Discipline Courses-I
Semester-I
Paper: Phycology and Microbiology
Unit-VI
Lesson: Introduction to Algae

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Introduction

Algae are a large, heterogeneous and polyphyletic group of simple plants referred to as thallophytes as their plant body is called as thallus – lacking true roots, stem, leaves. The first reference to algae is to be found in early Chinese literature but there are also references in Roman and Greek literature. The Greek word for alga was *Phykos* whilst in Roman times they were called *Fucus* and were used by matrons for cosmetic purposes. The Roman writer Virgil apparently did not have much use for them as the writer of 'nihil vilior alga'. The Chinese regarded them aesthetically and this is signified in their name of *Tsao*. In the eighth century there are references to several kind of *Tsao*. Algae have been known for a long time in Hawaii where they are used as a food and are called *Limu*. The branch of Botany dealing with the study of Algae is called as '*Phycology'.*

As with other plants real progress was made in our scientific knowledge of the algae with the invention of the microscope in the middle of the seventeenth century. At early as twelfth century, however, algae were being used for manurial purpose on the north coast of France from here it seems that the practice spread to Great Britain, because in the sixteenth century there is reference to their use for the same purpose. The use of the algae as manure have had something to do with the idea that they were bred of putrefaction as described in 1583 by Cesalpino. In 1754, Linnaeus introduced the term alga & included Hepaticae up to about 1800 of four great genera, *Fucus, Ulva, Conferva* and *Corallina*. *Chara* was known but commonly grouped with the horsetails (*Equisetum*). In the same century (seventeenth) the use of brown seaweeds for fertilizer in France had reached such a pitch that special decrees were passed in connection with their collection. At the other end of the world the art of making agar permeated from China to Japan, and thus the foundation was laid for what was later to become a great industry.

Habitat

Algae exhibit great diversity in size and morphology. The number of species worldwide is estimated to be between 36,000 to more than 10 million. They could be single cells as small as 1um to large seaweeds which may grow to over 50 m. They can be found growing in aquatic and terrestrial environments. Majority are aquatic, fresh, brackish & marine waters.

Table: Examples of some algae growing in diverse habitats

Source: Author

Habitat	**Genus**
Aquatic	*Volvox, Hydrodictyon*
Terrestrial	*Vancheria terrestris*
Epiphytic	*Oedogonium sp.*
Cryophilic	*Chlamydomanas nivalis*
Thermophilic	*Mastocladus laminosus*
Epizoic	*Acrosiphonia* on limpets *Basicladia chelonum* on Blanding's turtles
Endophytic	*Coleochaete nitellarum*
Endozoic	*Prochloron* as extracellular symbionts of sea-squirts

Aquatic algae may be attached to rock, wood, or other aquatic vegetation or may be free-floating. Attached algae in marine habitats often exhibit orderly zonation in the exposure of their substrates at low tides. A number of generation such as *Porphyra, Enteromorpha, Fucus* and *Ascophylum* grow in the intertidal zone they are thus exposed to and able to withstand desiccation.

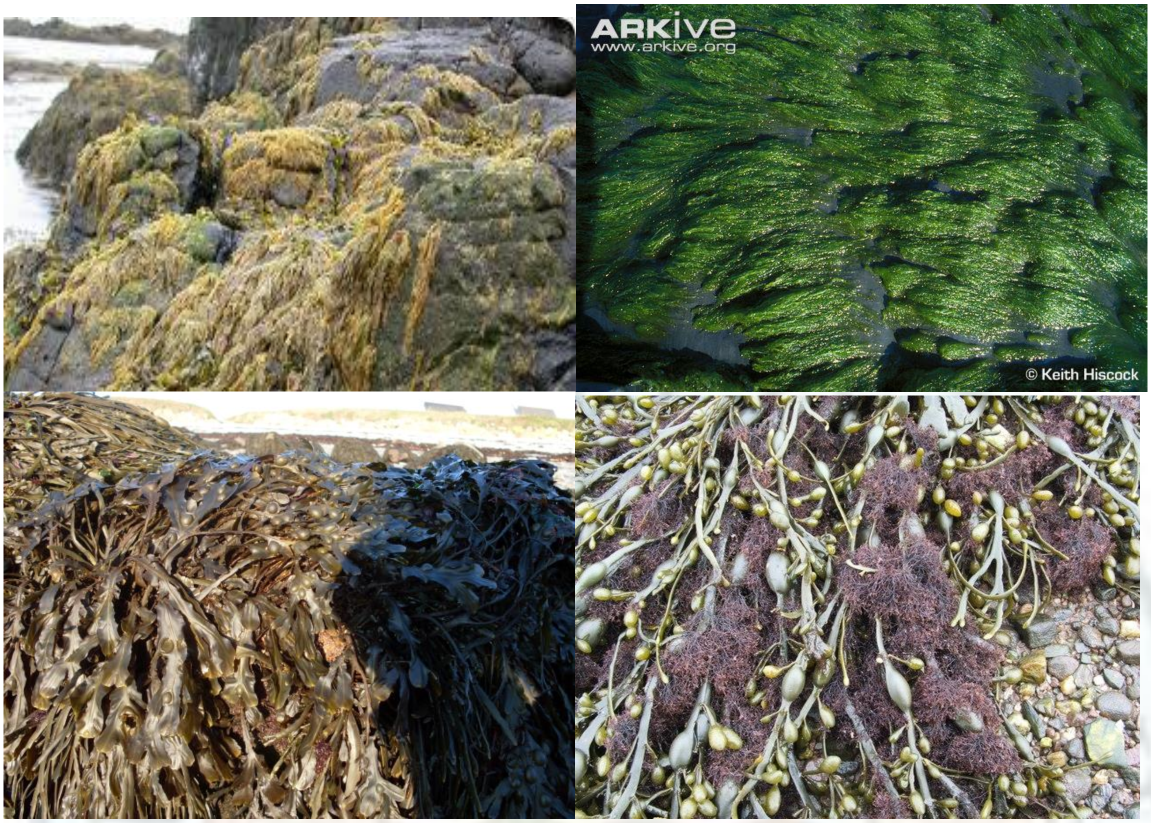


Figure: *Porphyra, Enteromorpha, Fucus, Ascophyllum* are marine algae found growing in the intertidal zones.

Source:http://content61.eol.org/content/2011/07/21/05/77197_260_190.jpg ,http://cdn1.arkive.org/media/08/08D6DB6C-20C3-44A7-AB3E-ECC398C5FEBF/Presentation.Large/Enteromorpha-on-rocks.jpg, http://upload.wikimedia.org/wikipedia/commons/2/24/Algen_Fucus_v._01.JPG, http://upload.wikimedia.org/wikipedia/commons/9/93/Ascophyllum_nodosum_with_Polysiphonia_lanosa.jpg (CC-BY-SA)

In contrast, other attached algae, like the kelps and *Polysiphonia* are usually sublittoral.

A vast array of unicellular, colonial and delicate filamentous algae permanently suspended in water where they may be associated with bacteria, fungi, protozoa and other marine animals to form a community known as the planktonic algae, under favourable conditions may multiply rapidly and become strikingly abundant as water blooms of which 'red tides' are an example.

Figure: Red tide caused by alga *Trichodesmium erythaeum.* Other examples of algae causing red tides include *Alexandrium catenella* and *Karenia brevis*

Source:http://www.greenprophet.com/wp-content/uploads/2013/03/red_tide_iran-500x436-350x305.jpg

In a habitat a variety of algae may be present or only a single organism may predominate. Planktonic organisms are of tremendous importance as a basis of food chain for larger animals in aquatic environments. Some may be found growing in such diverse habitats as tree trunks, show banks, hot springs or even within minute cavities in desert rocks. A number of algae live symbiotically with (or within) animals, fungi or other plants. Perhaps the most striking indication of the diversity of the algae is that they are placed in three separate divisions in the five kingdom concept of classification of organisms (R.H.Whittaker, 1969).

General characteristics of algae

(i) The plant body is a thallus and is not differentiated into true root, stem and leaves.

(ii) The zygote does not develop into a multicellular embryo while still contained inside the oogonium.

(iii) The reproductive organs whether spore producing or gamete producing are not enveloped by a wall of sterile cells. All the cells are fertile. In case of unicellular algae, the vegetative cells themselves become the gametes or behave as sporangia.

(iv) Most of them possess chlorophyll, however, certain forms are facultative or obligate heterotrophs, a few algae are even phagotrophic.

(v) Majority of the algae are photo-autotrophs (O_2 evolving type of photosynthesis).

(vi) Most of the algae are aquatic except a few.

Range of Morphological Diversity in Algae

A great deal of variation exists in the morphology of the algae thallus (algal body)

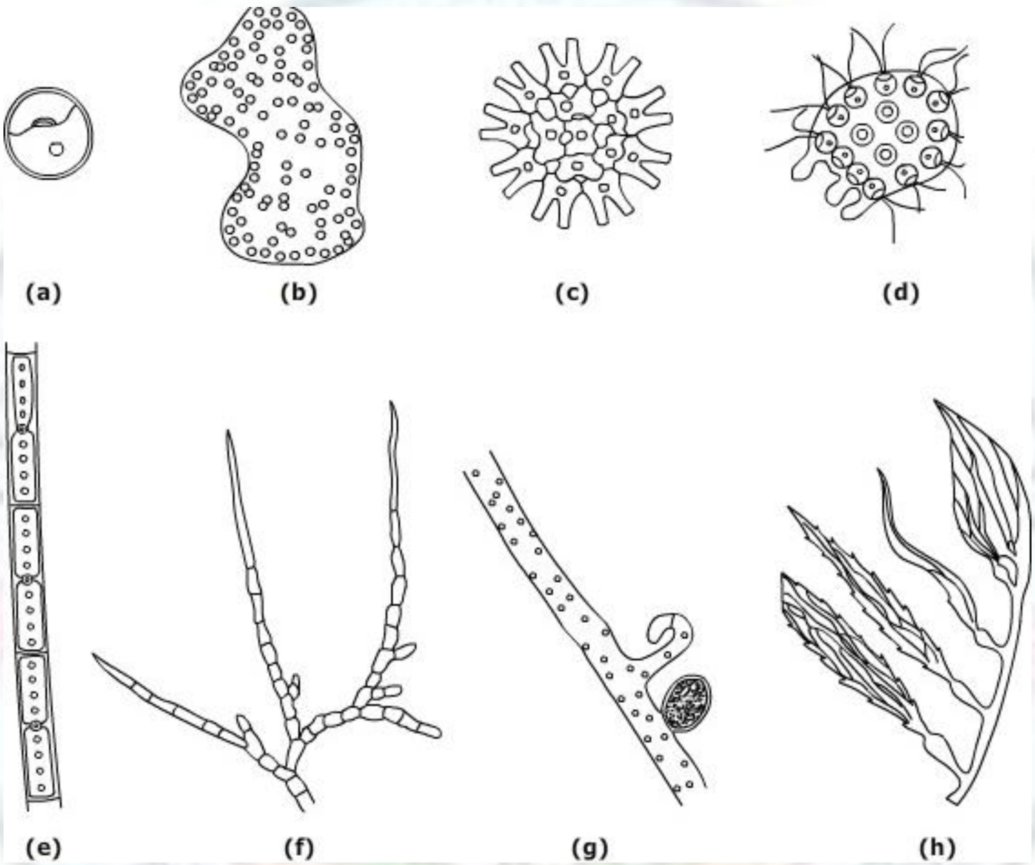


Figure: Some of the thallus types in algae- **a.** Unicelled green alga *Chlorococcum*;**b.** colonies of Cyanobacteria *Microcystis.* The cells are held together by the mucilage.; **c.** Coenobial thallus with non flagellate cells of green alga *Pediastrum;* **d.** Colonies of green alga *Platydorina* with flagellate cells;**e** The filamentous green alga *Mougeotia* ;**f.** Branched filamentous thallus of green alga *Stigeoclonium*; **g.**Coenocytic thallus of Xanthophyceae member *Vaucheria*. **h.** The giant brown alga (Kelp) with fronds.

Source: Author

Unicells and colonies : Many algae occur as unicells while others may be made up of several to many individual cells held together loosely or in a highly organized fashion. Some unicellular algae are non motile, while others possess one (or more) of the various means of locomotion found among the algae. As mentioned earlier, some algae have locomotory structures known as flagella. Such flagellates can be either unicellular or colonial. A colony is an assemblage of individual cells in which there may be either a variable number or predictable number of cells with an arrangement of cells that may remain constant throughout the life of the individual. Depending on the morphology the colonies may be – coenobial, palmelloid, dendroid and rhizopodial. A coenobium is defined as a colony of cells arranged in a particular manner. This pattern is defined in the juvenile stage itself and does not change subsequently even though the cells may grow in size. Depending on the organism, cells in coenobia may be either flagellated (*Volvox*) or non motile (*Hydrodictyon*).

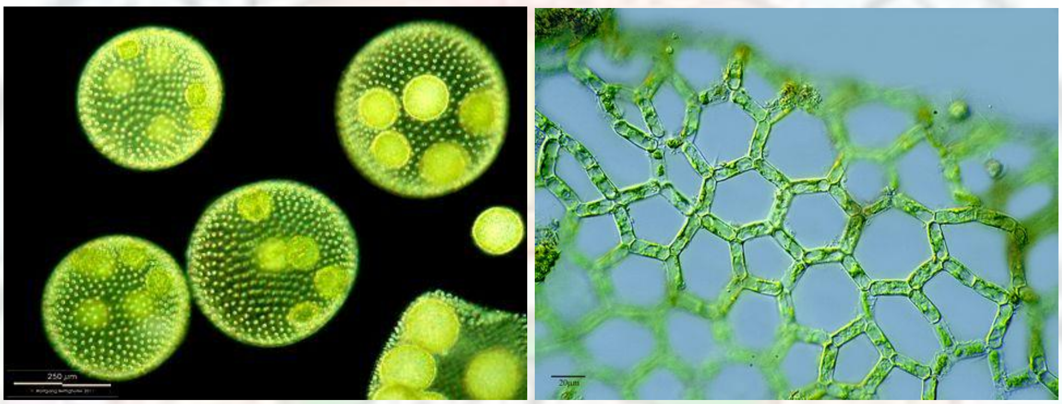


Figure: Coenobial forms-*Volvox* (motile) and *Hydrodictyon* (non motile)

Source: http://content65.eol.org/content/2012/07/30/04/04285_580_360.jpg; http://content62.eol.org/content/2012/01/14/02/41518_580_360.jpg

In palmelloid, dendroid and rhizopodial forms the cells are not arranged in definite pattern and the number of cells and therefore that of the colony also increases. The cells in the palmelloid colonies are non motile and are embedded in a mucilaginous matrix. They become motile only during reproduction.


