Ruma Pal · Avik Kumar Choudhury

An Introduction to Phytoplanktons: Diversity and Ecology

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Preface

Phytoplankton community in water bodies support the base of the natural food chain depending on which the natural fauna including the fish populations can survive. At the same time they produce almost 70 % of world's atmospheric oxygen. On the other hand, excessive phytoplankton production in the water bodies causes extensive problems like fish poisoning and deterioration of water quality in drinking water management, swimming pools and other water-based recreations. Therefore, it is dire necessity to study the different factors controlling phytoplankton growth or in other words phytoplankton ecology.

The microscopic phytoplanktonic genera are represented by different algal groups like Cyanobacteria, Chlorophyta, Bacillariophyta, Euglenophyta, Prymnesiophyta, etc. Therefore, identification of planktonic genera requires a good knowledge in algal taxonomy. Algal taxonomy is nowadays based on different characters like ultrastructure of algal chloroplast and flagella, cellular biochemistry, molecular characterization, etc., rather than morphotaxonomy of early days. With the advent of different sophisticated instruments like TEM, SEM, AFM, HPLC, HPTLC, etc., change in algal taxonomy is a regular phenomenon. For this reason, an attempt has been taken to discuss the chronological changes in algal taxonomy. Pigment composition is nowadays an important characteristic for classifying the algal kingdom, especially the marine phytoplanktons; therefore, we have attempted to discuss pigment composition of different groups of algae in detail.

To correlate the phytoplankton productivity together with varied physico-chemical parameters, different statistical methods are to be employed for data analysis, based upon which different ecological models are proposed. To study the phytoplankton diversity and ecology, sampling is an important factor to get the actual results. Different methods of samplings have also been discussed here. Therefore, phytoplankton ecology is a complex science, as it includes the interactions between biogeochemical cycling and environmental parameters. This phenomenon can be explained by the simple question, 'What lives where and why?', as stated by the famous phytoplankton ecologist Reynolds.

In general, there is scarcity of books on phytoplanktons related to diversity and ecology for students as well as researchers, which I experienced during my research work for the last 20 years on phytoplankton ecology. Therefore, presently for the benefit of students and phytoplankton researchers, we have

tried to compile a general account of phytoplanktons, their physical and chemical environments, sampling methods and the statistical analysis together with similar case studies on phytoplankton ecology. The results of the case studies are the doctoral work of my student Dr. Avik Kumar Choudhury and research findings of my other students, Sri Nirupam Barman, Sri Gour Gopal Satpati and Ms Anindita Singha Roy. I think this book will help the students of botany, zoology, microbiology and environmental biology together with the plankton researchers.

Kolkata, India   Ruma Pal
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About the Author

Dr. Ruma Pal did her M.Sc. and Ph.D. from University of Calcutta. Presently, she is Associate Professor in Botany, Department of Botany, University of Calcutta, India. Prior to this assignment she had served in Presidency College, Calcutta and Nara Sigh, Dutt College Howrah. She has more than 30 years of research experience in Phycology. Her research interest is related to various fields of algal biotechnology, like, Phycoremediation, aquaculture, biofuel production, nanotechnology, etc. Algal diversity study, phytoplankton dynamics and ecological modelling are also the areas of her interest. She has already conducted more than 15 research projects in the field of algal application and has published more than 50 papers in refereed journals.

Dr. Avik Kumar Choudhury completed his postgraduation from Banaras Hindu University in Botany in 2004. Subsequently, he worked as a UGC Project Fellow at Department of Botany, University of Calcutta. He completed his doctoral work from the same institute and received his Ph.D. degree in 2011 under the guidance of Dr. R. Pal. He also worked as a DBT (Department of Biotechnology, Govt. of India) Postdoctoral Research Associate at Department of Biological Sciences, Indian Institute of Science Education and Research. Presently he is in West Bengal School service.

