

Influence of physical and chemical environment of a water body together with the growth pattern of individuals plays important roles in phytoplankton dynamics.

2.1 Physical Factors

Among the physical factors light and temperature are the major ones which control the phytoplankton growth.

2.1.1 Light and Temperature

Pelagic ecosystems are dominated by phytoplankton populations that cover 70 % of the world's surface (Reynolds 2006). Falkowski (1995) also opined that 45 % of the earth's photosynthesis is accounted by phytoplankton populations around the world. Light absorption ability of natural phytoplankton populations is directly related to the spectral nature of the light-harvesting capabilities of the pigment molecules present in the phytoplankton population (Bergmann et al. 2004). It is well known among plant biologists that maximum light absorption of chlorophyll is achieved in blue-violet and red regions of the spectrum, while the accessory pigments like carotenoids and xanthophylls absorb mainly in the blue-green region with phycobiliproteins showing maximum absorption efficiency in yellow-red region of the spectrum. The exponential decrease in light intensity due to depth

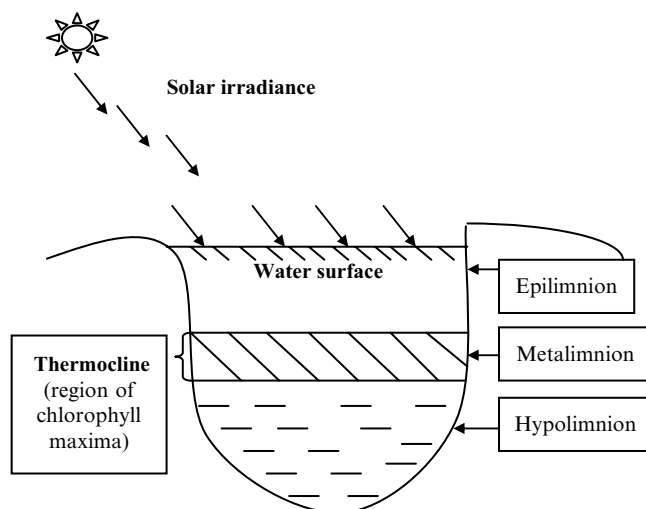
can be attributed to absorption and refraction, a phenomenon known as vertical light attenuation which can be mathematically expressed as

$$E_d(z) = E_d(0) \cdot e^{-kz} \quad [\text{Beer Lambert's Law}]$$

where $E_d(0)$ and $E_d(z)$ are light intensity at surface and at depth z respectively.

Light and temperature are the most widely studied environmental parameter that affects algal growth, both in situ and in vitro studies. Surface waters of different ecosystems get light and heat from solar irradiation on earth surface, and as a result different distinct vertical zones are developed. Actually sunlight enters into the water of ocean or lake and is converted into heat, as a result of which euphotic zone develops. In an aquatic ecosystem, the depth up to which light penetrates is called 'euphotic zone'. It is considered as the depth up to which 1 % of the surface irradiance is reached in the water column. Turbidity of the water column can act as an important regulator of the light availability in the water column in an aquatic ecosystem. An increase in turbidity is mainly caused due to SPM (suspended particulate matter) load and colloidal matter in the water column, including both inorganic (e.g. dispersed sediment particles) and organic (e.g. phytoplankton, zooplankton). Thus, it can be said that there will be an exponential decrease in light availability with depth at a rate which is dependent on the particle content of the water column. Thus, the euphotic zone may reach from a few meters in coastal and estuarine waters

Fig. 2.1 Specific zonations on the basis of light and temperature variations at different depths of the water column



to more than 100 m in the Mediterranean Sea and the Pacific gyre. Many plankton biologists have considered this depth as the lower limit beyond which phytoplankton cells become incapable of photosynthetic activity. Exceptionally, there are reports that picoplanktonic form like *Prochlorococcus* can photosynthesize at 0.01 % of surface irradiance availability (Goericke et al. 2000). With an increase in depth, light availability decreases and the spectral range narrows to the blue region since the blue wavelength is least attenuated in a water column. So it can be said that phytoplankton cells have the ability to acclimatize to depth and light availability by increasing their pigment content and by shifting their pigment composition (e.g. *Prochlorococcus* has the ability to increase their Chl b:Chl a ratio since chlorophyll b absorbs optimally blue wavelength). Under high irradiance (top 20 m in oligotrophic waters), photosynthetic activity of phytoplanktons becomes photoinhibited due to damage of the photosystem core proteins by UV exposure. Cells counteract these detrimental effects by increasing the amount of photoprotective pigments such as zeaxanthin or diatoxanthin. Thus, the diversity in a water column is dependent on the vertical distribution of algal population. On the basis of light variation, vertical distribution can be separated into two different heads: high light, epilimnion, and low light,