Figure: Examples of palmelloid colonial forms include- *Aphanothece* (Cyanophyta) and *Tetraspora* (Chlorophyta)

Source: http://content62.eol.org/content/2008/12/10/21/87718_580_360.jpg; http://content63.eol.org/content/2012/07/30/05/50059_580_360.jpg

In dendroid forms the cells in the colony are arranged in tree like branching manner in the mucilage that is secreted from the base of each cell.

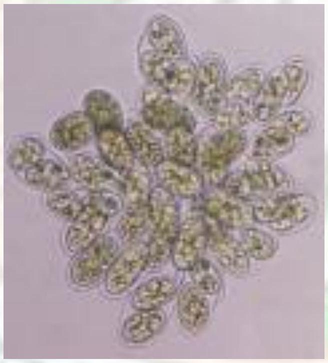



Figure: The colonial dendroid form *Ecballocystis* (Chlorophyta)

Source: http://acoi.ci.uc.pt/include/downloadCultureImgThumb.php?id=1863

In the rhizopodial foms the cells are connected to each other by their rhizopodia.

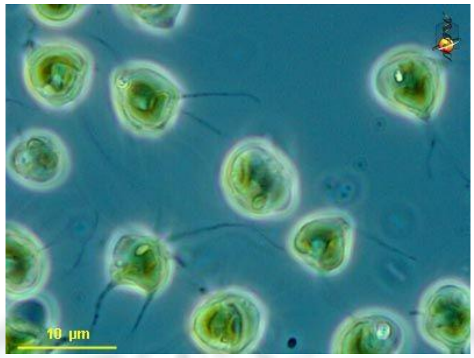


Figure: *Chrysidiastrum* (Chrysophyta) an alga with the cells connected to each other by their rhizopodia

Source: http://content61.eol.org/content/2008/12/10/21/96761_580_360.jpg

Filaments: A common growth form among the algae is the filament, where daughter cells remain attached to each other following cell division forming a chain of cells joined end to end. Filaments may be unbranched or branched and may be uniseriate (a single series of cells) or multiseriate, where a few to many individual filaments fuse together to form a larger, more complex structure. Linear colonies, formed by some diatoms, for example, can be distinguished from true filaments by the fact that cells of the former each possess their own individual walls, whereas adjacent cells of true filaments share a wall.

Figure: *Ulothrix* (Chlorophyta) filamentous unbranched thallus

Source:http://starcentral.mbl.edu/msr/rawdata/viewable/ulothrix_carmichaelii_1342864978_a_543w.jpg

Branching can be of two kinds- true and false. True branches are lateral outgrowths that arise from a single or a group of cells dividing transversely from the main filament. True branching can be of several kinds:

- Genus *Cladophora* exhibits simple branching
- Heterotrichous habit is one in which the thallus is differentiated into erect and prostrate filaments, example- *Ectocarpus*. In some genus however the prostrate (e.g. *Draparnaldiopsis*) or the erect system (e.g. *Coleochaete scutata*)are missing.
- Parenchyma like thalli result from repeated divisions of the filaments without the failure to separate. Parenchyma is a term used to describe algae tissue that is composed of relatively undifferentiated, isodiametric cells generated by a meristem. It results from cell divisions occurring in three directions, which gives rise to a 3-dimensional form. Examples- *Ulva , Porphyra.*
- Pseudoparenchymatous- algae have thalli that superficially resemble parenchyma, but which are actually composed of appressed filaments or amorphous cell aggregates. Example- *Coleochaete pulvinata*

Both Parenchymatous and pseudoparenchymatous algae assume a wide range of shapes (sheets, tubes, stem and leaf-like arrangements, etc.) and sizes (microscopic to lengths of 50m or more.)

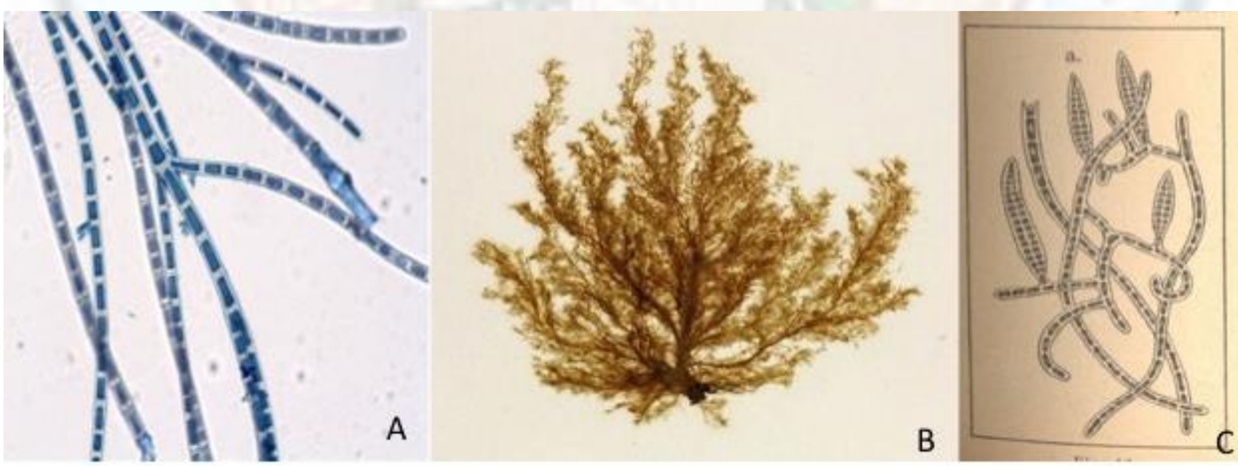


Figure: True branching**-** A. *Cladophora* simple branched filamentous alga; B. and C. *Ectocarpus* (Phaeophyta) –hetrerotrichous habit.

Source: http://calphotos.berkeley.edu/imgs/512x768/4444_4444/0311/5627.jpeg, http://upload.wikimedia.org/wikipedia/commons/f/f8/Ectocarpus_fasciculatus_Crouan_%281%29.jpg ,http://content61.eol.org/content/2012/06/14/17/34591_580_360.jpg

Figure: Parenchymatous thallus of *Ulva*

Source: http://upload.wikimedia.org/wikipedia/commons/2/21/Ulva_linza_Helgoland.JPG

False branching which is seen in family Scytonemataceae (Cyanophyta) results from the presence of several filaments in a common mucilaginous that come to have the semblance of branches. This may result from degeneration of an intercalary cell and both the ends grow out from the common matrix.

Figure: False branching as seen in *Scytonema* (Cyanophyta)

Source: http://www.jcu.edu/mcp/Cyano/SEV5-3c28.jpg

Coenocytic or siphonaceous forms: Less common are algae with a coenocytic or siphonaceous growth habit. Such organisms basically consist of one large multinucleate cell, without cross walls. Septa are formed only during the formation of reproductive structures. *Protosiphon* (Chlorophyceae) and *Botryidium* (Tribophyceae) are examples of algae having simple siphonaceous thallus that is attached to the substratum by rhizoids. *Vaucheria* (Xanthophyceae) on the other hand has a branched siphonaceous habit.

Figure: *Vaucheria* (Xanthophyceae) has a siphonaceous thallus

Source: http://www.bioimages.org.uk/html/p5/p57167.php

Cell structure

On the basis of their organization algal cells may be differentiated into prokaryotic, mesokaryotic and eukaryotic types. The prokaryotic cell organization is found in Cyanophyceae which is characterized by:

(1) the presence of incipient nucleus

(2) the absence of membrane bound organelles like plastids, endoplasmic reticulum, Golgi bodies and mitochondrion

(3) the absence of basic proteins like histones in DNA

(4) the presence of mucopeptide in the cell wall

(5) lack sexual reproduction and meiosis. Cells divide by binary fission.

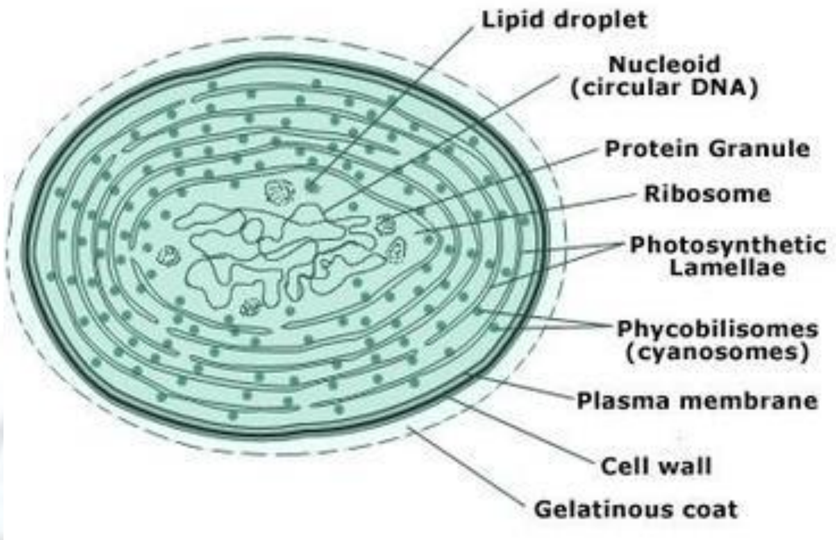


Figure: Diagrammatic sketch of a typical Cyanophycean cell

Source: http://vastandundetectable.wikispaces.com/file/view/cyanobacteria-cell-structure.jpg/283452824/371x252/cyanobacteria-cell-structure.jpg

A eukaryotic cell, on the other hand, is characterized by the presence of a well-organized nucleus and membrane bound organelles like plastids and membrane bound organelles like plastids, mitochondria and Golgi bodies.

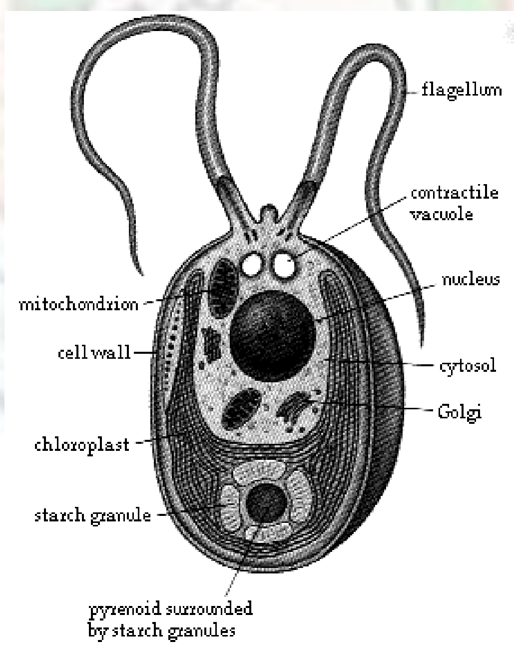


Figure: A diagrammatic sketch of a green alga *Chlamydomonas* representing an eukaryotic cell.

Source: http://www.jochemnet.de/fiu/bot4404/Chl_chlamydomonas_draw.gif

An intermediate type of cell organization i.e. mesokaryotic is found in the members of Dinophyceae, where although the nucleus has a nuclear membrane and chromosomes (eukaryotic characters) basic proteins are absent (prokaryotic character). (visit for additional information: http://tolweb.org/Dinoflagellates/2445)

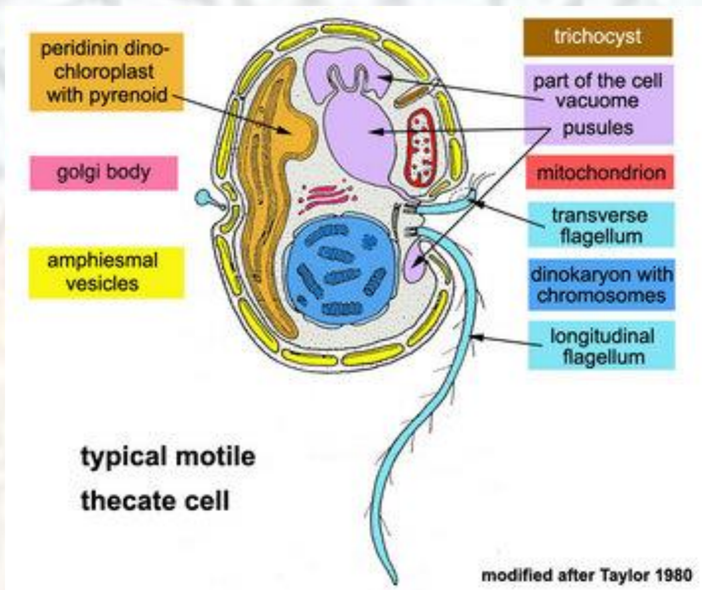


Figure: A drawing of typical dinoflagellate cell.

Source: http://tolweb.org/tree/ToLimages/dinogeneralmaxtol1.300a.jpg

Cell wall

Most eukaryotic plant cells are surrounded by a cell wall composed of polysaccharides. This wall occurs outside the plasma membrane which delimits the protoplasm unlike the plasma membrane which is living structure controlling the absorption and outflow of materials, the cell wall is non-living and made of a fibrillar component forming the skeleton of the cell wall and an amorphous matrix within which the fibrillar part is embedded. Sometimes, the wall contains proteins and may be impregrated with calcium carbonate or chitin. According to their composition, the algal cell walls may be predominantly cellulosic silicified or mucopolymeric.

The cellulosic walls are fibrillar composed of a polymer of glucose residues (1,4 linked B-D-glucose). Cellulose is replaced by a mannan (a polymer of 1,4 linked β-D-mannose) in some siphonaceous green algae. The amorphous mucilaginous components occur in the greatest amounts in the Phaeophyceae and Rhodophyceae, the polysaccharides of which are commercially exploited. Alginic acid is a polymer composed mostly of β-1,4 linked D-mannuronic acid residues with variable amounts of L-guluronic acid. Alginic acid is present in the intercellular spaces and cell walls of the Phaeophyceae. Fucoidin occurs in the Phaeophyceae and is a polymer of α-1,2; α-1,3 and α-1,4 linked residues of L-fucose sulfated at C-4. In the Rhodophyceae, the amorphous component of the wall is composed of galactans or polymers of galactose which are alternately β-1,3 and β-1,4 linked. These galactans include agar (made up of agaropectin and agarose) ,carrageenan, porphyran, fucelleran and fucoran.