1.1 General

'Phytoplanktons' are free-floating, photosynthetic, aquatic microorganisms, which move from one place to another, either actively by their locomotory organs (flagella) or passively by water currents. The name 'phytoplankton' came from the Greek words 'φυτόν' (phyton), meaning 'plant', and 'πλαγκτός' (planktos), meaning 'wanderer' or 'drifter'. The term 'plankton' was first used by the German biologist Victor Hensen in 1887. According to Hensen, 'plankton included all organic particles which float freely and involuntarily in open water, independent of shores and bottom (Ruttner 1940; Hutchinson 1957)'.

Most of the phytoplanktons survive on the open surface waters of lakes, rivers and oceans. The phytoplankton community is mainly represented by algal representatives including both prokaryotes and eukaryotic genera. Plankton populations are mostly represented by members of Cyanobacteria, Chlorophyta, Dinophyta, Euglenophyta, Haptophyta, Chrysophyta, Cryptophyta and Bacillariophyta. Planktonic representative taxa are absent in other algal divisions like Phaeophyta and Rhodophyta.

1.2 Historical Perspective

It has been proposed that studies related to plankton are included under 'limnology' where the name comes from the Greek word 'limnos'

meaning 'pool' or 'lake' or 'swamp'. The study of biological limnology originated in 1674 with the first microscopic description of *Spirogyra* from Berkelse Lake, Netherlands, by Leeuwenhoek. The first work on limnology was probably published in the USA by Louis Agassiz (1850) entitled *Lake Superior: Its Physical Character, Vegetation and Animals*. Professor Forel of the University of Lausanne, who is considered as the 'father of limnology', published the first textbook on limnology in 1869 on the bottom fauna of Geneva Lake entitled *Introduction a letude de la faune profonde du Lac Lema*n and for the first time he used the term 'limnology' in his book.

The study of lotic estuarine systems was initiated by J.R. Lorenz in the Elbe, Germany, in the 1860s. At the same time, pollution research started in the Thames in England, and the realization of the problems of survival in brackish waters was initiated with the biological approaches (Meyer and Möbius 1865–72). The importance of ecological concepts in limnology was first established by the English botanist Tansley which was later popularized by G.E. Hutchinson and R.L. Lindenman in the latter's paper entitled *The Trophic Dynamic Aspect of Ecology (1942)*. Professor Birge of the University of Wisconsin contributed to limnology in the USA through his study of the plankton of Lake Mendota (1917). Other eminent scientists like C.A. Kofoid, J.G. Needham and C. Juday also worked on different rivers and lakes. In the early

part of the twentieth century, Professor P.S. Welch wrote the first American textbook on limnology. Similar books were also written like *Fundamentals of Limnology* by Franz Ruttner (1940) and Professor G.E. Hutchinson published the book entitled *Treatise on Limnology* (1957, 1967) which is considered as standard reference work throughout the world.

In the nineteenth century, it was felt to publish the journals on limnology that would pull together the increasing volume of limnological informations that were developing every day. Thus, on January 1, 1936, the Limnological Society of America was established, which was later (1948) named as the 'American Society of Limnology and Oceanography' and used to publish till date the most well-circulated and popular journal titled *Limnology and Oceanography*. The year 1948 is also marked for the formation of the 'Freshwater Biological Association' in Britain. This association maintains a continuous record of physical, chemical and biological informations of 17 lakes in the Lake District of northwest England. Similarly 'Istituto Italiano di Idrobiologia' in Italy carried out intensive studies on northern Italian lakes, and the science of limnology in Europe flourished. Similar other renowned institutes developed around this time in Europe, for example, at Plön, Germany; Uppsala and Lund, Sweden; Copenhagen, Denmark; and on Lake Constance, Germany.

1.3 Algal Classification

Algae are considered as the most primitive plants with well diversifications. They all have a chlorophyll-bearing thalloid plant body and their reproductive structures are without sterile jackets. They have variations in morphology and cellular biochemistry together with reproductive behaviour and life cycle patterns. On the basis of these characters, algologists classified the entire algal kingdom into different divisions and classes from time to time.

The systematics or classification of algae has been changing dramatically through ages.