hypolimnion. Cells present in the hypolimnion undergo passive sedimentation due to cellular senescence or overwintering phase. Different planktonic species of the epilimnion like the dinoflagellates may migrate to the hypolimnion periodically for nutrient supplementation under nutrient replete conditions of the epilimnion. Thus, sampling by depth samplers and sedimentation chambers at different depths of the water column can provide important insights in the overall ecosystem functioning.

Temperature also follows the similar trend as was found for light, and the variation in temperature is directly related to solar irradiance. This process divides the water body into distinct layer or strata, called stratification. In lakes, the euphotic zone is divided into upper warm and less dense layer, termed epilimnion, and the lower cooler and denser layer is called the hypolimnion (Fig. 2.1). Between these two layers is an intermediate layer, the metalimnion, with a sharp decline in water temperature that gives rise to a prominent temperature gradient called the 'thermocline'. If metalimnion region lies in the euphotic zone, then maximum phytoplankton concentrates here, giving rise to the zone of 'chlorophyll maxima'.

A vertical gradient in ocean ecosystem due to differences in salinity or temperature is called 'pycnocline'. Thermal stratification in aquatic ecosystem has important consequences for

phytoplankton growth and abundance. The upper warmer region with maximum light intensity is most suitable for plankton growth. Moreover, the nutrient mixing is predominant in this region due to various forms of water motion developed by interactions of air current and other forces.

In recent times, excessive fossil fuel burning has enhanced the emission of ‘green house gases’, mainly CO_2 , that have become a major cause of concern among ecologists. This is mainly due to the high solubility of atmospheric CO_2 in oceanic water that results in an increase of sea surface temperature (SST). Increase in SST is responsible for thermal expansion of water that results in dissolution of more land mass along the low-lying coastal areas. Reports from the Sunderbans provide further evidence to this alarming issue where an average of 0.09°C rise in sea surface temperature has been observed, much higher than the global average of $0.6 \pm 0.2^\circ\text{C}$ (IPCC 2001). This has resulted in a sea level rise of 1.9 mm/year in the past 5 years around Sagar Island that have resulted in extinction of islands like Lohachara, Bedford, Kabasgadi and Mathabhanga. Moreover, such increase in temperature can alter the partial pressure in CO_2 as well as the mixed layer depth that causes drastic shifts in phytoplankton communities (Tortell et al. 2002; Kim et al. 2006). Other works have also suggested that similar increases in temperature may result in shifts in population from diatom dominance to diatom recedence due to decrease in nitrate reductase at elevated temperatures (Lomas and Gilbert 1999). Many workers have also opined that phytoplankton taxa may respond differently to temperature changes by expanding or contracting their ranges (Hays et al. 2005) or by shifting size and/or community composition, although these responses may not be consistent between different algal groups and trophic levels (Edwards and Richardson 2004).

2.1.2 Turbulence

A combination of forces from rotation of the earth, winds, solar irradiation and the tidal cycle generate different types of water motion which affect the

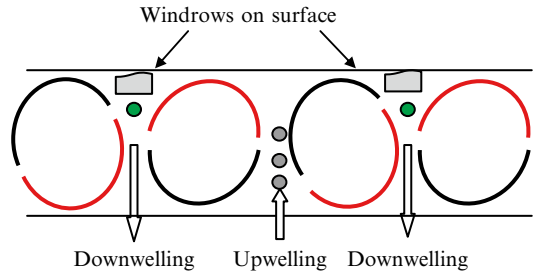


Fig. 2.2 Cross-sectional views of adjacent Langmuir cells which rotate in opposite directions, creating regions of downwelling (where the windrows occur) and upwelling. Accumulation of foam and positively buoyant algae (green circles) occurs in the downwelling region, whereas negatively buoyant algae (grey circles) accumulate in the upwelling regions beneath the surface

phytoplankton population to a greater extent. The buoyant genera with different floating devices like presence of vacuoles, flagella, other processes (setae, horns, etc.) and with less dense cell sap (with high concentration of K^+ ion instead of Na^+ ion) generally overcome the combined force and float on the water surface. Different planktons differ in their tolerance of turbulence due to structural and physiological variations (Fogg 1991), directly affecting the growth pattern and bloom formation. Following are the water motions that significantly affect the ecology of phytoplanktons:

