Lecture (8)&(9)

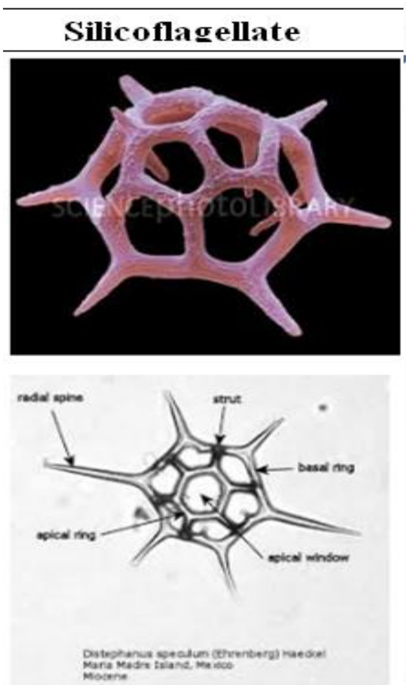
IV- Buoyancy of phytoplankton

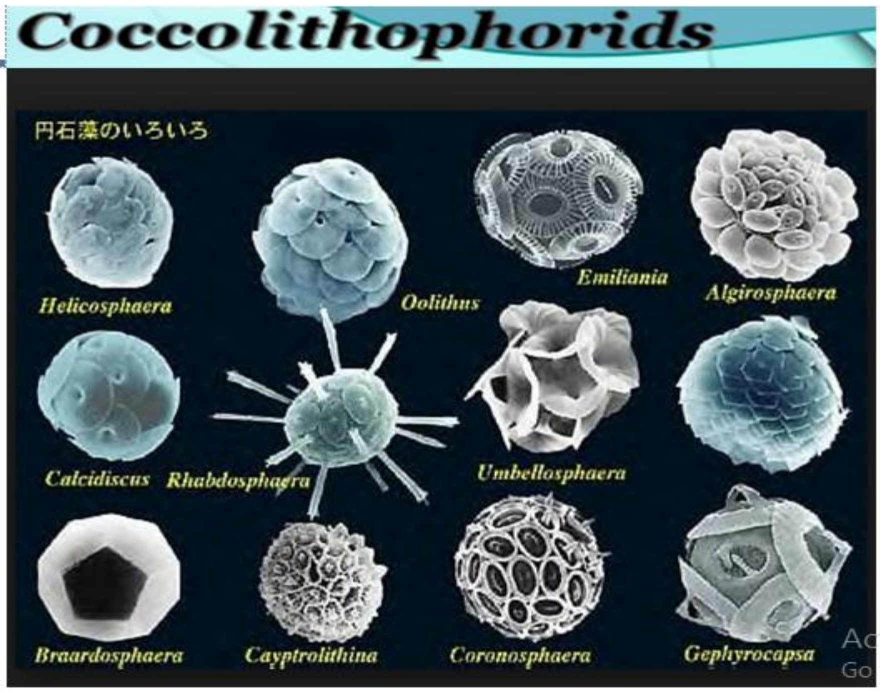
Although light dependency of photosynthesis and the attenuation of incident light in its passage through water, phytoplankton should sink into regions inadequately illuminated. This sinking may be attributed to the natural tendency of phytoplankton cells to sink. The periodicity of access to the light zone requires some slowing down or reversal of the downward drift, therefore the moving phytoplankton cells are more profitable than stationary cells. Moreover, their daily residence in the lighted zone allowing carbon fixation sufficiently satisfy the metabolic needs of the cell. We will discuss the causes of thinking and phytoplankton adaptations to overcome it?

Moving & Stationary Cells

For the cell to remain bathed in continuing supply of dissolved nutrients it must keep moving. Therefore, a stationary cell will be at a disadvantage because it will absorb the nutrients in its contact layer. Flagellum-bearing organisms expend appreciable energy if flagellum action is the sole mean of remaining in suspension. Too rapid a fall into the aphotic zone may prove lethal unless there is time for formation of resting spores or other resistant phases.