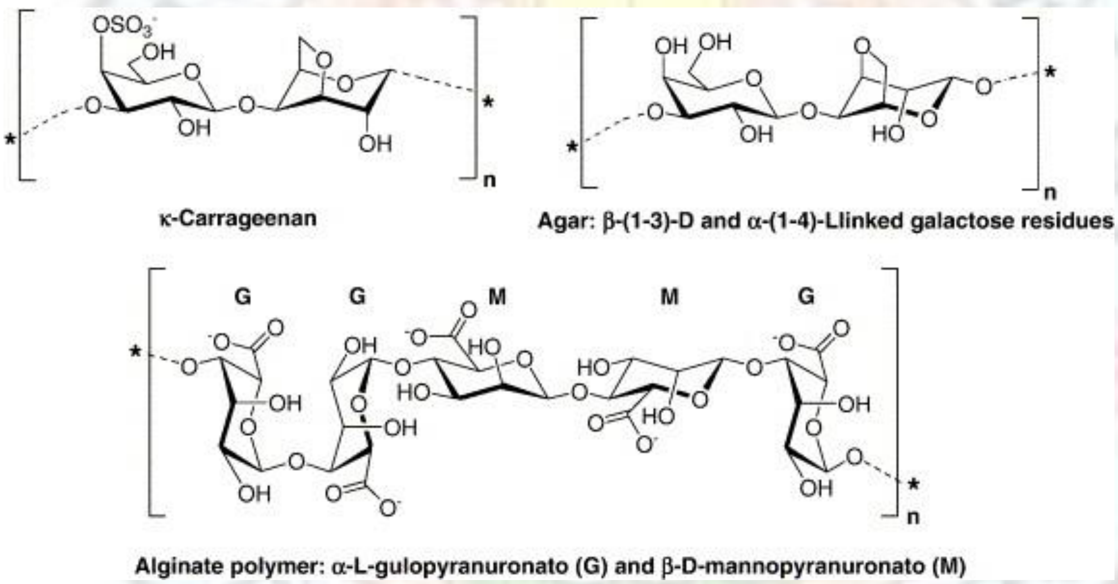


Figure: Structures of some of the common wall components in algae

Source: Author

The amorphous polysaccharides of the Chlorophyceae are more complex, containing residues of D-galactose, L-arabinose, D-xylose, D-glucuronic acid and L-rhamnose. The Dinophyceae have elaborate cell coverings consisting of several membranes and usually a layer of thecal plates. The Cryptophyceae also possess a several layered periplast with the outer most layer being the plasma lemma. The periplast is usually subdivided into a pattern of squarish or polygonal plates. Some Chrysophyceae possess loricae composed of ordered chitinous microfibrils.

The mucopolymeric cell wall is characteristic of cyanobacteria and *Prochloron* and contains acctylglucosamine, acetylmuramic acid, diaminopimelic acid, aminoacids and some sugar polymers.

A true cell wall is, however, absent in some algae like *Euglena, Gymnodinium* and *Pyrasimonas*. They simply have a bounding membrane of cytoplasm known as pellicle.

Flagella

Most algal classes except the Rhodophyceae, Cyanophyceae and Prochlorophyceae include some algae that are either themselves motile or reproduce by means of certain motile cells which bear flagella. Two or more flagella are commonly inserted anteriorly. Usually one flagellum is better developed than the other, the second may even be vestigial as in Chrysophytes and Euglenoids. In many Dinoflagellates, the flagella are inserted laterally and one of them is ribbon like.

Depending upon the presence or absence of hairs or **mastigonemes** the flagella may be of two types:

- Whiplash or acronematic which lacks hairs and
- Tinsel or hairy or pantonematic

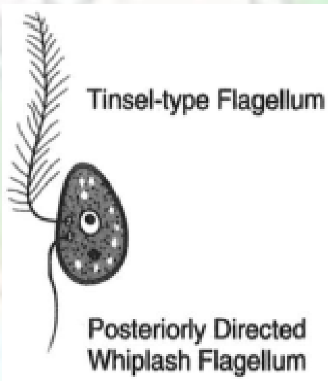


Figure: Two types of flagella are seen in algae depending upon the presence and absence of hair

Source:http://www.biocyclopedia.com/index/introduction_to_botany/images_brown/14-1.gif

Usually, the Chlorophytes have two acronematic flagella, whereas in the Phaeophyceae and Tribophyceae, there is one acronematic and one pleuronematic flagellum. In Cryptomonas, both flagella are pleuronematic.

The algae also differ in the length, number arrangement of the flagella. The flagella can be:

Isokont- flagella equal in length

Anisokont- Flagella unequal in length

Stephanokont- flagella form arising at one end of the cell

Heterokont: presence of both tinsel and whiplash types of flagella.

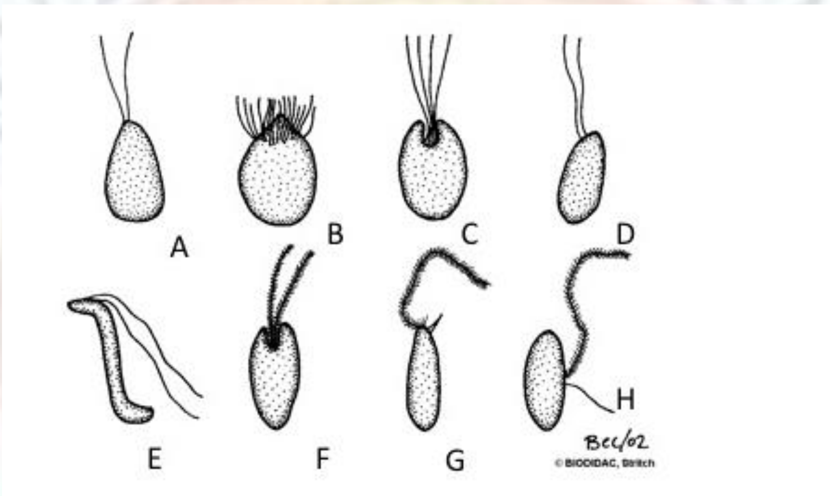


Figure: The point of insertion of flagella varies in different algal groups

Source:http://biodidac.bio.uottawa.ca/ftp/BIODIDAC/Botany/General/DIAGBW/Bota014b.gif

In a transverse section examined under the electron microscope, a flagellum (axoneme) is seen to consist of two central microtubules surrounded by a ring of nine doublet microtubules. In the transitional region the two central microtubules terminate and the triplets fuse to form a stellate structure.

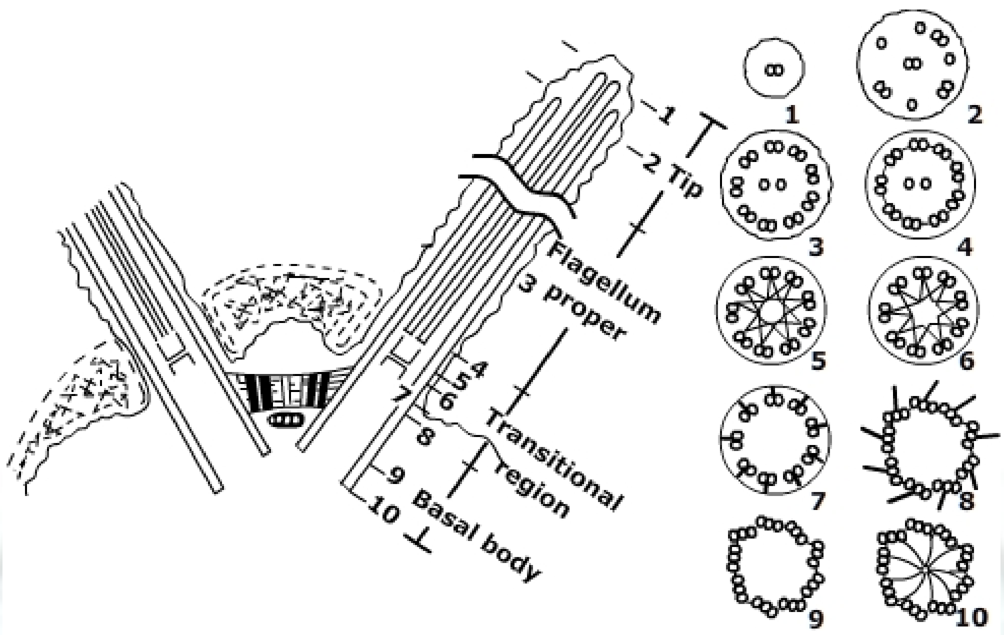
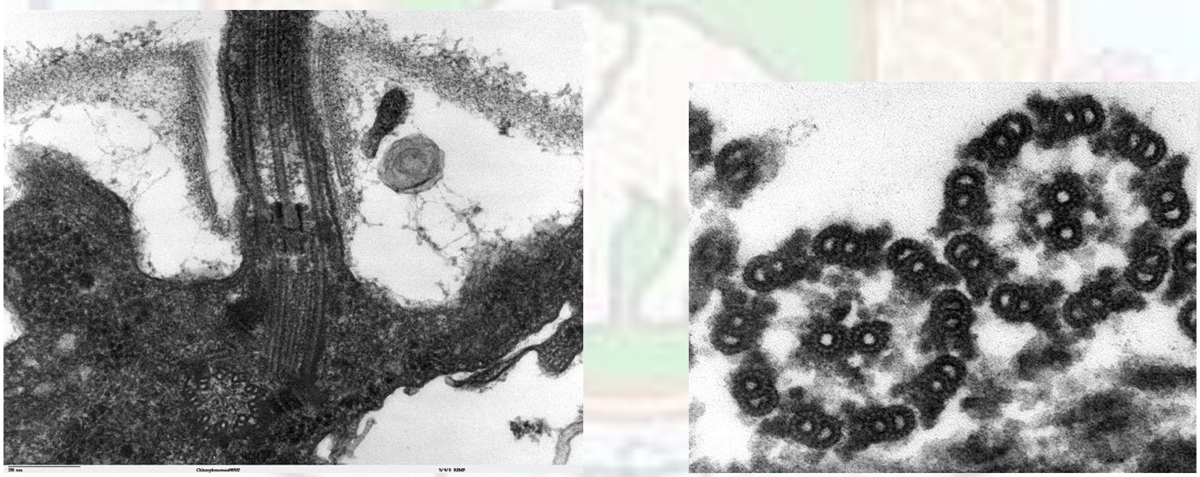


Figure: Diagrammatic representation of flagella showing details of cross section of the flagella at various levels. The numbers refer to the sections.

Source: Author



A B

Image: A. Longitudinal section through the flagella area. In the cell apex is the basal body that is the anchoring site for a flagella. Basal bodies originate from and have a substructure similar to that of centrioles, with nine peripheral microtubule triplets(see structure at bottom center of image). The two inner microtubules of each triplet in a basal body become the two outer doublets in the flagella. This image also shows the transition region, with its fibers of the stellate structure. The top of the image shows the flagella passing through the cell wall.

B. Section cut through the isolated axoneme. *Chlamydomonas* flagella have the "9+2" structure characteristic of all eukaryotic cells. The axoneme has a central unit containing two single microtubules and nine peripheral doublet microtubules (known as the "9+2"). Dynein side arms project from the A tubule of each doublet. Also visible in this image are the radial spokes and the inner sheath.

Source:http://upload.wikimedia.org/wikipedia/commons/thumb/9/99/Chlamydomonas_TEM_09.jpg/751px-Chlamydomonas_TEM_09.jpghttp://upload.wikimedia.org/wikipedia/commons/thumb/8/82/Chlamydomonas_TEM_16.jpg/751px-Chlamydomonas_TEM_16.jpg

The outer membrane seems continuous with the plasma membrane of the cell. At the base of the flagellum lies a basal body and often attached to this body are either some microtubular roots or striated fibrillar roots. The microtubular roots extend into the protoplasm. The striated fibrillar roots are characterized by the presence of groups of fibers having striations along their length.

The mastigonemes found on some flagella may be of two types, viz, (1) fibrous and solid hairs- these are solid fibrils 5-10nm , and (2) tubular. The tubular (tripartite) hair composed of a basal region attached to the flagellar membrane, microtubular shaff, and a terminal fibril.

The flagella of some algae (e.g. *Micromonas*) are covered with scales. In *Chrysochromulina*, an additional flagellum like structure called haptonema, is present which can coil and anchor the cell to the substratum.

Plastids

The basic type of plastid in the algae is a chloroplast, an organelle capable of photosynthesis. A leucoplast or amyloplast is a colorless plastid that has become adapted for the accumulation of storage product. A proplastid is a reduced plastid with few if any thylakoids. A plastid will usually develop into a chloroplast although in some heterotrophic algae it remains a proplastid.

In algae plastid which is coloured other than green is called chromatophore. These lack chlorophyll-*b* and contain other pigments like chlorophyll – *c,d,e* etc.

According to its location in a cell, the chromatophore may be parietal or axial. In the Cryptomonads, Prasinophytes, and motile colonial green algae, only a single chromatophore is usually present in a cell but the members of the Conjugales, Siphonales, Charales, Tribophyceae, some Dinoflagellates, and many diatoms generally contain more than one chromatophores per cell. The morphology of the chromatophore varies considerably in different algae but the following main types can be recognized (1) cup-shaped, as inn *Chlamydomonas*, (2) girdle-shaped, as in *Ulothrix* (3) discoid, as in *Vaucheria* and *Chara*; (4) reticulate, as in *Oedogonium*; (5) spiral as in Spirogyra; and (6) stellate as in *Zygnema*.