When the wind speed of adjacent water bodies like lakes, etc., is $11 \text{ km} \cdot \text{h}^{-1}$ or more, then some elongated wind-driven surface rotations are formed and move spirally according to wind directions in opposite ways. These are marked by conspicuous lines of foams called ‘windrows’, developed from wave action. This type of wind-driven surface rotations is called convection cells or Langmuir cells. Adjacent convection cells rotate in opposite directions creating alternate upwelling and downwelling regions. Buoyant phytoplankton like *Microcystis* sp. (with cyanophycean vesicles) can survive in the region of downwelling. In the region of upwelling, negatively buoyant planktons concentrate (Fig. 2.2).

When wind blows in a particular direction, it generates the waves on the water body which move from one side to the other (north to south). But after crushing of the wave on the opposite shore, the force will return again to the north

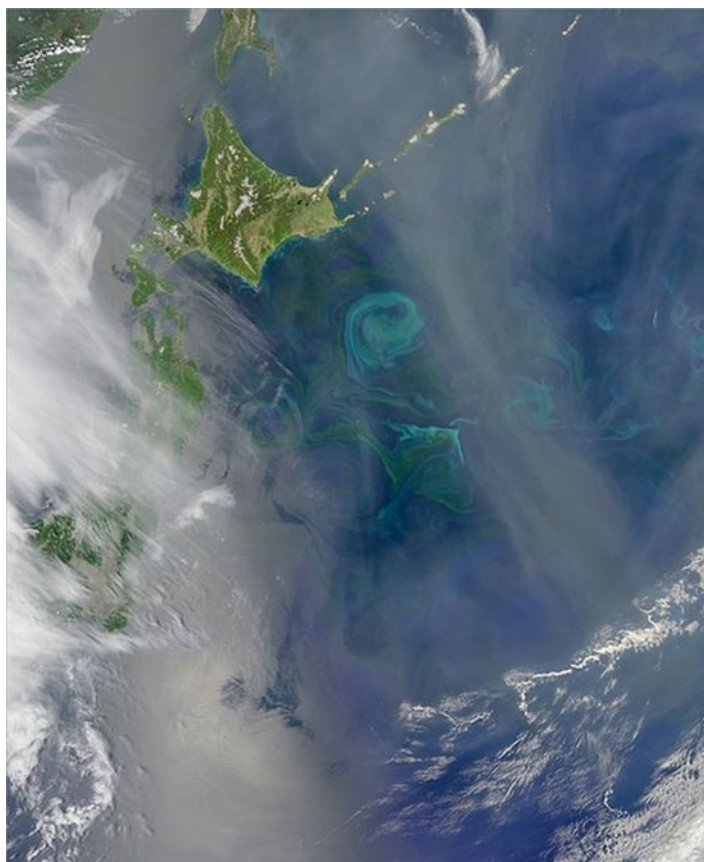


Fig. 2.3 The convergence of the Oyashio and Kuroshio currents. When two currents with different temperatures and densities (cold, Arctic water is saltier and denser than subtropical waters) collide, they create eddies. Phytoplankton growing in the surface waters becomes concen-

trated along the boundaries of these eddies. The swirls of colour visible in the waters southeast of Hokkaido (*upper left*), show different kinds of phytoplankton that are using chlorophyll and other pigments to capture sunlight for photosynthesis (Source: www.wikipedia.com)

shore with a subsurface return force and act like a conveyor belt. Some fraction of this force also flows to east and west coast. Here also buoyant species like *Microcystis* sp. can survive against the wind force, but the dinoflagellate member like *Ceratium* sp. floats with the help of return force along the subsurface area.

In oceanic environment, sometimes by tremendous wind speed along with gravitational and other forces, a special type of water current develops. Due to this current, a portion of the entire ecosystem including phytoplanktons, zooplanktons, fishes and other aquatic organisms is pinched off from the whole system with varying diameters (100–200 km) and forms discrete ecosystems. These wind-driven water currents are

called ‘eddies’ or ‘loops’. Besides this, the coastal water is enriched by nutrients by upwelling water together with wave action towards the coast or away from the coast (Fig. 2.3). This is brought about by the combined action of wind and the Coriolis force of the earth’s rotation. For these reasons, nutrient statuses of coastal waters vary from place to place, thereby controlling the phytoplankton diversity.