The sedimentary bottom deposits of diatom shells, coccolithophorid scales and silicoflagellate skeletons illustrate the steady drain of surface organisms into the depths.





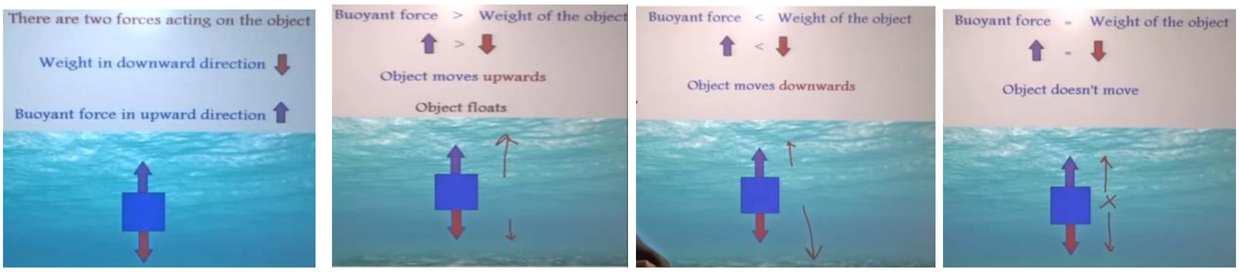
Phytoplankton suspension

Phytoplankton suspension is the result of cells being buoyed up by a force equal to the weight of water displaced (buoyancy force) minus the weight of the cell. There are two forces acting on the object: weight in downward direction and buoyant force in upward direction.

If buoyant force >weight of the object, object moves upwards and floats.

If buoyant force < weight of the object, object moves downwards and sinks.

If buoyant force = weight of the object, object doesn't move.



$$F = gkd^3\,(\sigma' - \sigma)$$

Where

F = resultant force of gravity

g = acceleration due to gravity

kd^3= cell (or chain) volume (d = a linear measurement)

$(\sigma' - \sigma)$= excess density

σ'= density of organism

σ= density of medium

When the excess density **$(\sigma' - \sigma)$** is zero, or, positive, there is a compensatory external force allow the organism to remain in suspension.

The density of cytoplasm of marine phytoplankton has been calculated as lying between 1.03 and 1.10 g cm^{-3}, because phytoplankton bear protein, carbohydrates, skeletal structures, silica, calcium carbonate and cellulose, that make up phytoplankton usually have a density greater than that of seawater, which has a density range of about 1.024-1.030 g/cm^3 hence, plankton tend to sink in the water column. Therefore they must employ strategies to aid their buoyancy or reduce their rate of sinking. Hence in both sea and freshwater phytoplankton cell densities are appreciably more than of the medium.

The paradox is the most phytoplankton organisms are too heavy ($\sigma' > \sigma$), and there must be some compensation for this overweight if they are to remain in suspension.

Bloom –forming freshwater blue–green algae and the marine blue–green alga *Trichodesmium* show positive buoyancies ($\sigma' < \sigma$).

Phytoplankton Mechanisms to Avoid Sinking

Phytoplankton cells can control their density by increasing its own hydrodynamic resistance or decreasing its density with respect to that of seawater to reduce their sinking rate. Phytoplankton have a number of ways of reducing their density and increasing their resistance. There are some mechanisms that they use to avoid sinking as follows:-

1- Morphological adaptations:

a- Cell shapes
b- The surface area – volume ratio
c- Cell size
d- Cell aggregation and Colony formation
e- Flagella and scales

2- Physiological adaptations:

a- Low-density waxes and oils;
b- Gas vacuoles
c- Exclusion of heavy ions

1- Morphological adaptations:

a- Cell shapes

The evolution of phytoplankton organisms have resulted in morphological forms which in themselves constitute flotation adaptations. For diatoms, these are bladders, plates or ribbons, needle or hair – like, and cells with hair – like projections.

