growth, metal biosorption and metabolism of the green algae *Chlorella vulgaris* (Chlorophyceae) Beijerinck exposed to cadmium and lead stress. *Polish Journal of Environmental Studies, 20*(1), 53-59.

Fierli, D., Aranyos, A., Barone, M. E., Parkes, R., & Touzet, N. (2022). Influence of exogenous phytohormone supplementation on the pigment and fatty acid content of three marine diatoms. *Applied Microbiology and Biotechnology, 106*, 6195-6207. https://doi.org/10.1007/s00253-022-12140-5

Flynn, K. J., Blackford, J. C., Baird, M. E., Raven, J. A., Clark, D. R., Beardall, J., Brownlee, C., Fabian, H., & Wheeler, G. L. (2012). Changes in pH at the exterior surface of plankton with ocean acidification. *Nature Climate Change, 2*, 510-513. https://doi.org/10.1038/nclimate1489

Gao, K., & Campbell, D. A. (2014). Photophysiological responses of marine diatoms to elevated CO_2 and decreased pH: a review. *Functional Plant Biology, 41*(5), 449-459. https://doi.org/10.1071/FP13247

Giordano, M., Beardall, J., & Raven, J. A. (2005). CO_2 concentrating mechanisms in algae: mechanisms, environmental modulation, and evolution. *Annual Review of Plant Biology, 56*, 99-131. https://doi.org/10.1146/annurev.arplant.56.032604.144052

Graff, J. R., Westberry, T. K., Milligan, A. J., Brown, M. B., Dall'Olmo, G., Reifel, K. M., & Behrenfeld, M. J. (2016). Photo-acclimation of natural phytoplankton communities. *Marine Ecology Progress Series, 542*, 51-62. https://doi.org/10.3354/meps11539

Guanyong, O., Hong, W., Ranran, S., & Wanchun, G. (2017). The dinoflagellate *Akashiwo sanguinea* will benefit from future climate change: The interactive effects of ocean acidification, warming and high irradiance on photophysiology and hemolytic activity. *Harmful Algae, 68*, 118-127. https://doi.org/10.1016/j.hal.2017.08.003

Hein, M., & Sand-Jensen, K. (1997). CO_2 increases oceanic primary production. *Nature, 388*, 526-527. https://doi.org/10.1038/41457

Hopkinson, B. M., Dupont, C. L., Allen, A. E., & Morel, F. M. M. (2011). Efficiency of the CO_2-concentrating mechanism of diatoms. *Proceedings of National Academy of Sciences of the United States of America, 108*(10), 3830-3837. https://doi.org/10.1073/pnas.1018062108

IPCC. (2014). *Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324

Kadioglu, A. (1992). The effect of gibberellic acid on photosynthetic pigments and oxygen evolution in *Chlamydomonas* and *Anacystis*. *Biologia plantarum, 34*, 163-166. https://doi.org/10.1007/BF02925815

Kim, J.-M., Lee, K., Shin, K., Kang, J.-H., Lee, H.-W., Kim, M., Jang, P.-G., & Jang, M.-C. (2006). The effect of seawater CO_2 concentration on growth of a natural phytoplankton assemblage in a controlled mesocosm experiment. *Limnology and Oceanography, 51*(4), 1629-1636. https://doi.org/10.4319/lo.2006.51.4.1629

Liu, J., & Vyverman, W. (2015). Differences in nutrient uptake capacity of the benthic filamentous algae *Cladophora* sp., *Klebsormidium* sp. and *Pseudanabaena* sp. under varying N/P conditions. *Bioresource Technology, 179,* 234-242. https://doi.org/10.1016/j.biortech.2014.12.028

Mansouri, H., & Talebizadeh, R. (2017). Effects of indole-3-butyric acid on growth, pigments and UV-screening compounds in *Nostoc linckia*. *Phycological Research, 65*(3), 212-216. https://doi.org/10.1111/pre.12177

Ogbonda, K. H., Aminigo, R. E., & Abu, G. O. (2007). Influence of temperature and pH on biomass production and protein biosynthesis in a putative *Spirulina* sp. *Bioresource Technology, 98*(11), 2207-2211. https://doi.org/10.1016/j.biortech.2006.08.028

Pan, X., Chang, F., Kang, L., Liu, Y., Li, G., & Li, D. (2008). Effects of gibberellin A_3 on growth and microcystin production in *Microcystis aeruginosa* (cyanophyta). *Journal of Plant Physiology, 165*(16), 1691-1697. https://doi.org/10.1016/j.jplph.2007.08.012

Parsons, T. R., Maita, Y., & Lalli, C. M. (1992). *A manual of chemical and biological methods for sea water analysis.* New York, US: Pergamon Press.