2.2 Major Nutrients

Four major nutrient elements like carbon, nitrogen, phosphorus and silica (C, N, P and Si) are regarded as the major chemical factors that

control the phytoplankton productivity in any type of aquatic ecosystem. Thus, the spatial and temporal distributions of these elements play an important role in plankton dynamics. Other factors like uptake, growth, grazing and sedimentation also interact with the chemical nutrients. Many authors investigated the relationships between the distribution of phytoplankton and major nutrients. The distribution of individual species can sometimes be correlated with the concentration of the major ions. Thus, Harris and Vollenweider (1982) observed that increase in *Coscinodiscus* (estuarine inhabitant) cell counts in English Lakes was due to urban run-offs and the use of salts on the roads in winter. Light and nutrients are perhaps the two most important parameters that regulate the quantity, the distribution and structure of phytoplankton populations in natural aquatic habitats (Huisman and Weissing 1995; Diehl 2002; Hansen 2002). Unlike light and temperature which tend to have a unidirectional flow in a natural ecosystem, nutrients can be recycled. In natural aquatic habitats, nutrients can be well mixed in a water column with homogeneous distribution (mixing condition) or it can accumulate in deeper layers (under stratified conditions).

2.2.1 Redfield Ratio

The Redfield ratio has remained as one of the tenets among both biologists and geochemists with regard to aquatic biogeochemistry. Named in honour of Alfred Redfield, this concept attempts to establish the relationship between organism composition and water chemistry. Redfield (1958) opined that the elemental composition of plankton was ‘uniform in a statistical sense’ and that quantitative variations in inorganic C, N and P content in seawater were ‘almost entirely as a result of the synthesis or decomposition of organic matter’. In this observation the C:N:P content in plankton was reported as 106:16:1.

With regard to Redfield ratio, biologists and geochemists interpret it differently. Geochemists use a C:N:P stoichiometry 105:15:1 based on the

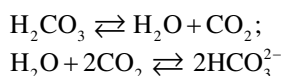
covariation of nitrate, phosphate and non-calcite contribution to total inorganic C in deep seawater, whereas biologists use a ratio of 106:16:1 based on Fleming’s analysis of the average elemental composition of marine organisms (Goldman et al. 1979). The Redfield C:N has its main application in oceanography for calculation of export production and for nutrient-based productivity calculations as well as in models of ocean productivity. The Redfield N:P ratio of 16:1 is often regarded as a standard value to distinguish between N-limited and P-limited habitats among the different water bodies especially with reference to oceans (Behrenfeld and Falkowski 1997; Tyrell 1999). Accordingly, it has often been suggested that if $N:P < 16$, the system is N-limited, whereas it is P-limited when $N:P > 16$.

However, some works on oceans in periods of glacial maxima showed that the generally accepted ratio of 16:1 may not hold true and can reach as high as 25 mol N:mol P (Broecker and Henderson 1998). Keeping in view of these findings, Falkowski (2000) opined that “the upper bounds of N/P ratios in the dissolved inorganic phase in the oceans is almost certainly a consequence of the intrinsic chemical composition of marine phytoplankton” although no numerical value for this upper boundary was suggested by him. It is remarkable that most oceans around the world have a deep water N:P ratio of approximately 16, although several biochemist and physiologists have questioned the plasticity of the elemental composition of phytoplankton populations both in field and in laboratory cultures (Hecky et al. 1993). Redfield later acknowledged this fact and opined that the deep water constancy of N:P ratio is due to a complex balance between several biological processes including nitrogen fixation and denitrification (Redfield 1958).

2.2.2 Carbon

Carbon (C) is the main element that regulates the functioning of natural waters because of the intricate equilibrium that exists between CO_2 ,

bicarbonate and carbonate that determine the acidity or alkalinity of natural waters. Moreover, this is the central element required in maximum quantity by photosynthetic organisms. The main source of carbon in water is the dissolved CO_2 from air. It is generally considered that about 90 % C in seawater exists as bicarbonate, 10 % as carbonate ion and approximately less than 1 % remains as unionized CO_2 . The presence of bicarbonate as the main source of C results in slightly alkaline nature of habitat that is about 7.9 for seawater and 6–9 for freshwater respectively. In slightly acidic waters ($\text{pH} \leq 6$), aerial CO_2 dissolved in water to form carbonic acid (H_2CO_3). For freshwater phytoplankton H_2CO_3 is available as the pH level of freshwater lakes and rivers remains slightly acidic (pH 6–6.5):