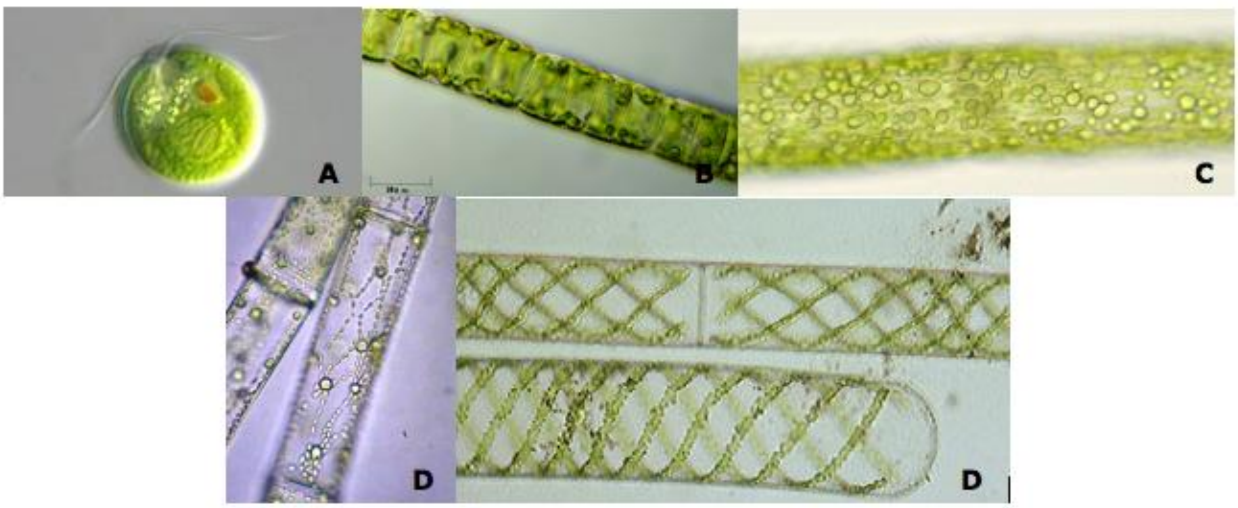


Figure: Types of chloroplasts in algae: A. cup shaped- *Chlamydomonas,* B. girdle shaped- *Ulothrix,* C. discoid- *Vaucheria,* D. reticulate- *Oedogonium,* E. spiral- *Spirogyra*

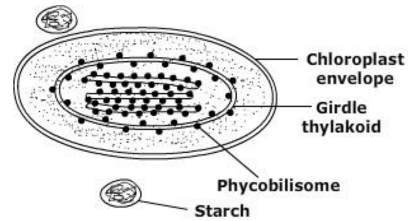
Source: http://content62.eol.org/content/2012/07/30/05/99002_580_360.jpg,
http://content61.eol.org/content/2011/11/01/23/29357_580_360.jpg,
http://content60.eol.org/content/2012/12/05/18/75076_580_360.jpg,
http://4.bp.blogspot.com/_Ne3bhx2j74s/TDt0dld4KDI/AAAAAAAAC5M/Xf0Qi3T-dmE/s1600/oedogoniumIMGP2524.jpg,
http://content60.eol.org/content/2012/12/04/15/76416_580_360.jpg

In some diatoms and in the Dinoflagellate *Pyrocystis lunula*, the chromatophores can change their shape and location within the cell in response to light. Light induced rotation of a chloroplast, mediated by phytochrome, occurs in the desmid *Mesotaenium*.

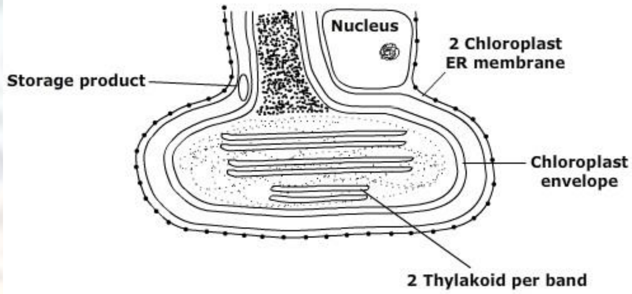
The electron microscopy of the algal chromatophore has revealed that it is generally a double – membrane structure composed of a photosynthetic lamellar system traversing the colourless granular matrix, the stroma. The structural unit of the lamellar system is a closed double membrane disc termed thylakoid. A thylakoid membrane consists of a central lipid layer covered on both sides with protein particles, the lipid layer containing the fat-soluble photosynthetic pigments. The water-soluble pigments (phycoerythrin and phycocyanin) of the Rhodophyceae and Cyanophyceae are located in characteristic particles, termed phycobilisomes, which are found linearly arranged along the surface of each thylakoid.

The chromatophore envelope is double-membraned in the Rhodophyta, Chlorophyta and Charophyta. In most other classes of eukaryotic algae, it is surrounded by one or two membranes of the chloroplast endoplasmic reticulum, which has ribosomes attached to the outer surface of the membrane. In the Cryptophyceae is unique in processing a nucleomorph, ribosomes, and storage granules in the compartment between the chloroplast and chloroplast endoplasmic reticulum.

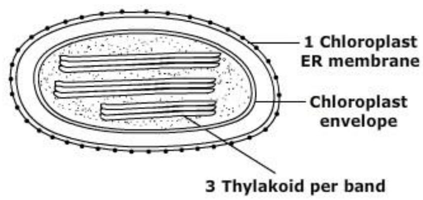
In the Rhodophyceae, the thylakoids are widely separated and occur singly like cyanophycean thylakoids. In all other classes, they are stacked together into bands. The Phaeophyceae generally contain a band of three thylakoids. In the Chlorophyta and Euglenophyceae, a band of 4-6 thylakoids predominates.



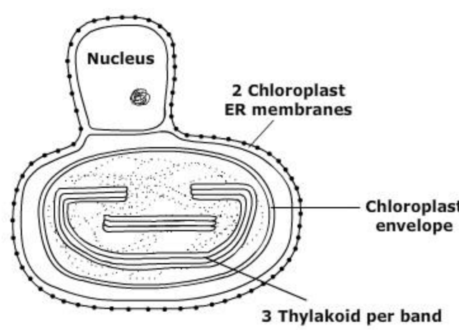
(a) Rhodophyta



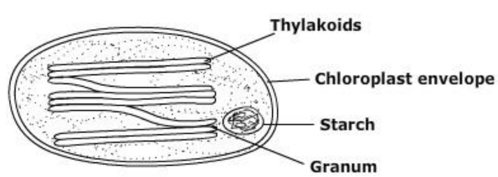
(b) Cryptophyta



(c) Dinophyta & Euglenophyta



(d) Prymnesiophyta & Heterokontophyta



(e) Chlorophyta

Figure: Types of chloroplasts

Source: Author

The chromatophores of most algae have electron-translucent areas containing DNA fibrils. In algae with a girdle band, e.g.,Ochromonas, the plastid DNA is located in a peripheral circular nucleoid inside the chromatophores, but in algae lacking girdle bands, in general, the DNA areas are randomly scattered in the chromatophore matrix. Another characteristic feature of the chromatophore which is of some taxonomic or phylogenetic significance concerns the location and storage of starch grains. In the green algae, starch grains are stored within the chloroplast; in the dinoflagellates and red algae, in the cytoplasm outside the chromatophores, but the Cryptophyceae, they are stored between the wall of the chromatophore and the sac of endoplasmic reticulum present around the plastid, Figure 1-6 illustrates a few types of chloroplast found in various classes.

The chromatophores are genetically semiautonomous systems containing histone-free DNA, messenger RNA, transfer RNA and ribosomes. Besides, new chloroplasts always arise from pre-existing ones. These features have made it highly probable that chromatophores are subcellular symbionts which had their origin in free-living photosynthetic prokaryotes.

Pyrenoid- A pyrenoid is a differentiated region within the chloroplast that is denser than the surrounding stroma that may or may not be traversed by thylakoids. A pyrenoid is frequently associated with storage products. Pyrenoids occur within every class are considered to a primitive evolutionary characteristic. Pyrenoids contains ribulose 1,5 biphosphate carboxylase (Rubisco) the enzyme that fixes carbon dioxide.

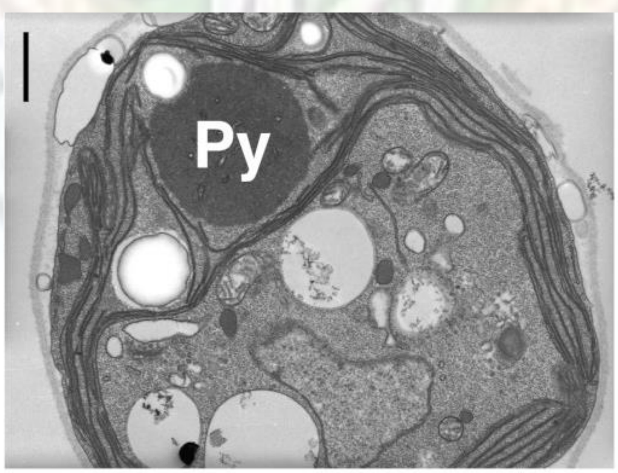


Figure: Electron micrograph of *Chlamydomonas* showing the pyrenoid(Py)

Source: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3511088/figure/fig01/

Photosynthetic pigments

The photosynthetic algae have chlorophyll in their chloroplasts. Chlorophyll has a chemical structure similar to that of Haemoglobin and is composed of a porphyrin ring system but has a magnesium atom instead of an iron atom.

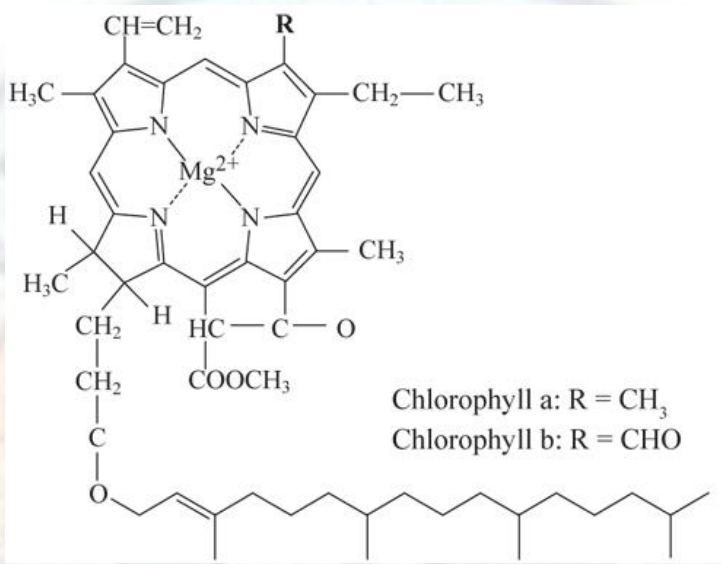


Figure: The structure of chlorophyll

Source: http://eng.thesaurus.rusnano.com/upload/iblock/46b/chlorofill_1.jpg

There are four types of chlorophyll found in algae- Chlorophyll *a, b, c, d*. The chlorophyll *a* is the primary photosynthetic pigment found in all photosynthetic algae.

Chlorophyll	**Found in the algal group**	**Solubility**	**Absorption spectrum**
a	In all photosynthetic algae	Insoluble in water and soluble in alcohol, diethyl ether, benzene and acetone.	Two absorption bands-663 nm and 430 nm.
b	Euglenophyta and	Insoluble in	645 nm and

	Chlorophyta	water and soluble in alcohol, diethyl ether, benzene and acetone.	435nm
C is distinguished in two spectrally different components: c_1 and c_2	Dinophyta, Cryptophyta and most of the Heterokontophyta	Insoluble in water and petroleum ether. Soluble in ether, acetone, methanol and ethyl acetate.	c_1 absorbtion maxima- 634, 583, 440 nm. c_2 – 635, 586, 452 nm.
d	Rhodophyta	Insoluble in water and soluble in alcohol, diethyl ether, benzene and acetone.	Main absorption bands in 696, 456 and 400 nm.

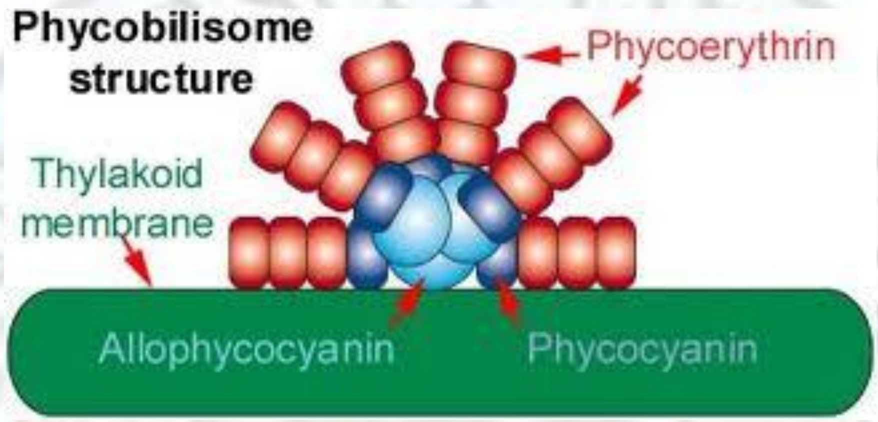
The Chlorophyll *a* act as the photochemical reaction center where light energy is converted to chemical energy.The other chlorophyll molecules act as light harvesting complexes that function as antenna molecules to collect and transfer the energy to the reaction centre.

In algae also have **carotenoids** the yellow, orange and red colored pigments. There are two naturally occurring classes of carotenoids:

- The **carotenes**- the oxygen free hydrocarbons
- The oxygenated **xanthophylls**

B-Carotene is the most widespread carotene in algae. Amongst the xanthophylls **fucoxanthin** is the characteristic pigment found in Chrysophyceae, Bacillariophyceae and Phaeophyceae responsible for their characteristic color.

Phycobiliproteins are the water soluble blue and red pigments of the Cyanophyta and Cryptophyta. These pigments are referred to as chromoproteins which have the chromophore the tetrapyrole – **phycolbilin**. The phycobilin is inseparably attached to the protein part therefore the name – Phycobiliprotein. The two major chromophores are the blue colored phycocyanin and the red colored phycoerythrin. The phycobiliproteins are aggregated on the surface of the thylakoids to form **phycobilisomes.** The core of the phycobilisomes are made of allophycocyanin and the phycoerythrin and phycocyanin are stacked on it as outwardly directed rods.



Source: http://www.biologie.uni-hamburg.de/b-online/library/webb/BOT311/Rhodophyta/PhycobilisomeDraw_small.jpg

Table: The distribution of algal pigments in some of the groups.

Source: Authors

	Cyanophyceae	**Rhodophyceae**	**Xanthophycese**	**Phaeophyceae**	**Chlorophyceae**
Chlorophyll Chlorophyll a	□	□		□	□
Chlorophyll b					□

Chlorophyll c_1			✓	✓	
Chlorophyll c_2				✓	
Chlorophyll d		✓			
Chlorophyll e			✓ (in some genera)		
Phycobilins Phycocyanin	✓	✓			
Allophycocyanin	✓	✓			
Phycoerythrin	✓	✓			
Phycobilisomes	✓	✓			
Carotenes **α**Carotene		✓			
βCarotene	✓	✓	✓	✓	✓
Xanthophyll	✓	✓			

Stigma or Eyespot

Chloroplasts commonly contain small (30-100nm), spherical lipid droplets between their thylakoids. These lipid droplets serve as a pool of lipid reserve for the synthesis and growth of lipoprotein membranes within the chloroplast.

