

# Carbon Dioxide Fixation by Phytoplankton

Subjects: Green & Sustainable Science & Technology

Contributor: Supriyo Ray

Marine phytoplankton account for more than half of the carbon dioxide fixation of Earth. The export of carbon is highest at the photic zone of the ocean, which is dominated by phytoplankton. Plankton can also be zooplanktons that feed on phytoplankton and release fecal pellets that are made of dissolved carbon particles. The growth of the phytoplankton mainly depends upon three factors, i.e., nutrients, sunlight, and carbon dioxide. Phytoplankton-like plants have chlorophyll that fixes carbon dioxide to glucose using the Rubisco enzyme.

Keywords: phytoplankton ; carbon dioxide fixation ; cyanobacteria ; dinoflagellates ; diatoms ; RubisCO ; carbonic anhydrase ; Coral reefs ; bioindicator ; global warming

---

## 1. Cyanobacteria

Cyanobacteria are a class of prokaryotic microorganisms that are blue-green photo-autotrophic Gram-negative bacteria or algae. These are the predecessors of green plants and possess carboxysomes, which are carbon dioxide concentration mechanisms. The enzymes used for carbon capture are the same as in plants, namely, RubisCO, and carbonic anhydrase. Carbon-concentrating mechanisms exist in cyanobacteria, similar to algae that increase the carboxylase activity of RubisCO enzyme by increasing carbon dioxide concentration near the fixing enzyme.

Among all the naturally found carbon-sequestering organisms, algae seem to be most efficient in converting carbon dioxide to biomass and fuel. Microalgae include microorganisms such as diatoms, euglenoids, and green, blue, golden, red, brown, and yellow algae, which fix carbon dioxide using RubisCO and are mostly single-celled. With a biomass accumulation rate that is 100-fold faster than terrestrial plants, microalgae are a very promising candidate for carbon-sequestering units <sup>[1][2]</sup>. Algae are high in lipids and could have direct use in the production of biofuels <sup>[3]</sup>. Biochar derived from algae has been studied and found to have excellent properties to be used as a fertilizer <sup>[4]</sup>. Microalgae have carbon-concentrating mechanisms, which increase the concentration of carbon dioxide near the RubisCO enzyme by separating it into a different membrane compartment, into which carbon dioxide and bicarbonates are transported. *Uluva* and *Laminaria* species of microalgae are prime choices for bioenergy production <sup>[5]</sup>.

Every 1 kg of algae can fix 1.83 kg of carbon dioxide in ideal conditions <sup>[6][7]</sup>. Atmospheric carbon dioxide concentrations range from 0.03–0.06% (v/v), and algae can grow efficiently at 2% or higher. Certain species such as *Scenedesmus* sp. have a carbon dioxide tolerance even at 10–20% (v/v) concentration of carbon dioxide. An increase in biomass is the most significant pointer to indicate carbon dioxide sequestering <sup>[8]</sup>.

## 2. Dinoflagellates

Dinoflagellate are a major part of oceanic phytoplankton that use Rubisco form II as a primary enzyme for carbon fixation <sup>[9]</sup>. The form II has both lower specificity and affinity for carbon dioxide/oxygen. This suggests that they have an advanced mechanism to increase carbon dioxide concentration, since they cannot fix carbon dioxide at lower ambient carbon dioxide concentration <sup>[10]</sup>. Of the various isomers of carbonic anhydrase ( $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$ ),  $\delta$ -carbonic anhydrase has been implicated in lowering carbon dioxide concentration <sup>[9]</sup>. The enzyme carbonic anhydrase (CA) catalyzes rapid conversion of carbon dioxide and bicarbonate ion <sup>[11]</sup>. Many dinoflagellates have carbon-concentrating mechanisms (CCMs) to transport carbon into the cell <sup>[9]</sup>. One of the biggest bio-indicators of global warming is the bleaching of coral reefs. Coral reefs that belong to Kingdom Animalia are a complex system of multiple species belonging to phylum coelenterates. The base of the ecosystem is built upon dinoflagellates that live as intracellular photosynthetic symbionts. Loss of these dinoflagellates is believed to be the primary cause of coral bleaching that eroded 85% of the Great Barrier Reef in Australia in 2016 <sup>[12][13]</sup>. How do coral reefs become bleached? A slight change in water temperature (2 °F) disturbs the photosynthetic electron transfer and in the process damages the *PsbA* (D1), a photosystem II reaction center protein. This disruption of photosynthesis triggers the bleaching of coral reefs <sup>[14][15][16][17][18]</sup>.

While genetically engineering cyanobacteria has some success, engineering genes to improve the carbon fixation in diatoms and dinoflagellates has been a challenge due to the lack of critical gene transformation strategies. Initial studies of transformation using silicon carbide whiskers were suggested, but the experiments were difficult to reproduce [19][20]. Experiments with glass beads were performed for transient expressions, but even these were hard to reproduce [12][21].