In early times, the classification was mainly based on the morphotaxonomy. But very recently the situation is marked by the quest of a compromise between the conventional (artificial) system and the phylogenetic system together with the molecular genetics. The classical approaches using morphological characters do not reflect the phylogenetic relationships, e.g. molecular data revealed that among the green algae, the genera with spherical ball-type thallus evolved independently in different lineages of algae. On the other hand, highly diverse morphotypes can belong to one and the same phylogenetic lineage.

In algal systematics nowadays, a polyphasic approach is widely suggested. Therefore, phylogeneticists suggest the following criteria for proper identification and phylogenetic placement of any algal groups:

1. Conventional morphological and ecophysiological study of algae under field condition
2. Isolation of unialgal culture for morphological, ontogenetic, biochemical and physiological studies under laboratory conditions
3. Ultrastructural studies of different cell organelles of algal cell, especially the chloroplast ultrastructure
4. Use of molecular markers (conserved sequences) for molecular phylogenetic analysis

The most commonly used sequences are the 16S rRNA or the small subunit (SSU) of ribosomal RNA (rRNA) for prokaryotic cells and 18S rRNA for eukaryotic cells. Besides some other markers are also used for phylogenetic analysis, e.g. *rbcL* and *tufA* gene.

Therefore, for convenience we can consider two phases of algal systematics. In the first phase, starting from placement of algae in plant kingdom by Eichler (1886), followed by algal classification by Fritsch (1935) and Smith (1950), up to Bold and Wynne's (1985) system, only morphological characters were considered for taxonomic purpose. Therefore, these classifications can be considered under 'old classical taxonomy'. In another approach or in the second phase, other parameters including

ultrastructural, biochemical and molecular characters are also considered – reflecting the evolution and phylogeny of and can be designated as 'modern system of classification'.

1.3.1 Old Classical Taxonomy

Eichler (1886) mentioned the phylogenetic position of algae in relation to other plant groups. He divided the entire plant kingdom into two groups: Cryptogamia (spore-producing plants) and Phanerogamia (seed plants). These two groups are again divided into three divisions and four classes. Algae are placed in Class I of division Thallophyta under Cryptogamia in close association with fungi. The only difference

between algae and fungi was recognized as the presence or absence of chlorophyll.

This system of classification is considered as incorrect by most of the scientists now. Indeed, we think it is still needed to be taught to a botanist to understand the phylogenetic position of algae and other plant groups which also indicate the evolutionary tendency among different plant groups in a broader sense.

In the old classical system of algal classification, famous algologists like Smith, Fritsch, Prescott, Bold and Wynne and Chapman and Chapman have classified the algal kingdom on the basis of variation in cell structure (prokaryotic and eukaryotic), flagellar position, number and structure, pigment composition, reserve food matters, mode of reproduction, etc.
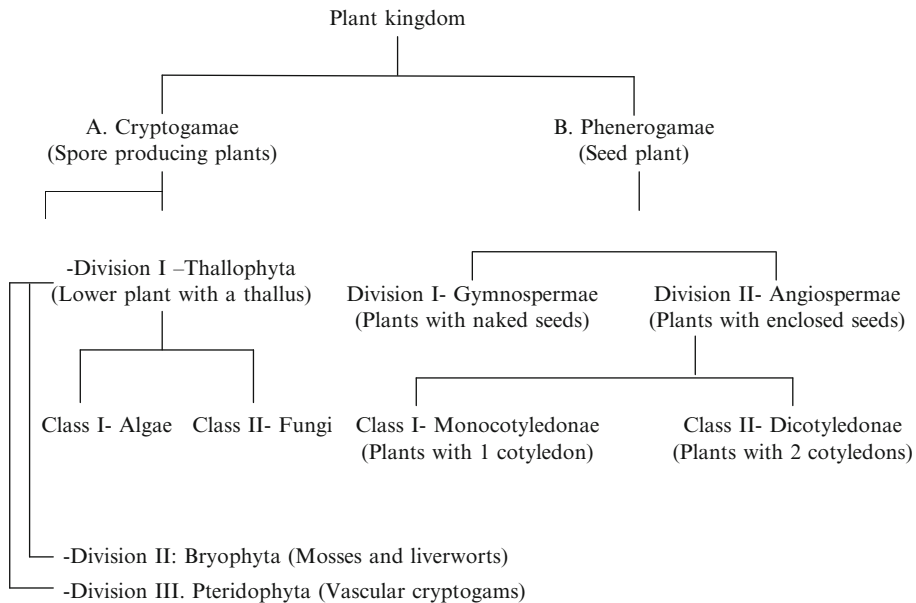
Eichler's system of classification (1886)