Many motile algae have groups of tightly packed carotenoid lipid globules that constitute an orange-red eyespot or stigma. These globules shade the photoreceptor, an area of the plasma membrane or flagella or chloroplast envelope containing specialized molecules. For example, the photoreceptor in motile cells of the green algae *Chlamydomonas* consist of a chromophore (coloured substance) linked to a protein that is embedded in the plasma membrane.

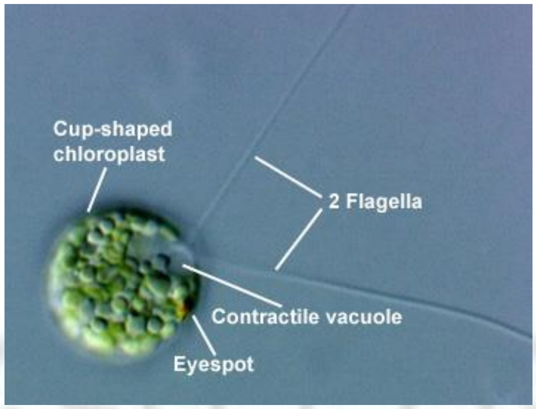
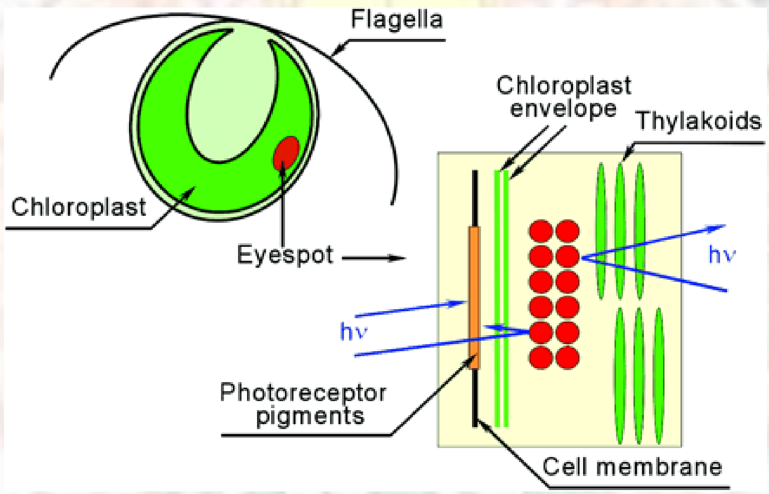


Figure: *Chlamydomonas*

Source:http://silicasecchidisk.conncoll.edu/Pics/Other%20Algae/Green_jpegs/Chlamydomonas_Key100.jpg



Source: http://www.pnas.org/content/99/13/8463/F1.medium.gif, Thomas G. Ebrey. 2002. A new type of photoreceptor in algae. PNAS. 99(13): 8463-8464.

The choromophore is 11-cis-retinol, a rhodopsin that functions as a photoreceptor in animals. As the alga swims through the medium it also rotates along the axis it is moving. The photoreceptor is shaded for varying periods of time by the eyespot (normally a group of lipid droplets near the photoreceptor), depending on the orientation of the alga to the light. The shading results in a change in the membrane potential of the plasma membrane by a photo inductive phenomenon involving rhodopsin. The change in membrane potential causes an influx of cations into the cell, which affects the beating of the flagella and the direction of cell movement. A motile cell may swim toward (positive photoaxis) or away from (negative photaxis) light. At high light intensities most zoospores are negatively phototactic, whereas at low light intensities they are positively phototactic.

In the Chlorophyta, Cryptophyta and most of the Heterokontophyta, the eyespot occur as lipid droplets in the chloroplast. In the Englenophyta, Eustigmatophyceae and Dinophyta, the eyespot occurs as a group of membrane bounded lipid droplets, free of the chloroplast.

Nuclei and chromosomes

Most eukaryotic algae have typical, organized nuclei, and chromosomes. In dinoflagellates, a nuclear membrane is present; during mitosis, the chromosomes of dinoflagellates attach to the nuclear membrane rather than to the spindle directly, and they lack centromere.

The nucleus is bounded by two unit membranes of which the outer is continuous with the membranes of the endoplasmic reticulum. The nucleus envelope is transversed by numerous pores. In the Tribophyceae, Chrysophyceae, Bacillariophyceae, and Phaeophyceae, the nuclear envelope is intimately associated with a sac of the endoplasmic reticulum found around the chromatophores but no such plastid endoplasmic reticulum is met with in the Chlorophyceae and Rhodophyceae. The interphase nuclei of most eukaryotic algae contain uncoiled and expanded chromosomes, but in the Euglenophyceae and Dinophyceae, the chromosomes, which lack centromeres, remain condensed. The persistence of the nuclear wall during mitosis, the attachment of chromosome to the nuclear wall, the lack of centromeres, and the absence of a compact spindle are primitive features.

The nucleoli and chromosomes remain suspended in the granular matrix of the nucleus. In general, there is a single nucleolus per nucleus but in Conjugales, for instance, there may be a several nucleoli in a nucleus.

In the Euglenophyceae, the nuclear membrane and nucleolus persist throughout the division cycle, whereas in the most other algae, the nucleoli break up during division and are reorganized after the completion of the nuclear division by a nucleolar-organizing chromosome.

In some species of *Spirogyra* and *Zygnema*, the nucleolar organizing chromosomes are associated with satellite chromosomes. The nuclear division may or may not be accompanied by wall formation. In the Conjugales, the chromosomes have diffused centromeres.

Characteristic synaptonemal complexes occur in the meiotic nuclei of some red and brown algae. Under the electron microscope, a synaptonemal complex consists of two lateral longitudinal rods which give rise transversely to minute fibrils extending inward. Each such complex is believed to correspond to a bivalent. The existence of synaptonemal complexes is the most reliable evidence for meiosis not only in algae but also in higher plants.

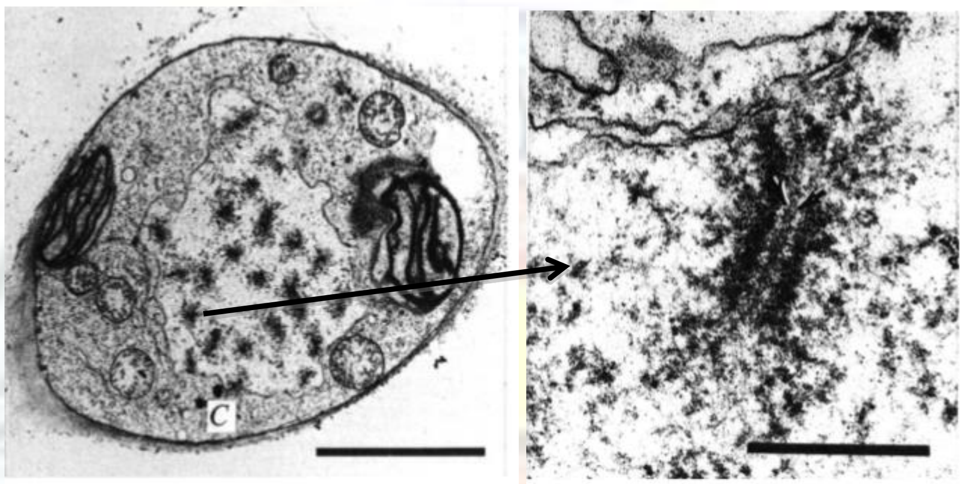


Figure: Electron micrograph showing synaptonemal complex (arrow) in *Chorda tomentosa*

Source: Toth, R and Markey, D.R. 1973. Nature Vol 243: 236-237.

Mitochondrion and Peroxisomes

There are two types of mitochondria in algal cells. Mitochondria with flat lamellae cristae occur in the red algae, green algae, euglenoids and cryptophytes. These algae have either phycobilisomes or chlorophylls a and b. Mitochondria with tubular cristae occur in heterokonts and haptophytes.

A **B**

Figure: Two types of mitochondria exist in algae A. with flat cristae and B. with tubular cristae.

Source: Author

Glycolate, the major substrate of photorespiration, can be broken down by either glycote dehydrogenase in the mitochondria, or by glycolate oxidase in peroxisomes, single membrane- bounded organelles found in the cytoplasm. The distribution of the 2 enzymes is as follows:

1) Glycolate dehydrogenase occurs in the cyanobacteria, cryptophytes, euglenids, diatoms and the green algae with exception of the Charophyceae.
2) Glycolate oxydase occurs in the glaucophytes, red algae, brown algae the charophyceae in the green algae and higher plants.

Endoplasmic Reticulum

A system of tubules and vesicles traversing the cytoplasm and termed the endoplasmic reticulum is present in all eukaryotic algal cells. These tubules appear to have some ribosomes disposed along their surface. The function of these ribosomes is to synthesize proteins or enzymes.

Vacuoles

The mature cells of eukaryotic algae have one or more vacuoles bounded by distinct membranes. These vacuoles play an important role in osmotic relations and the absorption of solutes and water.

In motile algae, two types of vacuolar apparatus are recognized, namely, (1) the simple vacuoles, called **contractile vacuoles**, which contract periodically and expel their contents to the exterior as in the green alga *Chlamydomonas.*

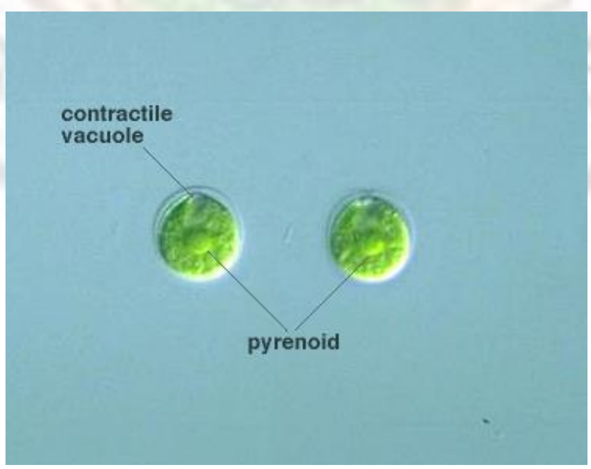


Figure: *Chlamydomonas sp. showing the contractile vacuole*

Source:http://protist.i.hosei.ac.jp/pdb/images/chlorophyta/chlamydomonas/Chlamydella/sp_4b.jpg

and (2) **the complex apparatus**, which consists of a cytopharynx (canal), a reservoir, and a group of vacuoles of varying size as is characteristic of the Euglenophyceae and Dinophyceae and some members of the Chrysophyceae. The smaller vacuoles feed their contents into one larger vacuole which then empties and releases the contents into the reservoir. A periodical contraction of the reservoir then expels the contents to the outside through the cytopharynx. In some holozoic algae, the cytopharynx functions as a gullet (for ingesting food particles) besides being an emptying canal for the vacuoles.

Ejectisomes

Many flagellates contain ejectile organelles. Some of these are sac-like bodies that produce and release mucilage. *Chattonella* (Chloromonadophyceae) produces some mucus which contains palmitic acid and can kill fish. Others may be discoidal or rolled up ribbons. The ejectile bodies of the dinoflagellate *Nematodinium* are so elaborate that they resemble the nematocysts of coelenterates and may possibly function in prey capture. This idea is supported by the presence of distinct ocelli which partly resemble the "eyes" of lower invertebrates.

Figure: *Chilomonas* having a ejectsome and an anterior contractile vacoule

Source:http://protist.i.hosei.ac.jp/movies/htmls/Mastigophora/Chilomonas/paramecium2.jpg, http://protist.i.hosei.ac.jp/pdb/C-L.Wang/Chilomonas/Chilomonas.jpg

The ejectisomes of *Chilomonas* and other cryptomonads typically occur in two sizes. The smaller ones, prior to ejection, occur in close association with the plasma membrane of the outer body surface. In contrast, the larger ejectisomes are associated with the gullet membrane. The two types further differ in respect of their intra membrane particle distribution. In small ejectisomes, the portion of the membrane in contact with the cell's plasmalemma has a rosette of fine particles; these ejectisomes and the plasma membrane both contain clumps of particles a short distance from the site of contact (called the docking site). The larger ejectisomes seem to lack rosettes. The particle clumps of *Chilomonas* broadly resemble the clusters of intramembrane particles of *Tetrahymena;* these latter particles are involved in the attachment of mucocysts to the plasma membrane.

Ribosomes: Ribosome fall into two general classes, based as their sedimentation coefficients in an ultracentrifuge (expressed in Sved Berg units or S) (1) the smaller 70 S prokaryotic type of ribosomes found in bacteria, cyanophyta, chloroplast and mitochondria and (2) the 80 S eukaryotic type of ribosomes found in the cytoplasm of eukaryotic cells outside the chloroplast and mitochondria.

Algal Reproduction

Algal reproductive cycles, both sexual and asexual, are also very diverse and sometimes not very well shown. However, the reproductive strategies found in various algae must be highly correlated with other aspects of the organisms Physiology & ecology.

ASEXUAL REPRODUCTION

A number of the more common processes and structures involved in asexual reproduction are discussed below.

1. **Cellular bisection** In many unicellular algae reproduction is simply by longitudinal or transverse cell division.

2. **Zoospore and aplanospore formation** – Zoospore are flagellate reproductive cells that may be produced within vegetative cells or in specialized cells, depending on the organism. They may be uninucleate (*Ulothrix*) or multinucleate (*Vaucheria*) and bear two or more flagella (*Ulothrix*) or a large number of flagella (*Vaucheria*). Multinucleate multiflagellate zoospore is referred to as synzoospore (*Vaucheria*). Zoospores after a shrt period of rest develop into new plants. Sometimes, rather than forming flagella, the spores perennate inside the parental cell or sporangium

when the conditions are not favourable. These non-motile spores are termed aplanospores (*Ulothrix, Chlorella, Drapernaldia*).

3. **Autospore or monospore production** –Autospores (green algae) and monospores (red algae) are also non-motile spores with cell wall and are enlarged, compared to typical vegetative cells. These are resistant structure with large amounts of stored food reserves that allow the alga to survive harsh environmental conditions germinating only under the favorable conditions.