Recent studies showed that the stable transformation of dinoflagellates is reproducibly possible when they bombarded microparticle-containing plasmid-like minicircles that carried chloroplast gene *psbA*. They successfully transformed two minicircles providing resistance to chloramphenicol and astrazine and in the process assisting the selection of successful transformants. Inability to stably transform has less to do with the inherent genetics of protists than it has to do with the DNA's inability to cross the membrane barrier [12].

### 3. Diatoms

Diatoms exhibit a wide range of metabolic diversity due to their evolution that includes endosymbiosis among diverse lineages. This is why they can be used to make a wide range of compounds. Previous studies have shown that manipulating carbon dioxide levels of *Navicula pelliculosa*, *P. tricornutum*, *T. pseudonana*, and *Asterionella formosa* [22] can increase the accumulation of both lipids and carbohydrates. Diatoms *T. weissflogii* and *P. tricornutum* have exhibited excellent absorption systems for carbon dioxide and bicarbonate at quantities typical of ocean surface waters. It has also been observed that their absorption rates can adjust to a wide range of inorganic carbon supplies [23]. Mixotrophic cultivation regimes, in addition to photoautotrophy, can aid in the production of higher biomass concentrations and productivities [24][25][26].

Marine photosynthetic organisms such as diatom and other microalgae uptake carbon dioxide using a mechanism called carbon-concentrating mechanism or CCM [24][25]. In diatoms, the carbon dioxide travels inside the cells similar to plants and concentrates near the site where Rubisco is located for fixation. This mechanism is important because it helps regulate the carbon flux and raise it to higher concentrations inside the cell compared to the outside for optimal Rubisco activity [24][25][26][27][28]. Very few mechanisms are known for the majority of diatoms. For the ones that are known, they use the Rubisco Calvin–Benson–Bassham (CBB) cycle in their chloroplasts, carbonic anhydrases, Glyceraldehyde-3-phosphate dehydrogenase (GAPDH), Phosphoglycerate kinase, Fructose 1,6 bis phosphatase, Sedoheptulose-1,7-biphosphatase, and various transporters [20][21][25][26].

Presently, there is a dearth of literature with regards to carbon fixation in diatoms. Studies have shown that the assimilation of carbon dioxide is not linearly proportional to the availability. *P. tricornutum* showed a higher fixation rate with supplemented carbon dioxide concentration but had reduced biomass productions. The carbon fixation rate did not change when subjected to diverse pH ranges. There is diversity among diatoms for carbon substrate specificity for fixation purposes. While *P. tricornutum* assimilates in the form of bicarbonate, *T. pseudonana* takes up carbon dioxide predominantly [22][23][24][25][26][27][28].

---

## References

1. Benedetti, M.; Vecchi, V.; Barera, S.; Dall'Osto, L. Biomass from microalgae: The potential of domestication towards sustainable biofactories. *Microb. Cell Factories* 2018, 17, 173.
2. Giordano, M.; Beardall, J.; Raven, J.A. CO<sub>2</sub> concentrating mechanisms in algae: Mechanisms, environmental modulation, and evolution. *Annu. Rev. Plant. Biol.* 2005, 56, 99–131.
3. Khan, M.I.; Shin, J.H.; Kim, J.D. The promising future of microalgae: Current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microb. Cell Factories* 2018, 17, 36.
4. Mona, S.; Malyan, S.K.; Saini, N.; Deepak, B.; Pugazhendhi, A.; Kumar, S.S. Chemosphere Towards sustainable agriculture with carbon sequestration, and greenhouse gas mitigation using algal biochar. *Chemosphere* 2021, 275, 129856.
5. Gerotto, C.; Norici, A.; Giordano, M. Toward Enhanced Fixation of CO<sub>2</sub> in Aquatic Biomass: Focus on Microalgae. *Front. Energy Res.* 2020, 8, 213.
6. Cheah, W.Y.; Show, P.L.; Chang, J.; Ling, T.C.; Juan, J.C. Biosequestration of atmospheric CO<sub>2</sub> and flue gas-containing CO<sub>2</sub> by microalgae. *Bioresour. Technol.* 2014, 184, 190–201.
7. Jiang, Y.; Zhang, W.; Wang, J.; Chen, Y.; Shen, S.; Liu, T. Bioresource Technology Utilization of simulated flue gas for cultivation of *Scenedesmus dimorphus*. *Bioresour. Technol.* 2013, 128, 359–364.