a- Bladders – like cells have thin silica walls and large vacuoles with cell - sap of low density (*e.g. Coscinodiscus*).

b- Needles – like cells sink slowly if their long axis is horizontal to gravitational pull, but rapidly if vertical (*e.g. Rhizosolenia)*.

c- Ribbon like colonies are broad and flat, and show some twisting in suspension (e.g. *Bacillaria*).

d-Hair – like cell outgrowths are also said to offer resistance to sinking (e.g. *Chaetoceros*).

e-The spiny and wing – like outgrowths of some dinoflagellate cell walls have been described as flotation devices which supplement flagellum activity.

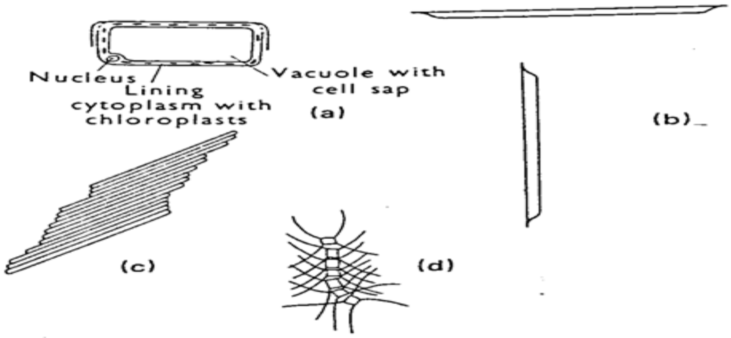


Fig **(a)** Bladder-like cell with large vacuole (*Coscinodiscus*). **(b)** Needle-like cell (*Rhizosolenia*)—floating position (upper) and sinking position. **(c)** Raft-like cell mass (*Bacillaria*). **(d)** Associated group of cells with spiny outgrowths (*Chaetoceros*).

b-Surface area–volume ratio

Stokes law for sinking bodies states that: "the slowest rates of fall will be obtained with those bodies in which the surface – area: volume ratios are greatest, conditions which entail a greater frictional drag with the water.

An object's rate of sinking in the ocean is determined by two factors:

i) The phytoplankton cell density relative to the water around it: Phytoplankton protoplasm is generally heavier than seawater and enough to sink, as previously mentioned.

ii) The drag or resistance offered by the medium.

The resistance of the medium is greater for small objects than for large ones. An object with a <u>large surface – to volume ratio sinks more slowly than one of the same density</u> but with a smaller ratio of surface area to volume.

- **The smaller the object, the larger the ratio:**

Ratio of surface area to volume = $$\frac{\textbf{Surface area}}{\textbf{Volume}} = \frac{4\pi^2}{4/3\pi^3} = \frac{3}{r}$$

Thus an object having radius of 0.1 mm has a surface – volume ratio of 30. whereas an object of the same shape and density with a radius of 0.01 mm has a surface / volume ratio of 300 and sinks more slowly.

A very <u>slow rate of sinking is advantage</u>, because <u>phytoplankton must remain in the photic zone long enough</u> to grow and reproduce, **yet** motion through the water column increases nutrient uptake.

c- Cell size

Theoretical interpretations showed that the relationship between shape and sinking rate is directly linked with size. Generally, the increase in cell size results in an increased sinking rate irrespective of cell shape.

a) For organisms of 5µm diameter the order of sinking rate is sphere > cylinder > plate.

b) For organisms of 50µm diameters the relationship is sphere > cylinder = plate.

c) For organisms of 500 µm, diameters the relationship is plate > sphere >cylinder.

d-Outgrowths and Surface area- volume ratio

A variety of superficial outgrowth and protuberances are borne by phytoplankton cells. These give a high surface – area to volume ratio and increase the frictional drag between the organisms and the water. But if they are silicified or calcified, the excess density would counteract any buoyancy.