But in marine water, where pH ranges from 7.5 to 8.4, bicarbonate ions become predominant. But above pH 10, carbon exists in the form of insoluble carbonate. Thus, pH level regulates the carbonate–bicarbonate– $\text{CO}_2/\text{H}_2\text{CO}_3$ equilibrium in freshwater or marine habitats. Therefore, total carbon pool in aquatic ecosystems can be represented as follows:

$$\text{TCO}_2 = [\text{CO}_2] + [\text{H}_2\text{CO}_3] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}].$$

As natural waters are open systems, addition or removal of CO_2 is a common feature of these habitats, especially in marine systems. The solubility of CO_2 is much higher in water than oxygen. Over the last century the burning of fossil fuels for energy generation has resulted in atmospheric CO_2 increase from 280 to 390 μatm and a consequential decrease in surface ocean pH by 0.12 units. The current CO_2 emission scenario is predicted to raise CO_2 to 700 μatm over the next 100 years, which will decrease seawater pH by a further 0.3 units, and raise the sea surface temperature (SST) by 2–6 $^\circ\text{C}$ (IPCC 2007). Climatic changes due to an increase in CO_2 concentrations can enhance algal growth (Wolf-Gladrow et al. 1999; Hutchins et al. 2007) which may also affect coccolithophores by reducing the calcification rates (Tortell et al. 2002).

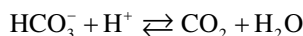
Further experimental studies revealed that an excessive increase in pCO_2 may result in a shift towards diatom dominated population.

Phytoplankton abundance in relation to concentration of carbon depends upon the form it exists. Some taxa (dinoflagellate *Amphidinium carterae* and *Heterocapsa oceanica*) require CO_2 as their inorganic carbon source. Therefore, in the marine environment, they depend upon the carbon concentrating mechanism (CCM) to get CO_2 from HCO_3^- or CO_3^{2-} . Almost all members of Heterokontophyta are with CCM present inside the cell and can thrive well exploiting HCO_3^- of marine environment.

2.2.2.1 CCM in Phytoplanktons

Algal cells primarily assimilate environmental CO_2 through C3 pathway (Calvin cycle) using RuBisCO. But very few algal forms also assimilate CO_2 by following alternative pathways in CO_2 starvation due to the weak binding affinity of RuBisCO as carboxylase. Thus, under these conditions, algal cells tend to produce phosphoglycolate as a by-product during RuBisCO performance as oxygenase. The phosphoglycolate thus produced inhibits RuBisCO activity which is further alleviated by formation of glycolate by the enzyme phosphoglycolate phosphatase. The glycolate thus produced can be excreted out by algal cells or can be further utilized as a substrate during photorespiration. In cyanobacteria CO_2 is converted to bicarbonate in the wall of the thylakoids. They also accumulate bicarbonate ion using plasma membrane transporter. This bicarbonate ion is converted to CO_2 by the enzyme carbonic anhydrase (CA) present in carboxysomes. In eukaryotic phytoplankton genera, diverse types of CCM are available. Among them, CA enzymes and membrane transporter are important. In some algal genera, pyrenoids also help in CCM. CCM that is operative in algae pumps HCO_3^- from outside the algal cell via the plasma membrane and the chloroplast membrane into the algal chloroplast. Within the chloroplast, HCO_3^- remains unchanged due to the alkaline nature of the stroma. A significant proportion of this HCO_3^- is subsequently passed into the thylakoid lumen. The enzyme carbonic anhydrase (CA)

attached to the thylakoid membrane converts HCO_3^- in the lumen to CO_2 at a rate hundred times faster than nonenzymatic conversion of the same:



This CO_2 formed by CA rapidly diffuses away from the thylakoid lumen to the chloroplast stroma that inhibits oxygenase activity of RuBisCO and promotes carboxylase activity of RuBisCO initiating the carbon reduction cycle.

Some algae have C_4 -like photosynthesis where enzyme PEP carboxylase traps inorganic carbon. Among these CCM processes, CA is the most abundant among algal genera. CA may be secreted externally (*Skeletonema costatum*) or present at periplasmic space (*Chlamydomonas reinhardtii*). Some algae excrete protons (H^+) across the cell membrane to get CO_2 from external bicarbonate source, which is on the other hand related to CaCO_3 deposition (calcification). Presence of HCl in the intermembrane space between chloroplast membrane and chloroplast ER (endoplasmic reticulum) also converts CO_2 from HCO_3^- in the group Heterokontophyta that allows it to acclimatize in marine environment.