8. Loganathan, N.; Tsai, Y.C.; Mueller-cajar, O. Characterization of the heterooligomeric red-type rubisco activase from red algae. *Proc. Natl. Acad. Sci. USA* 2016, 113, 14019–14024.
9. Morse, D.; Salois, P.; Markovic, P.; Hastings, J.W. A nuclear-encoded form II RuBisCO in dinoflagellates. *Science* 1995, 268, 1622–1624.
10. Whitney, S.M.; Andrews, T.J. The CO<sub>2</sub> specificity of single-subunit ribulose-bisphosphate carboxylase from the dinoflagellate. *Funct. Plant Biol.* 1998, 25, 131–138.
11. Lapointe, M.; Mackenzie, T.D.; Morse, D. An external delta-carbonic anhydrase in a free-living marine dinoflagellate may circumvent diffusion-limited carbon acquisition. *Plant Physiol.* 2008, 147, 1427–1436.
12. Nimmo, I.C.; Barbrook, A.C.; Lassadi, I.; Chen, J.E.; Geisler, K.; Smith, A.G.; Aranda, M.; Purton, S.; Waller, R.F.; Nisbet, R.E.R.; et al. Genetic transformation of the dinoflagellate chloroplast. *eLife* 2019, 8, e45292.
13. Hughes, T.P.; Kerry, J.T.; Álvarez-Noriega, M.; Álvarez-Romero, J.G.; Anderson, K.D.; Baird, A.H.; Babcock, R.C.; Begeer, M.; Bellwood, D.R.; Berkelmans, R.; et al. Global warming and recurrent mass bleaching of corals. *Nature* 2017, 543, 373–377.
14. Spalding, M.D.; Brown, B.E. Warm-water coral reefs and climate change. *Science* 2015, 350, 769–771.
15. Slavov, C.; Schrameyer, V.; Reus, M.; Ralph, P.J.; Hill, R.; Büchel, C.; Larkum, A.W.; Holzwarth, A.R. “Super-quenching” state protects Symbiodinium from thermal stress—Implications for coral bleaching. *Biochim. Biophys. Acta* 2016, 1857, 840–847.
16. Rehman, A.U.; Szabó, M.; Deák, Z.; Sass, L.; Larkum, A.; Ralph, P.; Vass, I. Symbiodinium sp. cells produce light-induced intra- and extracellular singlet oxygen, which mediates photodamage of the photosynthetic apparatus and has the potential to interact with the animal host in coral symbiosis. *New Phytol.* 2016, 212, 472–484.
17. Warner, M.E.; Fitt, W.K.; Schmidt, G.W. Damage to photosystem II in symbiotic dinoflagellates: A determinant of coral bleaching. *Proc. Natl. Acad. Sci. USA* 1999, 96, 8007–8012.
18. Howe, C.J.; Nisbet, R.E.; Barbrook, A.C. The remarkable chloroplast genome of dinoflagellates. *J. Exp. Bot.* 2008, 59, 1035–1045.
19. Te, M.R.; Lohuis; Miller, D.J. Genetic transformation of dinoflagellates (Amphidinium and Symbiodinium): Expression of GUS in microalgae using heterologous promoter constructs. *Plant J.* 1998, 13, 427–435.
20. Walker, T.L.; Collet, C.; Purton, S. Algal transgenics in the genomic era<sup>1</sup>. *J. Phycol.* 2005, 41, 1077–1093.
21. Ortiz-Matamoros, M.F.; Villanueva, M.A.; Islas-Flores, T. Transient transformation of cultured photosynthetic dinoflagellates (Symbiodinium spp.) with plant-targeted vectors. *Cienc. Mar.* 2015, 41, 21–32.
22. Jensen, E.L.; Yangüez, K.; Carrière, F.; Gontero, B. Storage Compound Accumulation in Diatoms as Response to Elevated CO<sub>2</sub> Concentration. *Biology* 2019, 9, 5.
23. Burkhardt, S.; Amoroso, G.; Riebesell, U.; Sültemeyer, D. CO<sub>2</sub> and HCO<sub>3</sub><sup>–</sup> uptake in marine diatoms acclimated to different CO<sub>2</sub> concentrations. *Limnol. Oceanogr.* 2001, 46, 1378–1391.
24. Clement, R.; Jensen, E.; Prioretti, L.; Maberly, S.C.; Gontero, B. Diversity of CO<sub>2</sub>-concentrating mechanisms and responses to CO<sub>2</sub> concentration in marine and freshwater diatoms. *J. Exp. Bot.* 2017, 68, 3925–3935.
25. Granum, E.; Raven, J.A.; Leegood, R.C. How do marine diatoms fix 10 billion tonnes of inorganic carbon per year? *Can. J. Bot.* 2005, 83, 898–908.
26. Hopkinson, B.M.; Dupont, C.L.; Matsuda, Y. The physiology and genetics of CO<sub>2</sub> concentrating mechanisms in model diatoms. *Curr. Opin. Plant Biol.* 2016, 31, 51–57.
27. Li, Y.; Zhou, Z.; Li, Y.; Wang, Y.; Xu, M.; Zhou, B.; Lu, K.; Wang, Y. The Bloom-Forming Dinoflagellate *Karenia mikimotoi* Adopts Different Growth Modes When Exposed to Short or Long Period of Seawater Acidification. *Toxins* 2021, 13, 629.
28. Pierella Karlusich, J.J.; Bowler, C.; Biswas, H. Carbon Dioxide Concentration Mechanisms in Natural Populations of Marine Diatoms: Insights from Tara Oceans. *Front. Plant Sci.* 2021, 12, 657821.