Additional functions of surface outgrowth

Surface outgrowth or protuberances on phytoplankton cells can be interpreted as:-

i-Anti-predatory devices, spiny-growths reduce the chance of the cells being eaten by animals (e.g. desmids).

ii- A means of enlarging the absorptive area for uptake,

iii- Cell orientating devices in some genera (e.g. *Rhizosolenia* spp.).

Some examples of organisms having Outgrowths:-

-Scenedesmus is a green alga with aggregations of up to four flattened cells with spiny out-growths.

-Staurastrum is a green alga with spiny desmid, having a mucilaginous cover that often gives it an overall spherical appearance. Such a mucilage envelope will help to reduce the cells specific gravity.

e- **Cell aggregations / colony formation**

Cell aggregations or colony formation by planktonic algae are considered to be floatation adaptations as follows:-

i) Spherical colonies: small cells of low density embedded in a mass of mucilage (e.g. *Phaeocystis*) will clearly approach conditions of positive buoyancy.

ii) Increase the colony size, the common marine diatom *Skeletonema costatum*, increased colony sizes have apparently resulted in decreased rates of sinking. Where the colony of this species consists of linear series of small cells linked by minute silica rods which may induce micro-turbulence in their immediate vicinities counteracting the tendency to sink .

iii) The density of mucilage layer: The density difference between mucilage and the organisms must be at least twice the difference between the densities of mucilage and medium if such a covering is to be an effective buoyancy mechanisms.

f- Flagella and scales

It is well known that the loss of flagella or cessation of their beat results in immediate sinking of algal cells. Fagellar motility as an aid to flotation in organisms which classified as ultra- and nanoplankton can be regard as superfluous.

The flagellated nanoplankton organisms that bear coccoliths and siliceous scales will excess density conditions. Thus coccolith– bearing organism *Coccolithus huxleyi* (which lacks flagella) has been shown to sink at a **rate five times that** of a coccolith – free variant of similar cell size.

Dinoflagellates have specialized arrangements such as horn-like and wing –like outgrowths of the cell walls in some species. The more surface expansions reduce the swimming speed.

If these cell wall extension serve to increase from resistance and assist in maintaining the cells in suspension, then flagellar action as an aid to suspension would be superfluous.

Physiological regulation of cell density

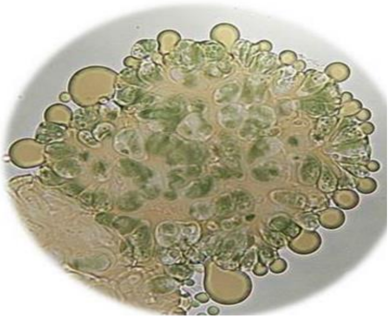
An intracellular control of cell density would seem an effective mean of regulating the sinking process such as reserve substances, gas vacuoles, and ionic composition of cell sap.

a-Fat reserves

- Fat accumulations in phytoplankton cells are regarded as means of counter- balancing the excess density due to mineralized cell walls. In diatoms appreciable fat deposition regularly occurs in species with heavily silicified cell walls.
- Accumulations of fat can develop in cells **under certain stress conditions** (e.g. interruptions in nitrogen metabolism; nitrate deficiency in water; high light intensity stresses, and ageing of cells).
- Also fat accumulations accompany **breakdown of cellorganization**. So that appreciable fat deposits in cells are **not necessarily indications of buoyancy adaptations**. It would seem odd if diatom cells were **most buoyant** at times when they **least viable** because of **fat accumulations**.
- Rate of **sinking increases with ageing** of the cells presumably because of physiological changes which increase the density of the cell sap or cytoplasm. Aging diatom cells sink more rapidly, however, **fat laden cells of the freshwater diatom *Nitzschia palea*** were found to sink at an appreciably **slower rate than normal cells lacking these extensive fat deposits**.

Botryococcus brauni

- Colonies of the freshwater organism *Botryococcus braunii* sh**ow marked flotation properties**, and this is attributed to its high lipid content (30 – 40 % of dry weight). This organism forms aliphatic hydrocarbons which will increase buoyancy.