Afterwords, Fritsch (1935) divided the algal kingdom into 11 classes:

Class

   I. Chlorophyceae
  II. Xanthophyceae
 III. Chrysophyceae
 IV. Bacillariophyceae
  V. Cryptophyceae
 VI. Dinophyceae
VII. Chloromonadineae
VIII. Euglenineae
 IX. Phaeophyceae
  X. Rhodophyceae
 XI. Myxophyceae

On the basis of the morphological characters, Fritsch distinguished clearly 11 classes of the

algae. The termination 'phyceae' has been adopted wherever the class includes forms with an algal organization, while for flagellates the old designation is retained. Therefore, he designated the different groups of algae as 'classes' – rather than 'divisions'.

The 11 classes were characterized as follows:

1. Chlorophyceae (Isokontae) – Members with grass-green-coloured chromatophores and contain the same pigment compositions and approximately in the same proportions as in higher plants. Starch is the customary form of storage products of photosynthesis, often (especially in resting stages) accompanied by oil, and pyrenoids commonly surrounded by a starch sheath are frequently present inside the chloroplasts. Cells are surrounded by a cell wall in which cellulose is the constituent. The motile cells are with equal whiplash type of flagella (commonly two or four) which arise from the front end of swarmers. In many members the cells contain only one or few chromatophores. The members of Chlorophyceae exhibit sexual reproduction – ranging from isogamy to advanced oogamy. Most of the taxa are haploid with zygote representing the only diploid phase, but some exhibit a regular alternation of generation with similar haploid and diploid individuals. The class is more widely represented by freshwater members than in salt water, and there is a marked terrestrial tendency. Examples are *Chlamydomonas* and *Spirogyra.*

2. Xanthophyceae (Heterokontae) – The members are with yellow-green chromatophores due to presence of xanthophylls as major pigment. Starch is absent and storage product is oil. The algal members have a cell wall which is often rich in pectic compounds. The motile cells possess two very unequal flagella (or sometimes only one) arising from the front end. As a general rule the cells contain a number of discoid chromatophores. Sexual reproduction is always isogamous. The most advanced forms have a simple filamentous habit. All are probably haploid. The class is more widely distributed in freshwater than in the sea. An example is *Vaucheria.*

3. Chrysophyceae – Members are with brown- or orange-coloured chromatophores containing one or more accessory pigments. Starch is absent, but naked pyrenoid-like bodies are occasionally present. Fat and a compound leucosin are found in the form of rounded whitish opaque lumps as the food storage. A large proportion of the members are flagellate and devoid of a special cell membrane. The motile cells possess one or two (rarely three) flagella attached at the front end. The cells typically contained one or two parietal chromatophores. The most advanced habit is that of a branched filament. Sexual reproduction is extremely rare and not yet quite clearly established in any one case; the existing records point only to isogamy. The class is widely distributed in freshwaters, but a few are marine. An example is *Chromulina.*

4. Bacillariophyceae (diatoms) – Unicellular members with yellow or golden-brown chromatophores containing accessory brown pigments. Pyrenoid-like bodies are often present and the products of photosynthesis are fat and volutin. All the members are unicellular or colonial. A cell wall is always present and is composed of mainly silica and partly of pectic substances. The cell consists of two halves, each composed of two or more pieces, and is commonly richly ornamented. One set of forms (Centrales) is radially and the other (Pinales) bilaterally symmetrical. The diatoms produce a special type of spore – the auxospore. The Pinales show a special type of sexual fusion between the protoplasts of the ordinary individuals. The members of this class are probably diploid. Diatoms are very widely distributed in the sea and in all kinds of freshwaters, as well as in the soil and in other terrestrial habitat. Examples are *Navicula* and *Chaetoceros.*