Pasciak, W. J., & Gavis, J. (1974). Transport limitation of nutrient uptake in phytoplankton. *Limnology and Oceanography, 19*(6), 881-888. https://doi.org/10.4319/lo.1974.19.6.0881

Portela, E., Meyer, M. G., Heywood, K. J., & Smith, W. O. (2025). Unprecedented summer phytoplankton bloom in the Ross Sea. *Geophysical Research Letters, 52*(3), e2024GL111264. https://doi.org/10.1029/2024GL111264

Price, N. N., Hamilton, S. L., Tootell, J. S., & Smith, J. E. (2011). Species-specific consequences of ocean acidification for the calcareous tropical green algae *Halimeda*. *Marine Ecological Progress Series, 440*, 67-78. https://doi.org/10.3354/meps09309

Ramamurthy, V. D., & Seshadri, R. (1966). Effects of gibberellic acid (GA) on laboratory cultures of *Trichodesmium erythraeum* (Ehr.) and *Melosira sulcata* (Ehr.). *Indian Academy of Science: Proceedings-Section B, 64*(3), 146-151.

Reimann, B. E. F., Lewin, J. M. C., & Guillard, R. R. L. (1963). *Cyclotella cryptica*, a new brackish-water diatom species. *Phycologia, 3*(2), 75-84. https://doi.org/10.2216/i0031-8884-3-2-75.1

Reinfelder, J. R. (2011). Carbon concentrating mechanisms in eukaryotic marine phytoplankton. *Annual Review of Marine Science, 3*, 291-315. https://doi.org/10.1146/annurev-marine-120709-142720

Riebesell, U., Schulz, K. G., Bellerby, R. G. J., Botros, M., Fritsche, P., Meyerhöfer, M., Neill, C., Nondal, G., Oschlies, A., Wohlers, J., & Zöllner, E. (2007). Enhanced biological carbon consumption in a high CO_2 Ocean. *Nature, 450*, 545-548. https://doi.org/10.1038/nature06267

Rost, B., Riebesell, U., Burkhardt, S. S., & Sültemeyer, D. (2003). Carbon acquisition of bloom-forming marine phytoplankton. *Limnology and Oceanography, 48*(1), 55-67. https://doi.org/10.4319/lo.2003.48.1.0055

Rost, B., Zondervan, I., & Wolf-Gladrow, D. (2008). Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions. *Marine Ecology Progress Series, 373*, 227-237.

Shapiro, J. (1984). Blue-green dominance in lakes: the role and management significance of pH and CO_2. *International Review of Hydrobiology, 69*(6), 765-780. https://doi.org/10.1002/iroh.19840690602

Shen, C., & Hopkinson, B. M. (2015). Size scaling of extracellular carbonic anhydrase activity in centric marine diatoms. *Journal of Phycology, 51*(2), 255-263. https://doi.org/10.1111/jpy.12269

Shetye, S., Sudhakar, M., Jena, B., & Mohan, R. (2013). Occurrence of nitrogen fixing cyanobacterium *Trichodesmium* under elevated pCO_2 conditions in the Western Bay of Bengal. *International Journal of Oceanography, 2013*(1), 350465. https://doi.org/10.1155/2013/350465

Tan, S.-I., Han, Y.-L., Yu, Y.-J., Chiu, C.-Y., Chang, Y.-K., Ouyang, S., Fan, K. C., Lo, K.-H., & Ng, I.-S. (2018). Efficient carbon dioxide sequestration by using recombinant carbonic anhydrase. *Process Biochemistry, 73*, 38-46. https://doi.org/10.1016/j.procbio.2018.08.017

Thangaraj, S., & Sun, J. (2020). The biotechnological potential of the marine diatom *Skeletonema dohrnii* to the elevated temperature and pCO_2. *Marine Drugs, 18*(5), 259. https://doi.org/10.3390/md18050259

Tortell, P. D. (2000). Evolutionary and ecological perspectives on carbon acquisition in phytoplankton. *Limnology and Oceanography, 45*(3), 744-50l. https://doi.org/10.4319/lo.2000.45.3.0744

Tortell, P. D., DiTullio, G. R., Sigman, D. M., & Morel, F. M. M. (2002). CO_2 effects on taxonomic composition and nutrient utilization in an equatorial Pacific phytoplankton assemblage. *Marine Ecological Progress Series, 236*, 37-43.

Trimborn, S., Brenneis, T., Sweet, E., & Rost, B. (2013). Sensitivity of Antarctic phytoplankton species to ocean acidification: growth, carbon acquisition, and species interaction. *Limnology and Oceanography, 58*(3), 997-1007. https://doi.org/10.4319/lo.2013.58.3.0997

Wolf-Gladrow, D. A., Riebesell, U., Burkhardt, S., & Bijma, J. (1999). Direct effects of CO_2 concentration on growth and isotopic com-position of marine plankton. *Tellus B: Chemical and Physical Meteorology, 51*(2), 461-476. https://doi.org/10.3402/tellusb.v51i2.16324

Wolf-Gladrow, D., & Riebesell, U. (1997). Diffusion and reactions in the vicinity of plankton: a refined model for inorganic carbon transport. *Marine Chemistry, 59*(1-2), 17-34. https://doi.org/10.1016/S0304-4203(97)00069-8

Wu, Y., Campbell, D. A., Irwin, A. J., Suggett, D. J., & Finkel, Z. V. (2014). Ocean acidification enhances the growth rate of larger diatoms. *Limnology and Oceanography, 59*(3), 1027-1034. https://doi.org/10.4319/lo.2014.59.3.1027