Botryococcus brauni

Characteristics of *Botryococcus brauni*

-It is a green, pyramid shaped planktonic microalgae of the order Chlorophyceae.

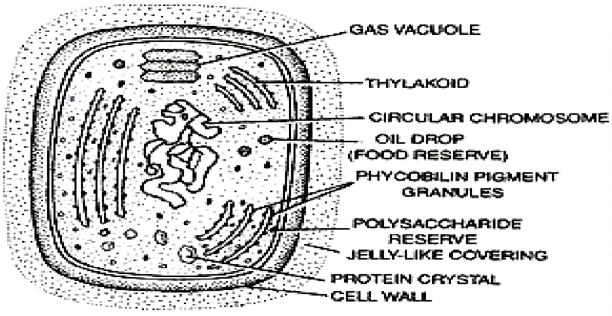
-Colonies held together by a lipid biofilm matrix. It inhabit in temperate or tropical oligotrophic lakes and estuaries. It can form bloom in the presence of elevated levels of inorganic P. It is important in the field of biotechnology.

-It produces high amounts of hydrocarbons, especially oils in the form of Triterpenes. It has a relatively thick cell wall that is **accumulated from previous cellular divisions**; making extraction of cytoplasmic components.

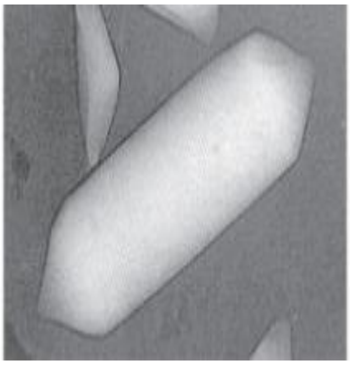
- Fortunately, much of the useful hydrocarbon oil is outside of the cell.

b) **Gas vacuole**

Surface "blooms" of blue green algae are a well-known feature of lakes and ponds in periods of **calm weather**. These blooms are commonly of filamentous and colonial species whose cells contain gas vacuoles.



Ultrastructure of a cyanophycean cell.



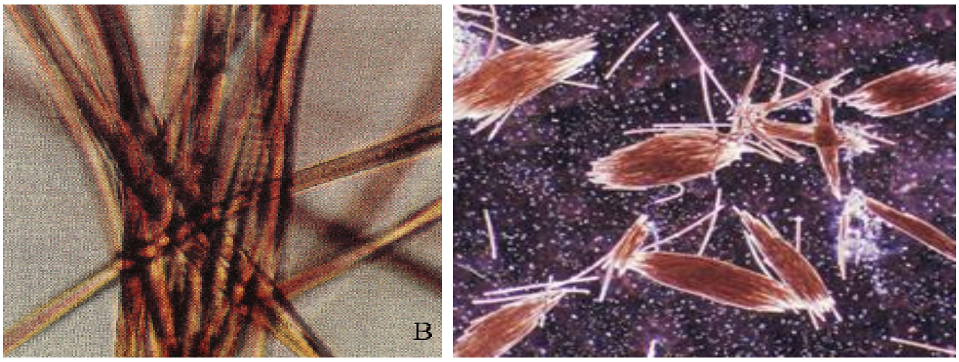
-Gas vacuoles are gas–filled spaces within the **gel-like cell protoplasm**, bounded by cytoplasm which **confers some rigidity to vacuole shape**. In each vacuole there are a number of **minute gas cylinders** of vesicles which **can be isolated from** the cells without loss of integrity. Each cylinder is kept distended by minute hoop- like proteinaceous structures. The **rigidity of the membrane** allows the vacuole **to withstand pressure changes** caused by **movements of the cells** in **water column**.

-The gas mixture in vacuole resembles that in the water (mainly **N** mixed with **argon** and occasionally **oxygen**), and would seem not to be specific products of metabolic activity.