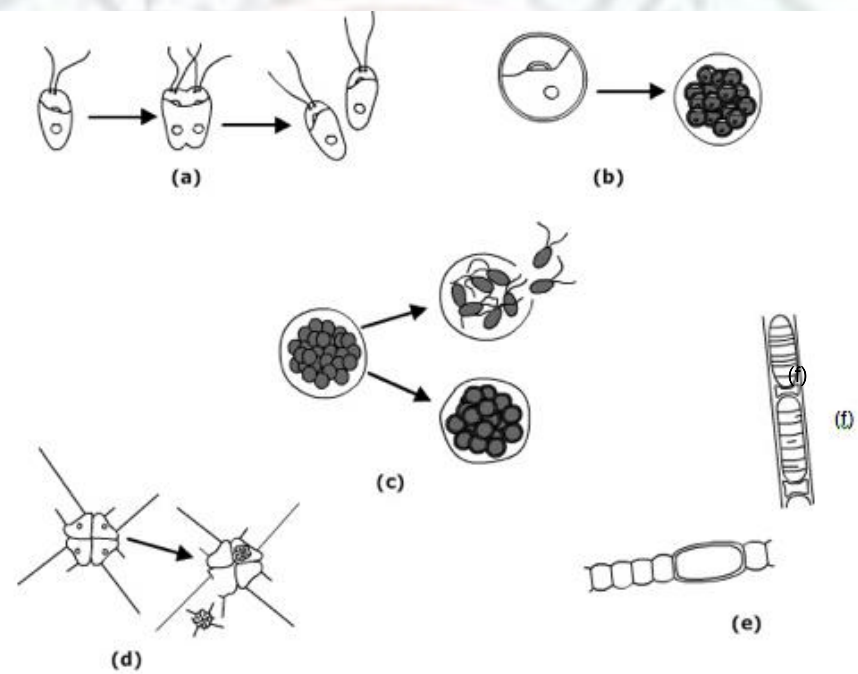


Figure: Reproduction by (a) cellular bisection (b) Autospores (c) Aplanospores(non motile) and zoospores (motile) (d) Autocolony formation (e) Akinete (f) Hormogonium

Source: Author

Sexual Reproduction

Sexual reproduction involves the formation and fusion of gametes. Three types of sexual reproduction based on structure and function of the gametes is distinguished:

1. Isogamy- Fusion of morphologically and physiologically similar gametes. The gametes are referred to as plus (+) and minus (-) strains.

2. Anisogamy- The motile gametes are structurally and/or morphologically different. The larger is the female and the smaller is the male. Physiological anisogamy refers to the presence of a sluggish female gamete.

3. Oogamy- The fusion of large non-motile egg or ovum with a smaller motile male gamete (except in Rhodophyta where the reproduction is oogamous but the male gamete or sperm is non motile). The egg are found in the oogonium and the sperm within the anthredium.

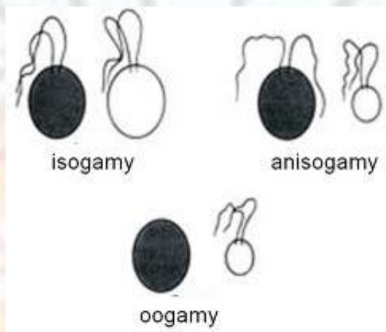


Figure: Isogamy- The fusion of two identical gametes, Anisogamy- Fusion of two gametes different in size , Oogamy - Fusion between one large, non-motile female gamete and a smaller motile male gamete.

Source: Author

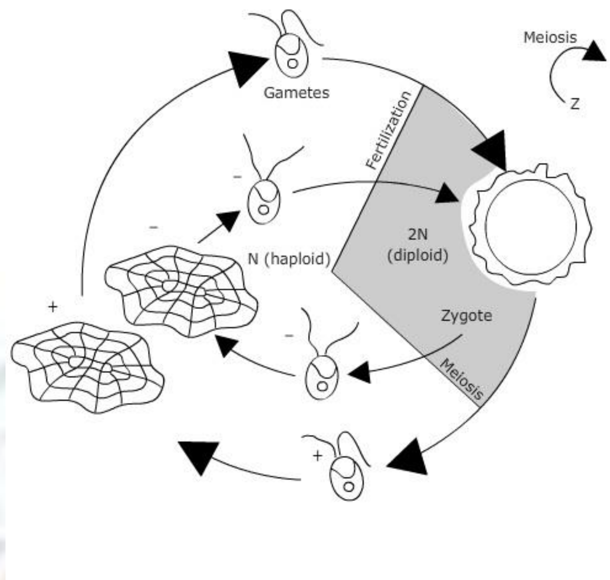
The species may be described as homothallic or heterothallic.

Homothallic (monoecious) species gametes of different mating types are formed on the same plant.

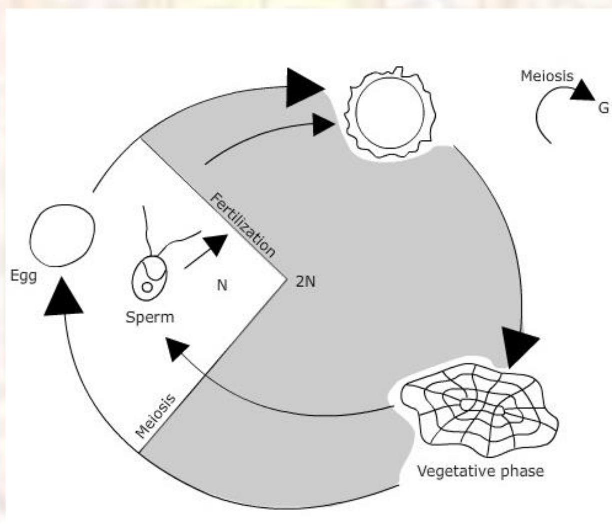
Heterothallic (dioecious) species the gametes of different stains are formed on different plants.

Life Cycle Patterns

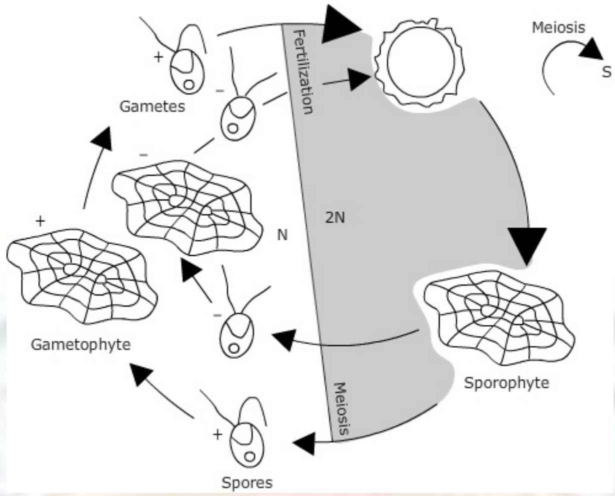
Sexual reproductive cycles in most algae can be generalized to fit one of the three basic patterns.



A. Zygotic meiosis



B. Gametic meiosis



C. Sporic meiosis

Figure: Sexual reproduction in algae

Source: Author

They differ from one another in the point at which meiosis occurs and in the ploidy state (haploid or diploid) of the mature organism. In the first case, the mature individual is haploid, the only diploid cell in the cycle is the zygote and meiosis occurs upon germination of the zygote (hence **zygotic meiosis**). The zygote in this type of cycle often undergoes a period of dormancy, a state in which the alga is able to withstand unfavourable environmental conditions. This type of cycle is, therefore, more common among freshwater and terrestrial algae than among those in the more stable marine environments.

In second life cycle pattern the mature individual is diploid and undergoes meiosis during gamete formation (hence **gametic meiosis**). The gametes are the only haploid cells in this type of cycle. The zygote usually germinates without undergoing a period of dormancy.

In the third pattern both haploid and diploid, free living individuals occur in what is termed a life cycle involving an alternation of generations. The haploid phase (gametophyte) releases gametes which fuse to form the zygote which in turn grows into the diploid phase (the sporophyte). Meiosis occurs during the production of haploid spares in the sporophyte (hence **sporic meiosis**). The haploid and diploid phases of the life cycle may resemble one another (an alternation of isomorphic generations) or may differ morphologically (an alternation of heteromorphic generations). In some case the two phases of the heteromorphic cycle were originally as different genera.

The third life pattern is common among brown and red algae as well as in some of the marine green algae. The life cycle in red algae is referred to as **triphasic** as it consists of a haploid gametophyte, a diploid carposporophyte and another diploid tetrasporophyte.

The third type of life cycle also typifies the land plants. It is quite clear that the type of life cycle has evolved multiple times. Therefore, the possession of this life history pattern by plants and a particular algae should not be taken as evidence of a close relationship between the two.

Classification

Chlorophyll is present in all groups of algae but in same groups pigments other than chlorophyll are dominant and mask the green colour of chlorophyll. On the basis of their colour following four groups were recognized.

(i) Cyanophyceae (blue-green algae) dominant pigment – C- phycocyamin.
(ii) Chlorophyceae (green algae) dominant pigment chlorophyll a and b.
(iii) Phaeophyceae (brown algae) dominant pigment fucoxanthin.
(iv) Rhodophyceae (red algae) dominant pigment phycocrythrin.

In the last few decades a lot of information has become available on the structure, reproduction and physiological processes of algae which has been used to develop more natural system of classification.

Although specialists do not agree on the details of algal classification algae are generally classified on the basis of the following characteristics:

1. Nature and properties of pigments.
2. Chemistry of reserve food products or assimilatory products of photosynthesis.
3. Type and number, insertion (point of attachment) and morphology of flagella.
4. Chemistry and Physical features of cells and thalli.
5. Morphological characteristics of cells and thalli.
6. Life history, reproductive structures and methods of reproduction.

Classification by Smith

The classification of algae proposed by Smith (1933,51,55) is based on the physiological characteristics of vegetative cells and the morphology of motile reproductive cells. He divided algae into seven divisions and then related classes were included in each division. According to him, the number of divisions necessary for complete classification of algae less than the number of classes as those classes which show close affinity should be placed in the same divison. For example, Xanthophyceae, Chrysophyceae and Bacillariophycear show certain resemblances in the structure and composition of the cell wall, flagellation and nature of food reserves and despite differences in their pigment there is enough ground for placing them together in the same division Chrysophyta. The seven divisions of algae recognized by Smith are as follows:

Division 1. Chlorophyta

Class 1. Chlorophyceae (grass-green)

Class 2. Charophyceae

Division 2 Englenophyta

Class 1 Englenophyceae

Division 3 Pyrrophyta

Class 1 Desmophyceae (dinophysids)

Class 2 Dinophyceae (dimoflagelloids)

Division 4 Chrysophyta

Class 1 chrysophyceae (golden brown)

Class 2 Xanthophyceae (yellow green)

Class 3 Bacillariophyceae (diatoms)

Division 5 Phaeophyta (brown algae)

Class 1 Isogenerateae

Class 2 Heterogenerateae

Class 3 Cyclosporeae

Division 6 Cyanophyta (Blue Green algae)

Class 1 Myxophyceae

Division 7 Rhodophyta (Red Algae)

Class 1 Rhodophyceae

Algae of uncertain Systematic position

Chloromonadales

Cryptophyceae

Classification proposed by Fritsch

The first most comprehensive and authorative classification of algae was given by F.E Fritsch (1935,48) in his book. The structure and reproduction of the Algae. His classification was based on such criteria as pigmentation types of flagella, assimilatory products, thallus structure and methods of reproduction. He divided algae into the following 11 classes.

1. **Myxophyceae (Cyanophyceae)**. Plants simple, no definite nucleus, chromatophores and motile cells; reproduction by fission; pigments *phycocyanin* and *phycoerythrin* in addition to chlorophyll; commonly blue-green; products of photosynthesis sugar and glycogen; sexual reproduction absent, e.g. *Nostoc, Anabaena, Rivularia, etc.*

2. **Euglenophyceae**. (Flagellates). Plants unicellular, combining characters of plants and animals. Fresh- water or salt- water, mostly solitary and free-swimming, but some form gelatinous colonies and some are attached. Plants motile, green, with one or two cilia, nucleus, contractile vacuole, chloroplasts and prominent eye spot; reproduction by fission only, e.g. Euglena, Heteronema, etc.

3. **Chlorophyceae**. Plants variable in structure with definite nucleus, chloroplasts and motile reproductive cells bearing variable number of flagella; commonly green due to *chlorophyll*; products of assimilation starches and sugars; sexual reproduction ranges from isogamy to anisogamy and oogamy, e.g. *Volvox, Ulothrix, Spirogyra, Vaucheria, etc.*

4. **Chloromonadineae**. Plants bright - green with excess of *xanthophyll*; products of assimilation fats; chloroplasts many, discoid; reproduction by longitudinal division of individuals. Not much is known about the representatives of this class as yet.

5. **Xanthophyceae (Heterokontae**). Chloroplasts yellow-green owing to an excess of xanthophyll; oil replaces starch; flagella two, of unequal lengths; sexual reproduction rare, but isogamous; cell wall of two equal or unequal halves, overlapping each other, e.g. *Botrydium, Tribonema*, etc.

6. **Chrysophyceae**. Plants primitive; chloroplasts brown or orange due to the presence of accessory pigments such as phycochrysin; cell wall may or may not be present; fat and leucosin (aprotein- like substance) are usual forms of food storage; cysts silicified; motile cells with one, two, rarely three equal flagella, rarely unequal; sexual reproduction rare but isogamous when present, e.g. *Chromulina, Chrysamoeba*, etc.

7. **Bacillariophyceae** (Diatoms). Cell wall partly silicified and partly pectose, symmetrical halves ornamented with delicate markings; chromatophores yellow or golden-brown, one set of forms radially symmetrical, the other bilaterally so; sexual reproduction isogamous or anisogamous, e.g. *Pinnularia, Navicula, Melosira,* etc.

8. **Cryptophyceae**. Each cell with two large parietal chloroplasts with diverse colours though frequently of a brown shade; starch as product of photosynthesis; motile cells with two unequal flagella; mostly flagellate forms; sexual reproduction isogamous in one species only; cysts common and endogenous, e.g. *Cryptomonas, Chilomonas*, etc.

9. **Dinophyceae** (Peridineae). Most members unicellular and motile with a tendency towards filamentous habit: cell wall sculptured; chromatophores discoid, dark-yellow or brown in colour; starches and fats are product's of photosynthesis ; motile cells with a longitudinal and transeverse furrow, bifagellate ; sexual reproduction rare. But isogamous when present, e.g. *Heterocapsa, Ceratium, Peridinium*, etc.