Organic carbon is also used by phytoplankton genera like *Chlorella* spp., *Cocconeis* spp., etc. Lewitus and Kana (1994) reported about the use of glucose as carbon source by *Closterium* at estuarine region.

2.2.3 Nitrogen

Phytoplankton productivity and their diversity are highly controlled by nitrogen. Presence and cycling of nitrogen in ocean and lakes is a complex phenomenon because it exists in four dissolved forms of inorganic nitrogen (dissolved N_2 gas, NO_3^- , NO_2^- and NH_4^+). Both atmospheric nitrogen and dissolved inorganic nitrogen (DIN) of water bodies play an important role in controlling phytoplankton population. Organic nitrogen sources like urea and amino acids are present in ocean surfaces. Nitrogen is primarily present in water as dissolved inert nitrogen gas. In ocean, almost 95 % of nitrogen occurs as N_2 . Dissolved inorganic nitrogen includes the nitrate (NO_3^-) ion

in oxygen-rich water, nitrite (NO_2^-) ion in moderate oxygen level and ammonium (NH_4^+) ion in water body with less oxygen with high BOD. Previously it was assumed that nitrogen was the universal limiting nutrient in marine waters. Although planktonic populations are capable of assimilating different forms of nitrogen, the more preferred form is ammonia as it directly gets utilized in the biosynthesis of amino acids. In cyanobacterial species ammonia is considered to be a complete inhibitor of nitrogen fixation and heterocyst formation. In contrast, conversion of nitrate to ammonia is a more energy-requiring process and requires the enzyme nitrate reductase. Thus, to minimize the energy currency, ammonia is often preferred by natural phytoplankton populations especially cyanobacteria. In natural habitat like oceans and lakes, the dynamics of nitrogen cycling is complex as it involves the interconversion between four dissolved inorganic forms which can be achieved only by bacterial action in the environment or within living cells. It is opined that more than 90 % of oceanic N presents as molecular N_2 and the rest in other forms. Thus, it is believed that the concentrations of these nutrients primarily depend on the degradation of biological material synthesized by the biotic components in the surface waters of these habitats. The supply of NO_3^- in the surface waters from the cooler hypolimnetic nutrient-rich waters depends upon vertical advection and eddy diffusion across the thermocline. Due to the high rate of nitrification and ubiquitous presence of oxygen in the surface waters of natural lotic systems, NO_2^- concentrations are much lower as compared to NO_3^- concentrations. The higher concentrations can only be expected at deeper waters beyond the thermocline where oxygen concentrations are relatively low as compared to that of surface waters.

In oligotrophic waters, NO_3^- is the dominant form of DIN (dissolved inorganic nitrogen) because of the high rate of nitrification and the even distribution of oxygen, leading to the more oxidized form of nitrogen. In contrast, for eutrophic waters, the utilization of oxygen is more for decomposition processes in

the deep waters and the sediment layers. This would allow the build-up of other reduced forms of nitrogen as well, released primarily from organic sources. In the temperate region, winter mixing brings up nitrogen from the deep oceans mainly as nitrate. Thus, sources of nitrogen for natural phytoplankton populations can be (a) surface water DIN, (b) DIN brought up in the surface waters from deep waters through physical processes like upwelling and vertical advection, and (c) localized inputs brought down by rivers and ground water as well as seasonal precipitation.

In locations like the central subtropical oceans, recycling of surface waters is the main source of DIN where upwelling events are not prominent due to the existence of a vertical thermocline. Moreover, due to the remoteness of these locations, localized coastal inputs are also not very common. On the other hand, in coastal oceanic waters, upwelling, vertical advection as well as localized inputs from riverine sources cumulatively contribute to nitrogen concentrations in these waters. During spring as the water stratifies, phytoplankton population increases and absorbs nitrate that eventually depletes to nanomolar levels in the surface layers. In marine environment, cyanobacterial taxa *Trichodesmium erythraeum* appear as a surface bloom, turning the ocean water red. They fix N_2 from dissolved nitrogen of ocean water. In most temperate oligotrophic and mesotrophic freshwaters, NO_3^- is present in comparatively more amount together with phosphorus. In highly eutrophic waters NH_4^+ and NO_2^- are also present in both surface and subsurface area. If oxygen is present, NO_2^- is converted to NO_3^- , whereas in anoxic waters, it is reduced to NH_4^+ . In nitrate-enriched water maximum plankton diversity can be recorded. Green algal genera like *Scenedesmus* spp., *Chlorococcum* spp., *Kirchneriella* spp., *Ankistrodesmus* spp., etc., generally flourished in mesotrophic to moderately eutrophic waters. But in NO_3^- - and NH_4^+ -enriched water, phytoplankton genera like *Spirulina* spp. and *Trichodesmium* spp. appear in large quantities, sometimes resulting in algal blooms.