-The buoyancy properties conferred on the filaments by **gas vacuoles can be readily demonstrated** if the vacuole membranes are **ruptured by a sudden high pressure shock**, filaments so treated **sink rapidly to the bottom** of the container.

-Gas vacuoles also occurred in **certain non-planktonic blue** – green algae, and certain of these vacuoles is **induced by exposure to bright light**.

-Gas **vacuole formation is largely a feature of freshwater blue green** algae, and is **rare in marine** representatives. The bloom-forming **freshwater *Trichodesmium*** *erythraeum* is the best known example gives positive buoyancy, this is attributed to gas – vacuole formation.



Trichodesmium erythraeum

Other functions suggested for gas vacuoles

-Gas vacuoles have included **light- shielding properties**, **metabolic by–products**, and residues, and **bubbles of gas produced during of anaerobiosis**, but the gas mixture present is unlikely to be produced during anaerobiosis.

-Not all blue–green algae with gas vacuoles show such **positive buoyancy**, where some organisms remain for long periods in the vicinity of the metalimnion of lakes, maintaining this position **by metabolic control**.

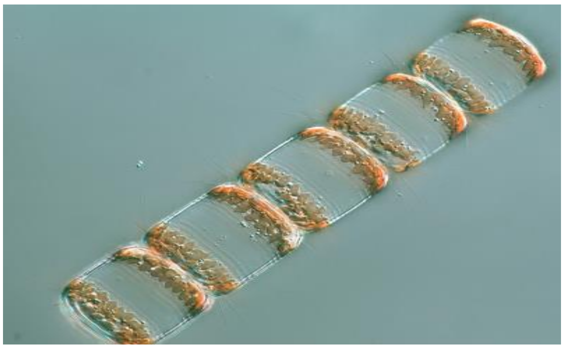
c) Ionic composition

i- *Lauderia annulata*

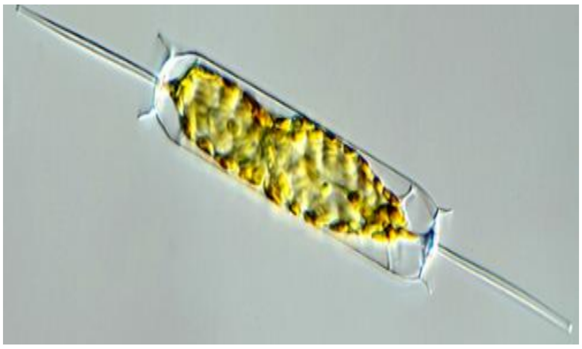
In diatoms of "bladder" type a great part of the cell volume is vacuole and cell sap (vacuole volume has been estimated as 50 % of the total volume of cells of *Lauderia annulata*). Under suitable physical conditions marine plankton diatoms do not sink because their specific gravity is **equal** to that of sea water'. **Much of the weight of the diatom cell is in the wall,** the vacuolar sap specific gravity would have to be appreciably reduced to compensate for this.

ii) *Ditylum*

Ditylum vacuole sap specific gravity was estimated **as 0.0025 less than that of sea** water when cells were growing and remaining in suspension. Actively growing *Ditylum* cells have a **neutral buoyancy**.



Lauderia annulata



Ditylum

The neutral buoyancy of *Ditylum* was in part due to the selective absorption of monovalent ions (e.g. Na and K) and the maintenance of low concentrations of divalent ions, both processes involving energy expenditure on the part of the cell.

The lowered specific gravity of cell sap is sufficient to counterbalance the silica "ballast" of the cell. The silica ballast of *Ditylum* cell has been estimated as 0.1% of total cell density but only 0.05% of the total volume.