10. **Phaeophyceae.** Mostly marine; colour brown due to the presence of a brown pigment, the *fucoxanthin*; products of photosynthesis alcohols, fats, polysaccharides and sugars; plants filamentous, or highly organized into large sea weeds with internal and external differentiation; reproductive cells biflagellate, the flagella attached to one side, one directed forward and other backward, produced in uni-or plurilocular sporangia; sexual reproduction iso-aniso-or oogamous, e.g. *Ectocarpus, Fucus, Dictyota, Laminaria, etc.*

11. **Rhodophyceae.** Mostly marine, only a few fresh-water, coloured blue or violet, etc. due to the presence of *phycoerythrin* and *phycocyanin;* products of photosynthesis floridean starch; reproductive cells non-flagellate; plants filamentous or highly organized showing complex differentiation, though not as in phaeophyceae; protoplasmic connections present between cells of all forms except proto-florideae; sexual reproduction oogamous; male cells or spermatia carried by water currents to the trichogyne of the female cell ; cystocarps procuce carpospores which germinate to produce tetrasporic diploid plants ; alternation of generations common, e.g. *Nemalion, Batrachospermum, Ploysiphonia,* etc.

12. **Nematophyceae.** A fossil group with two genera. Whose true affinities are still doubtful; internal morphology akin to higher Chlorophyceae, while spore tetrads akin to Rhodophyceae.

Classification by R.E Lee

There are 4 distinct groups within the algae.

Group 1 – It contains the only prokaryotic algae, the Cyanophyta or blue-green algae. It forms a natural group by virtue of being the only prokaryotic algae.

Prokaryotic algae have an outer plasma membrane enclosing protoplasm containing photosynthetic thylakoids, 70S ribosomes and DNA fibrils not enclosed within a separate membrane. Chlorophyll a is the main photosynthetic pigment and oxygen is evolved during photosynthesis.

Group 2 – It contains 1) Glaucophyta 2) Rhodophyta and 2) Chlorophyta. These form a natural group of algae in that they have chloroplasts surrounded by only the 2 membranes of the chloroplast envelope. The evolutionary event that led to the chloroplast occurred as follows. The uptake of a cyanobacterium by a protozoan into a food vesicle.This resulted in the establishment of an endosymbiosis between the cyanobacterium and the protozoan.

Through evolution, the endosymbiotic cyanobacterium evolved into a chloroplast surrounded by two membranes of the chloroplast envelope.

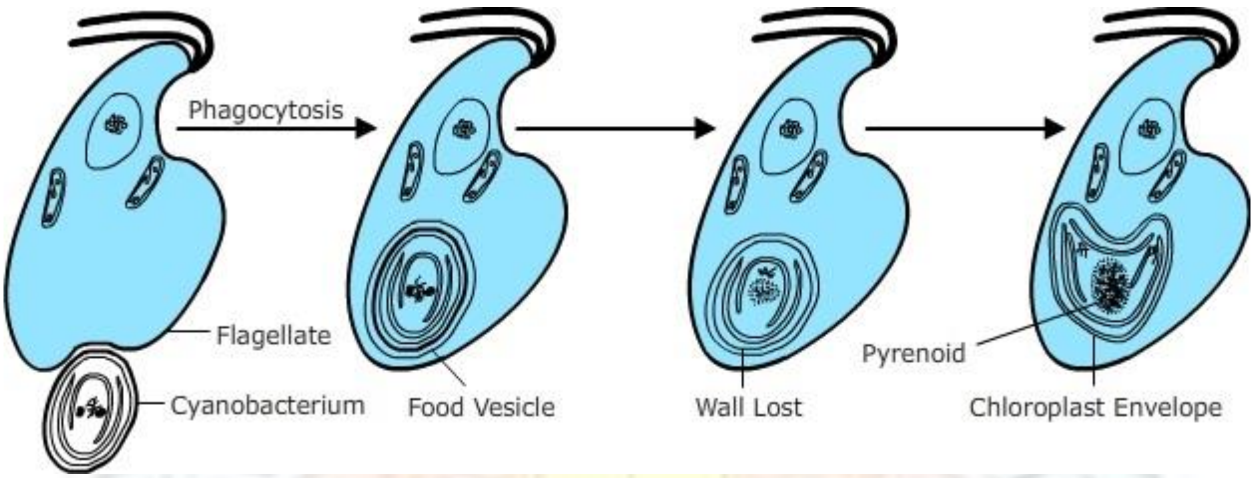


Figure: Primary endosymbiosis

Source: Author

During evolution the wall of the endosymbiotic cyanobacterium was lost to facilitate the transfer of compounds between the host and the endosymbiont. The food vesicle membrane of the phagocytotic host became the outer membrane of the chloroplast envelope. The plasma membrane of the cyanobacterium symbiont became the inner membrane of the chloroplast envelope. Rearrangement of the thylakoid membranes and evolution of polyhedral bodies into a pyrenoid completed the transition to a true chloroplast such as it occurs in green algae.

Glaucophyta represents an intermediate stage where they have endosymbiotic cyanobacteria in the cytoplasm instead of chloroplast. The host is called cyanome, the blue green alga is called cyanelle and the association between the two a syncyanosis.

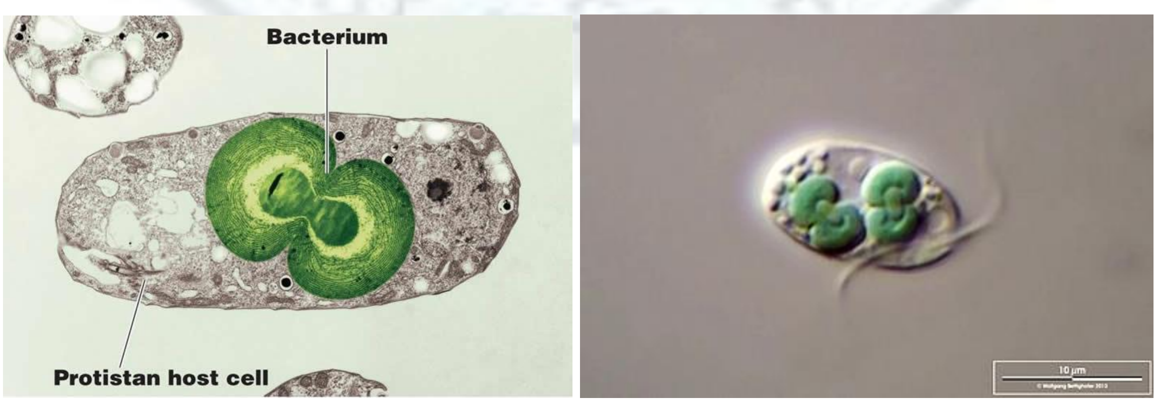


Figure: *Cyanophora paradoxa* a fresh water algae belonging to Glaucophyta has two cyanelles (endosymbiont cyanobacteria) where nitrogen fixation occurs along with photosynthesis.

Source: http://classes.midlandstech.edu/carterp/Courses/bio225/chap10/Slide3.JPG, http://starcentral.mbl.edu/msr/rawdata/viewable/cyanophora_paradoca_1362787195_a_543w.jpg

Group 3 -The Euglenophyta and Dinophyta are a natural grouping in that they are the only algal groups to have one membrane of chloroplast endoplasmic reticulum. Chloroplast endoplasmic reticulum resulted when a chloroplast from a eukaryotic alga was taken up to as a food vesicle by a phagocytotic euglenoid or dinoflagellate. Initially a chloroplast was taken up by a phagocytotic protozoan into a food vesicle. An endosymbiosis resulted, with the food vesicle membrane eventually evolving a single membrane of chloroplast endoplasmic reticulum surrounding the chloroplast.

Group 4- Algae with two membranes of chloroplast endoplasmic reticulum (chloroplast ER) has the inner membrane of chloroplast E.R. surrounding the chloroplast envelope. The other membrane of chloroplast ER is continuous with the outer membrane of the nuclear envelope and has ribosomes on the outer surface.

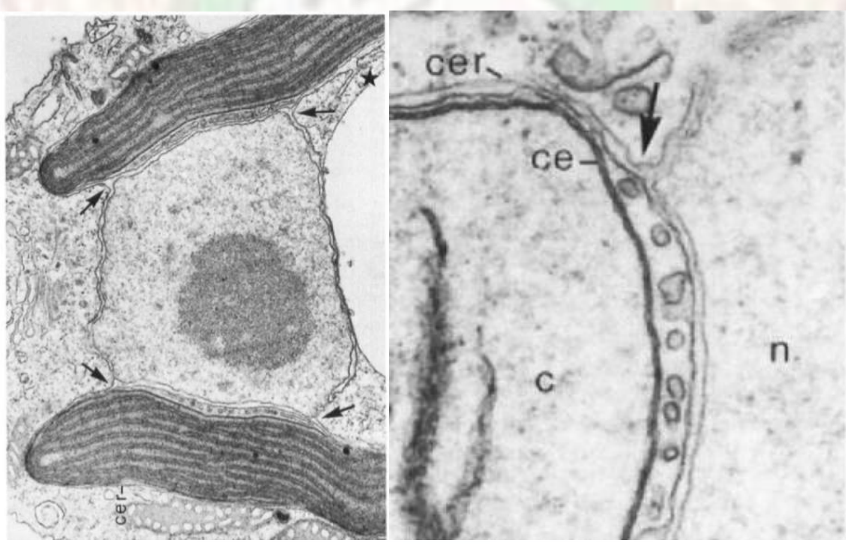


Figure: Section through the nucleus (n) and adjacent chloroplast (c) of *Ochromonas danica* showing the continuity of the chloroplast ER (cer) with the nuclear envelope (arrow).

Source: Gibbs, S.P. 1978. Annals New York Academy of Sciences.

The algae with two membranes of chloroplast ER evolved by a secondary endosymbiosis. In the secondary endosymbiosis, a phagocytic protozoan took up a eukaryotic photosynthetic alga into a food vesicle. Instead of being phagocytosed by the protozoa, the photosynthetic alga became established as an endosymbiotc within the food vesicle of the protozoa. The endosymbiotic photosynthetic alga benefitted from the acidic environment in the food vesicle that kept much of the inorganic carbon in the form of CO_2 i.e. the form needed by ribulose biphosphate/ carboxylase for Carbon fixation. The host benefitted from receiving some of the photosynthate from the endosymbiotic alga.

The food vesicle membrane eventually fused with the ER of the host protozoa, resulting in ribosomes on the outer surface of the membrane which became the outer membrane of chloroplast ER.

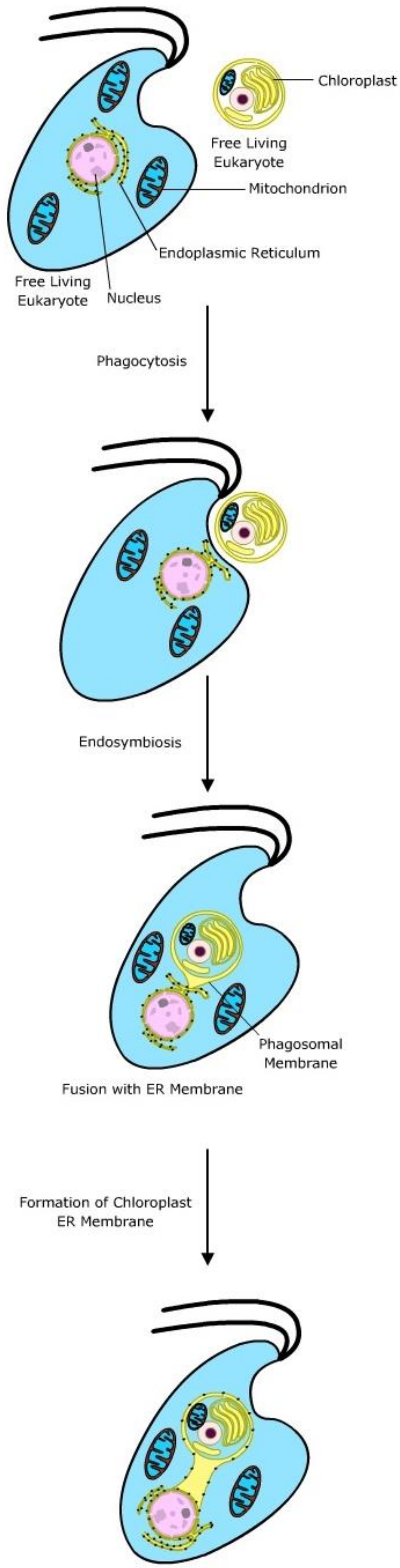

Chloroplast
Free Living
Eukaryote
Mitochondrion
Endoplasmic Reticulum
Free Living
Eukaryote
Nucleus
Phagocytosis
Endosymbiosis
Phagosomal
Membrane
Fusion with ER Membrane
Formation of Chloroplast
ER Membrane

Figure: Evolution of the two membranes of the chloroplast endoplasmic reticulum

Source: Author

Through evolution, ATP production and other functions of the endosymbiont's mitochondria of the endosymbiont were lost. The host nucleus also took over some of the genetic control of the endosymbiont. The resulting cytology is characteristic of the extant cryptophytes which have a nucleomorph representing the degraded endosymbiont nucleus, as well as starch produced in what remains the endosymbiont cytoplasm.

The type of chloroplast ER that exists in the Heterokontophyta and the Prymnesiophyta resulted from further reduction. The nucleomorph was completely lost and storage product formation was taken over by the host. The resulting cell had two membranes of chloroplast envelope surrounding the chloroplast. Outside of this was the inner membrane of chloroplast ER that was the remains of the plasma membrane of the endosymbiont. Outside of this was the outer membrane of chloroplast ER which was the remains of the food vesicle membrane of the host.

	Chlorophyceae	**Phaeophyceae**	**Xanthophyceae**	**Rhodophyceae**	**Cyanophyceae**
Thallus form	Unicellular,colonial or filamentous, siphonaceous or thalloid	Filamentous, branched or usually heterotrichous	Unicellular, filamentous or siphonaceous	Unicellular, filamentous, pseudoparenchymatous	Unicellular colonial or filamentous
Cell Structure	Eukaryotic	Eukaryotic	Eukaryotic	Eukaryotic	Prokaryotic
Cell Wall Constituents	Cellulosic & Pectic material	Outer layer contains alginic & fucinic acid & the inner layer is of cellulose	Major constituent is pectin and small quantities of silica and cellulose	Outer layer is pectin & inner layer is cellulose	Mucopeptides and muramic acid
Pigments	Chlorophylll a &b, alpha-and **β-** carotene,	Chlorophyll a &c, **β-** carotene Xanthophyll	Chlorophyll a and e, **β-** carotene &	Chlorophyll a and d, **β-** carotene , xanthophylls	Chlorophyll and **β**-carotene xanthophyll and

	Xanthophyll	(Violaxanthin & fucoxanthin).	xanthophylls.	& r-phycoerythrins.	c-phycocyanins.
Reserve food materials	Starch & fats	Laminarin,mannitol& sucrose.	Oils & fats chrysolaminarin	Floridean Starch.	Cyanophycean starch & protein.