2.2.4 Phosphorus

Phosphorus concentrations in surface waters are mainly accounted by geochemical processes that occur in a basin adjoining an aquatic habitat. Unlike N, P remains mostly in bound forms in clay minerals and different soil components (Vollenweider et al. 1998). Thus, while studying P availability, mainly two sources of P are to be considered: (1) DIP (dissolved inorganic phosphate) and DOP (dissolved organic phosphate) and (2) particulate P mainly accounted for biological availability. Unlike N, for P the more common form of the element is PO_4^{3-} that is abundant both in biomolecules and in the environment. The requirement of phosphorus by phytoplankton populations is much smaller as compared to carbon, nitrogen and silicon. Thus, phytoplankton populations flourish even under nanomolar phosphorus concentrations, as can be observed in the Eastern Mediterranean and the Aegean Sea.

DIP is mostly constituted by orthophosphate (PO_4^{3-}) with much lower concentration of monophosphates (HPO_4^{2-}) and dihydrogen phosphate (H_2PO_4). Phytoplanktons primarily utilize DIP as a phosphorus source, but under limiting conditions extracellular alkaline phosphatase (AP) promotes utilization of phosphate bound to organic substances. Thus, level of AP activity is an indication of phosphate limitation in aquatic habitats (Rengefors et al. 2003). Under P-limited conditions, if there is a sudden pulse of soluble reactive phosphorus (SRP), planktonic algal cells have the unique ability to make 'luxury consumption' and develop polyphosphate bodies, thereby creating an internal pool of phosphorus to deal with phosphate shortage.

In oligotrophic waters, DIP turnover rate is very low in winter and accounts for only 10 % of total phosphorus (TP). This results in low phytoplankton populations with low growth rates. In coastal marine waters, DIP builds up in periods of vertical mixing. Under stratification, DIP pool is depleted that results in species-wise drop in phytoplankton populations. In contrast, in eutrophic freshwater, DIP may constitute 100 % of TP due

to uncontrolled discharges from point (industrial effluents, sewage) and nonpoint sources (runoffs from agricultural and urban areas) (Capone et al. 2005). The increased concentration of DIP may be surplus to algal requirements, thereby building up in water column, with a slow turnover rate. This excess phosphorus provides an opportunity for cyanobacteria populations to develop and can even reach blooming proportions.

2.2.5 Silicon

Small amounts of silicon are required by all planktons for protein synthesis. In freshwater, soluble reactive silica (SRSi) exists as monosilicic acid (H_4SiO_4) that ranges from 0.7 to 7 mg/L (25–250 μM). In oceanic environment, maximum concentrations of SRSi (~3 mg/L) present in upwelling zones. Utilization of SRSi by diatom for development leads to reduce the levels of SRSi in both freshwater and oceanic habitats. During periods of summer stratification, concentration of SRSi may reach below detectable levels (<0.1 μM) and becomes a limiting nutrient in these habitats.

Diatom cell covering or frustule is made up of polymerized silica that increases the density of diatom cell. Thus, development and abundance of diatoms is dependent on turbulent mixing conditions that render them buoyant in the euphotic zone of the water column. Polymerized silica decomposes slowly (~50 days) which is a possible hindrance in rapid recycling of silicon in the epilimnion of shallow lakes. Dead diatom cells often reach the benthos in intact forms and settle down as sediments. Dissolved silicon is available in surface waters of habitat by external inputs and turnover of the water column during mixing conditions. In oceans, as the mixing depth is much greater than lakes, silicon in diatom valves redissolves between the surface and about 1,000 m depth.

Parameters like nitrate, nitrite, ammonia, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP) and dissolved silicate (DSi) contents can be measured spectrophotometrically within 30 min of sample collection

following the protocols of APHA (1998). The values thus obtained are fitted to a standard curve prepared for determination of nutrient concentrations of water samples.