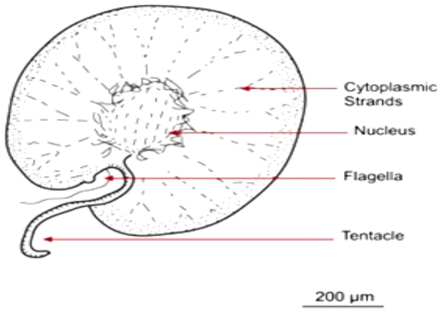
Each 1 μm^3 of silica wall requires 2.5 μm^3 of cell sap of density 1.02 to ensure buoyancy. Hence, it is estimated that the ionic composition of the cell sap becomes significant feature when there is a surface – area to vacuole – volume ratio of 0.45 and below. High surface – area to volume ratios are obtained with small cells. So that selective ion accumulation and exclusion would seem in applicable to small diatoms.

***Ditylum* resting spores** were observed to sink rapidly, and a similar result was obtained if any check occurred on cell growth. Resting – spore formation is accompanied by contraction of cell contents and loss of cell sap.

iii-Dinoflagellate *Noctiluca*

The holozoic dinoflagellate *Noctiluca miliaris* accumulates in vast numbers at the sea surface during calm weather and apparently **regulates its density with accompanying volume changes.**

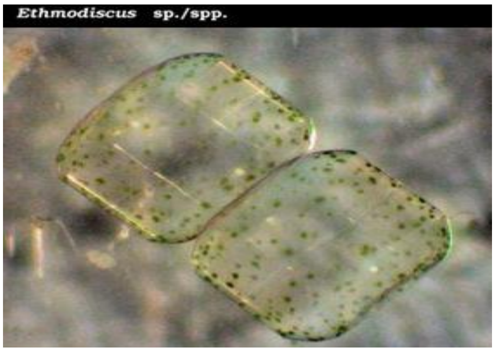
Cell – sap analyses show :- **a)** very low concentrations of divalent ions, **b)** a high concentration of Na relative to k, and **c)** quite high concentrations of ammonium (NH_4) ions. The buoyancy of this species would seem to be due to a selective accumulation of light monovalent ions and low concentrations of divalent ions (particularly SO_4^2).



Ammonium ions are unlikely to accumulate in autotrophic plant cells which are nutritionally dependent on exogenous sources of dissolved combined nitrogen.

iv- *Ethmodiscus rex*

-In healthy cells of *Ethmodiscus rex*, there was a tenfold concentration of Na over K and a complete absence of NH_4. Ca^2 ions were present in very small quantities, and Mg ions were not detected. SO_4 ions were present in similar quantities to K ions in living cells, but SO_4^{2-} ion concentration increased tenfold in damaged and dead cells.



Physical factors due to surrounding medium

The two principal factors are water movement and viscosity.

i-**The viscosity** of water decreases with increasing temperature and in tropical waters this would clearly make plankton suspension more difficult in the warmer.

Organic substances liberated by phytoplankton would also affect water viscosity, particularly during periods of "bloom". These substances would indirectly affect suspension.

ii- Water movement

Water turbulence has a considerable influence on phytoplankton. Turbulence arises from a number of sources.

Vertical eddy diffusion currents are reflected upwards from water flowing over uneven areas of sea or lake bed. Tiling of the discontinuity layers in lakes through surface **wind action** and the **see-sawing action** of the seiche will induce turbulence above and below the metalimnion.

Wind induced "convection cells", localized regions of down welling and upwelling, are known in ocean waters and lakes. Wind of varying force and direction is a persistent feature; even when minimal there is still a significance effect on water movement and surface turbulence.

Questions

i-Write short notes on the following :-

1- Sinking rate and phytoplankton cell forms or shapes

2- Sinking rate and cell size

3- Rate of sinking and surface area– to volume ratio

4- Outgrowths and Rate of sinking.

ii- Discuss the following

1- Fat deposits are not necessarily indications of buoyancy adaptations.

2- *Noctiluca* can regulate cell density to float.

3- *Ditylum* can reduce its specific gravity to be buoyant.

4- *Ditylum* can be buoyant whereas its resting spore can't.

5- Freshwater *Botryocococcus braunii* has marked floatation.

6- Blue green algae can easily float.

7- fat reserves is considered as physiological regulation of cell density.

8- Botryococcus brauni