Reproduction	**Chlorophyceae**	**Phaeophyceae**	**Xanthophyceae**	**Rhodophyceae**	**Cyanophyceae**
Asexual	Fragmentation, Zoospores aplanospores Akinetes	Motile zoospores aplanospores	Synzoospores aplanospores	Monospores neutral spores tetraspores carpospores	Fragmentation akinetes, hormogonia,endospores,exospores.
Sexual	Isogamy Anisogamy &Oogamy	Isogamy Anisogamy &Oogamy	Isogamy Anisogamy &Oogamy	Complex & Advanced oogamy	Sexual reproduction completely absent.
Flagella	Present	Present	Present	Absent	Absent
Type	Acronematic	Acronematic & Pantonematic	Acronematic & Pantonematic	-	-
Point of Insertion	Anterior	Lateral	Anterior	-	-
Length	Equal	Unequal	Unequal	-	-

Contributions of some noted phycologists

Professor F.E. Fritsch (1879-1954) was one of the greatest and eminent Phycologists. He obtained his Ph. D. from Munich University(Germany) in 1902. Later he went to London and worked in the Department of Botany in various capacities and finally became professor of Botany in 1948. In 1938, he came to India to attend the Indian Science Congress and delivered the lecture on the algal problems peculiar to the tropics. For his valuable contributions, he was awarded the Gold Medal from the Linnaean Society of London his main interest was the study of the fresh water algae. In 1902, he published a paper on the germination of zoospores in *Oedogonium*. Later, in 1935 and 1945, his famous books "Structure & Reproductions of the Algae Vol. I & II were published. These books are used even now for the study of algae .

F.E. Round proposed a modern classification of algae taking into consideration various aspects such as pigmentation and chemical nature of the food reserves. He separated BGA from other algae due to their close resemblance with bacteria & kept them under prokaryota. 1965, he wrote the Book "The Biology of the Algae" which contains information on the morphology, life history, ecology, physiology and classification of Algae.

M. O. Parthasarthy Iyengar (1886-1963) was an outstanding and internationally famous Indian Phycologist. He is considered as the "Father of Indian Phycology". He obtained his Ph. D. from London from 1909. He worked in the University of Madras and did lot of researches on algae. From 1929 to 1950, he published various papers in reputed Journals such as Journal of Linnean Society London, Journal of Indian Botanical Society and the Proceedings of Indian Science Congress.

He also wrote a monographs on Volvocales. He was especially interested in Chlorophyceae. The topics of his publications include the colonial volvocales of south India, Fertilization of *Eudorina elegans*, lateral conjugation in *Spirogyra jogensis*, conjugations in *Caulerpra*, Morphology and cytology of *Polysiphonia platycarpa*, life cycle of *Cylindrocapsa*, *Dictyosphaerium, Microdictyon, Hydrodictyon indicum* and *Botrydium*. He also discovered and studied many new genera of algae such as *Dendrocystis, Fritschielle tuberosa, Pseudovalonia, Charaoisiphon, Cladospongia* etc, The well – known phycologists such as Desikachary and Sundarlingam were trained by Iyengar.

He was the recipient of Birbal Sahani Gold medal from Indian Botanical Society and Sunder Lal Hora Gold Medal of the National Institute of Sciences, India. To honour and remember him, certain algae are named after him – they are *Iyengaria, Iyengariella, Anabaena iyengarii, Chlamydomonas iyengarii* & *Scytonema iyengarii*.

Among his other important of papers, "Some interesting green algae" is fascinating in which he recorded the occurrence of *Chlomydomonas volvocinae* – a new species inhabiting the coenobium of Volvox and a few new species such as *Physicocytium indicum, Chlamydomonas eudorineae, C. ulotrichae, C. oocysticola, C.dictyosphaeriae, Paulschulzia indica , Gloeococcus pyriformis, Charadosiphon rivularis*. Iyengar and Desikachary established a new genus *Mastigocladopsis* which has both lateral and terminal heterocysts.

T.V. Desikachary was a student of Prof. M.O.P Iyengar. From 1940 onwards , he worked in the University of Madras and published papers on *Gloeotricha, Nostochopsis, Camptyloneus* and *Iyengaariella tirupatiensis*. In 1969, he wrote a monograph on cyanophyta which was published by the ICAR. This book gives information on blue green algae (BGA) of India and neighboring countries. It comprises neat drawings of 139 plates of more than 150 genesis of BGA.

R. N. Singh has carried out exemplary work on varied branches of algae such as Cyanophyceae, Zygnemataceae, Oedogoniaceae and Chaetophorales. He studied the life histories of *Fritschillea tuberosa* and *Draparnaldiopsis indica*. He has suggested the cultivation of BGA for the reclamation of usar land in India and has also written a monograph entitled "Role of the BGA in the economy of Indian agriculture". He has contributed on N_2 fixation by BGA and has established that *Aulosira fertilissima* tops the list of Indian algae.

Dr H.D. Kumar has worked on parasexuality and metabolic behavior of BGA mainly *Anacystis nidulans*. He has written several books on various topics. Because the Indian subcontinent is fringed with oceanic water, studies on marine algae have tremendous prospects from fundamental and economic point of view. He is the author of the Book 'Text Book of Algae.

M.S. Randhawa (1932-1960) published a series of papers especially on Zygnemaceae, Oedogoniales and Vancheriaceae from Punjab and Uttar Pradesh. He recorded seventy species in Zygnemaceae which include eleven new Sp. of *Spirogyra*. In 1939, he described *Sirocladium kumaoense* a new genes & species from Kumaon. He described certain terrestrial green algae including *Zygnema terrestre* and two new Sp. of *Oedogonium*. He has reported a new kind of akinete formation in *Vaucheria germinata* and six Sp. Of *Vaucheria* from Punjab. It includes one new sp. *Vaucheria amphibian*.

B.N. Prasad is well known for his contribution on cytology of algae , especially of *Schizomeris, Zygnema, Mougeotia*. His other work of general interest includes the systematic description of algae some Nostocaceae from U.P.; algae of alkaline usar soil; thermal algae of Himalyan hot springs; notes on conjugation in *Zygnema*; loop formation in heterothrix and some interesting morphological features in *Tolypothorix*. He has a credit of first time collection of certain forms in India such as *Uronema gigas. Heterothrix trichodes, Botrydiopsis arrhiza, Coleochaete nitellarum* etc. He has described nearly 6 genera and several species as new records from India.

K.V. B. Tilak – Former Head, Department of Microbiology, IARI worked on Bio fertilizers.

D.B. Sahoo is a noted Indian phycologist known for his efforts to popularize the use of algae for carbon sequestration, biodiesel production, marine biotechnology and importantly for societal benefit.

Some important books, bulletins and journals in the field of Phycology:

1) The records of Botanical survey of India by K. Biswas (1945)

2) Cyanophyta by T.V. Desikachary (1959)

3) Zygnemaceae by M.S. Randhawa (1959)

4) Charophyta by B. P. Pal, V.S. Sundaralingam & G.S. Venkataraman (1962)

5) Proceedings of Symposium on Algelogy ICAR (1960)

6) Role of BGA in the nitrogen economy of Indian Agriculture by R.N. Singh (1961)

7) Vancheriaceae by G.S. Venkataraman (1964)

8) Cultivation of algae by G.S Venkataraman (1969)

9) Algae : Forms & function by G.S. Venkataraman, S.K. Goyal, B.K. Kaushi & P. Roy choudhary (1974)

10) Phaeophyceae in India by J.N. Mishra (1966)

11) International Symposium : Taxonomy and Biology of BGA, University of Madras (1970)

12) Work Done on Blue Green Algae in Relation to Agriculture by A. Sankaram (1971)

13) Advances in Applied Phycology (II Vol.) Eds. A.C. Shukla & S.N. Pankey.

14) Phykos, published periodically from New Delhi.

15) Research Journal of Plant and Environment published periodically from Kanpur. Editor S.N Pandey.

Summary

Linnaeus (1754) was the first to apply name algae to a group of plant, however, group consisted of a mixture of algae and Hepaticae. A.L.De.Jussieu (1789) was the first to limit

the algae. The algae thus constitute in heterogeneous assemblage of oxygen producing photosynthetic, non-vascular organisms with non-protected reproductive structures. The definition bridges both pro and eukaryotic forms with the exception of the Charophyceae. The algae are distinguished from the bryophytes by their lack of multicellular sex organs contained within sterile jackets of cells and by their lack of retention of the sporophyte within the female organ- archegonium.

They exhibit great diversity in size and morphology. They can be found growing in aquatic and terrestrial environments. Majority are aquatic growing in fresh, brackish and marine waters. Majority exist in normal temperatures (20-40^{o}C) and a few are known to grow under extreme conditions and in polluted environments. They can be even seen on the snow laden mountains and are called cryoflora. Some algae exhibit symbiotic associations with fungi (lichens), plants (endophytes) or animals (endozooic).Some algae, particularly the red and browns, are harvested and eaten as a vegetable, or the mucilages are extracted from the thallus for use as gelling and thickening agents.

Two types of cell organization are found –

- Prokaryotic as in Cyanophyceae and Prochlorophyceae and
- Eukaryotic represented by higher algal groups.

The structure of the plastids in each group is different and is characteristic of each group.

The earliest attempts to distinguish separate groups of algae relied on pigmentation. On that basis Brown, red, and green algae and diatoms are recognized. The classes are distinguished principally on differences in pigmentation, storage products, cell wall characteristics and the fine structure of organelles such as flagella, the nucleus, chloroplast, pyrenoids and eyespots. In this treatment six divisions are recognized two of them prokaryotic (Cyanophycota and Prochlorophycota) Fritsch (1938,40) recognized 11 classes. Lee (1992) recognized 4 groups on the basis of the nature of chloroplast and its formation.

Reproduction in algae varies from asexual to sexual. In asexual reproduction the cell/thallus may divide by binary fission, fragmentation or by formation of nonmotile aplanosopre, motile zoospores etc. Sexual reproduction ranges from isogamous, anisogamous and oogamous. The life cycle patterns depend on the occurrence of the stage in which meiosis occrrs- zygotic, sporic, gametic.

Exercises

1. Who coined the term algae?
2. What is the study of algae called?
3. Give four most important characteristic features of algae.
4. Give one example of unicellular, colonial, filamentous and parenchymatous type of algae.
5. Differentiate between
    a) Algae and fungi
    b) Isogamy and Oogamy
    c) Acronematic and pantonematic
    d) Aplanospore and zoospore
6. Write short notes on:
    a) Eye spot
    b) Pyrenoid
    c) Phycobiliproteins
7. Discuss the three types of life cycles found in algae.
8. Discuss briefly the different types of storage products found in various algal groups.
9. What are water blooms?
10. Give one example each of Epiphytic, epizooic, endophytic and endozoic alga.
11. Discuss in brief, the classification given by R.E.Lee.
12. What are the main criteria for the classification of algae.
13. How are BGA distinguished from the other algae.
14. What is the name of the book written by Fritsch?
15. How would you justify the inclusion of the cyanophyta & Charophyta among algae.
16. What are the reserve food materials found in the cells of Rhodophyceae.
17. How many classes were recognized in algae by G.M Smith.
18. What are the common pigments present in algae. State the importance of these pigments in the classification of algae.
19. Give Systematic position of the following algae on the basis of G.M Smith classification.
    1) *Nostoc*
    2) *Chara*
    3) *Ectocarpus*
    4) *Polysiphonia.*
20. What are the different types of chloroplasts found in Chlorophyceae.
21. Discuss the three types of sexual reproductions found in algae.

22. Discuss the four major groups of algae based on nature of the plastids and its evolutionary origin according to Lee's classification.
23. What is a sexual reproduction? How it is different from the sexual reproduction.

Glossary

Acronematic: Flagella with smooth surface and ending in a thin hair.

Akinete: Non motile resting spore.

Amyloplast- A colorless plastid.

Anisogamy: Fusion of two dissimilar gametes.

Anisokont: Cell with flagella of dissimilar length

Aplanospore: Non motile spore.

Aplanospore: Non-motile spore

Autospores: Aplanospore similar in shape to the parent cell

Axoneme: The shaft of the flagellum**.**

Coenobium: Colony consisting of a definite number of cells arranged in a definite manner.

Coenocyte: Multinucleate cell.

Cyanelle: Endosymbiotic cyanobacterium

Cyanome: Host cell containing cyanelle

Endophytic: Plant living within another plant.

Endosymbiosis: Term that describes an organism living inside a host in a mutually beneficial relationship- symbiosis

Endozoic: Living within the tissues of animal but not parasitic.

Epizoic: Growing attached to the outer surface of animals.

Eye spot or Stigma: Pigmented area inside the algal cell composed of lipid droplets associated with phototaxis.

Gametangium: Gamete bearing organ.

Haptonema: Appendage that arises between the flagella in Prymnesiophyta

Heterokont: The presence of unequal flagella.

Heteromorphic alternation of generation: Morphologically dissimilar generations

Heterothallic (Dioecious): Producing male and female gametangia on different plants

Heterotrichous: Thallus differentiated into prostate and erect system.

Holophytic or autotrohic: Needing only light and inorganic substances for growth

Holozoic or phagocytosis: Absorbing food particles whole into food vesicles for digestion

Homothallic (Monoecious): Producing both male and female gametangia on the same plant (Self compatible)

Isokont: Cell with flagella of the same length

Isomorphic alternation of generation: Morphologically similar generations

Mastigoneme: Hair like appendage on flagella**.**

Mesokaryote: The nucleus in which the chromosomes persist in condensed. condition throughout the cell cycle e.g. in Dinoflagellates and Euglenoids.

Monophyletic: Term used in systematics to describe a group of organisms that have descended from a common ancestor.

Oogamy: Fusion of non motile male gamete with large non motile female gamete.

Palmelloid: Palmella like habit.

Pantonematic: Flagellum with surface covered with hairs.

Phycobilisome: Particles containing phycobiliproteins

Polyphyletic: Used in systematics to describe a group that contains members that are actually more closely related to members outside the group.

Pseudoparenchymatous: Collection of cells, filaments forming tissue that resembles parenchyma.

Rhizopodia: False feet for locomotion or attachment.

Siphonaceous: Tubular thallus in algae lacking septa or cross walls.

Stephanokont: Cell with a ring of flagella at one end

Thallus: Undifferentiated plant body.

Zoospore: Motileflagellated asexual cell.

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