The procedures are mentioned below:

Nitrate

Reagents required: Silver sulphate solution, phenol disulphonic acid, liquid ammonia.

Procedure: An aliquot of 50 mL filtered sample water is taken in a conical flask to which an equivalent amount of silver sulphate solution is added and heated slightly to precipitate any chloride content that may be present. The filtrate of sample thus obtained is evaporated to dryness in a porcelain basin. The residue obtained is dissolved in 2 mL of phenol disulphonic acid and the contents are diluted, if necessary. Subsequently, 6 mL of liquid ammonia is added to the solution to develop a yellow colour.

Absorbance is recorded at 410 nm. Concentration of nitrate was calculated from standard curve, prepared from known nitrate concentration.

Nitrite

Reagents required: EDTA solution, sulphanilic acid, α -N-naphthylethylene amine, sodium acetate solution.

Procedure: Filtered sample water of known volume (50 mL) is taken in a conical flask. To it, 2 mL of each of EDTA solution, sulphanilic acid, α -N-naphthylethylene amine and sodium acetate solution is added in succession. The reagents are thoroughly mixed and allowed to stand for 5 min. A wine red colour developed.

Absorbance is recorded at 543 nm. Concentration of nitrite is calculated from standard curve.

Ammonia

Reagents required: Nessler's reagent.

Procedure: 50 mL filtered sample water is taken in a conical flask. To it, 2 mL of Nessler's reagent is added. The reagent is thoroughly mixed and is allowed to stand for 5 min. A pale yellow colour developed. Absorbance is recorded at 640 nm. Concentration of ammonia is calculated from standard curve.

Dissolved Inorganic Phosphate (DIP)

Reagents required: Ammonium molybdate solution, stannous chloride solution.

Procedure: An aliquot of 50 mL of filtered sample water is taken in a clean conical flask and 2 mL of ammonium molybdate is added to it. This is subsequently followed by addition of five drops of stannous chloride solution. A blue colour developed. Absorbance is recorded at 690 nm after 5 min but before 12 min of the addition of the last reagent. Concentration of phosphate in the sample water is calculated from a standard curve.

Dissolved Silicate (DSi)

Reagents required: Ammonium molybdate solution, 1(N) hydrochloric acid, oxalic acid.

Procedure: 50 mL of filtered sample water is taken in a clean conical flask and 2 mL of ammonium molybdate is added to it. This is subsequently followed by addition of 0.5 mL of 1(N) hydrochloric acid. After thorough mixing, 2 mL of oxalic acid is added. A bright yellow colour developed. Absorbance is recorded at 530 nm. Concentration of dissolved silicate in the sample water is calculated from a standard curve.

2.2.6 Nutrient Uptake Model

During the growth of phytoplanktons, the minerals are consumed and several models have been proposed to establish the relations between the rate of nutrient uptake, their storage inside the cell and ultimately the growth pattern of the phytoplankton.

2.2.6.1 Michaelis–Menten Model (1913)

This model was based on the kinetics of enzyme function where ρ is considered as the nutrient transport rate (μ mole of nutrient per cell per minute). The term ρ_{\max} is the maximum velocity of the nutrient transport, and S is the substrate concentration. ρ approaches to ρ_{\max} , when the substrate concentration S is high and the internal store of that same nutrient (Q) is low. K_t is the half saturation constant, which equals to the values of S where $\rho = \frac{1}{2}\rho_{\max}$, and unit of K_t is same as that of substrate ($\mu \text{ mol L}^{-1}$).

Therefore, according to Michaelis–Menten model, the nutrient uptake pattern is as follows:

$$\rho = \rho_{\max} \left(S / K_t + S \right)$$

2.2.6.2 Droop Model

Droop (1983) proposed an equation for establishment of growth rate and internal nutrient quota as follows:

$$\mu = \mu_{\max} (1 - Q_0) / Q$$

where μ is the gross growth rate or the rate of reproduction and μ_{\max} is the maximum rate of reproduction. Q is the internal quota of nutrient. When Q approaches Q_0 , then μ is zero.

By this model, we can understand the relationship between the growth rate and the nutrient storage within the phytoplankton cell. When phytoplankton can store nutrient at higher level, i.e. Q is more, then growth rate will also be more. When internal storage is exhausted, i.e. Q is 'zero', then growth also stops.

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Pal, R.; Choudhury, A.K.

2014, XII, 167 p. 69 illus., 44 illus. in color., Hardcover

ISBN: 978-81-322-1837-1