5. Cryptophyceae – The members are of flagellate organization and with oogamous type of reproduction. The cells are with usually two large parietal chromatophores showing very diverse pigmentation. Pyrenoid-like bodies occur, but appear often to be independent of the chromatophores; the products of photosynthesis are

solid carbohydrates, in some cases starch, in others a compound akin to it. The motile cells are pronouncedly dorsiventral, have two slightly unequal flagella and possess a very specialized and characteristic structure. There is often a complex vacuolar system. The class is relatively small and appears to be equally scantily represented in the sea and freshwater. An example is *Cryptomonas*.

6. Dinophyceae (Peridiniidae) – The majority of the members are motile unicells and many possess a very elaborate cellulose envelope composed of a large number of often richly sculptured plates; some are with a branched filament. The members usually have numerous discoid chromatophores which are dark yellow, brown, etc., and contain a number of special pigments. The products of photosynthesis are starch and oil (fat). Many species are colourless saprophytes or exhibit holozoic nutrition; one extensive series is parasitic. The motile cells have two furrows, the transverse one harbouring the transverse flagellum which usually encircles the body and the other longitudinal constituting the starting point for the longitudinal flagellum which is directed backwards. Resting cysts of characteristic form are often produced. Isogamous sexual reproduction is certainly of rare occurrence and not yet clearly established. A class of mainly plankton organisms is more widely represented in the sea than in freshwaters. An example is *Gymnodinium.*

7. Chloromonadineae – The members of this class are motile flagellates, with two almost equal flagella. Cells are with numerous discoid chromatophores having a bright green tint and containing an excess of xanthophylls. Pyrenoids are lacking and oil is the assimilatory product. Although superficially like Xanthophyceae the detailed structure of the cells is altogether different (complex vacuolar apparatus, etc.). The class is only recorded from freshwaters. An example is *Gonyostomum* (raphidophytes).

8. Euglenineae – Unicellular thallus with pure green chromatophores, each cell usually with several pyrenoid-like bodies. The product of

photosynthesis is a polysaccharide, paramylum, which occurs in the form of solid grains of diverse and often very distinctive shape. Only flagellate members are known and the majority is motile with the help of one or two flagella which arise from the base of a canal-like invagination at the front end. There is a complex vacuolar system and a large and prominent nucleus. Only few cases of sexuality (isogamous) are known and these are not quiet fully substantiated. The bulk of the members of this class probably inhabits freshwaters. The class is highly specialized and no really simple form is known. An example is *Euglena*.

9. Phaeophyceae – The majority of cells are with brown chromatophores containing, apart from the usual pigments, the yellow fucoxanthin. Naked pyrenoid-like bodies occur in some of the lower forms. The assimilatory products are sugar alcohols (mannitol) with only traces of sugars, as well as polysaccharides (laminarin) and fats. Characteristic fucosan vesicles are present which probably represent waste products. The motile reproductive cells have two laterally attached flagella, of which one is directed forwards and the other backwards. These swarmers are always formed in special organs which are either unilocular or septate with numerous small compartments (plurilocular sporangia). Sexual reproduction is of wide occurrence and ranges from isogamy to oogamy of a primitive type, with liberation of the ovum prior to fertilization. The zygote exhibits no resting period. The life cycle is very diverse, with varied types of alternation of generations. An example is *Laminaria*.

10. Rhodophyceae – The majority attains to a considerable complexity of structure, though the simplest forms are filamentous. Cells are with chromatophores containing, apart from the usual pigments, others like the red phycoerythrin and blue phycocyanin. Pyrenoid-like bodies are found in the lower groups and the product of assimilation is a solid polysaccharide similar to starch (floridean starch). Neither motile reproductive stages

nor flagellate members are known. Evident protoplasmic connections are the rule between the cells of the majority of forms. Most of the Rhodophyceae are marine. All exhibit sexual reproduction of an advanced oogamous type, the female organ having a long receptive neck and the antheridium producing but a single motionless male cell. As a result of fertilization, special spores (carpospores) are produced from bunches of threadlike structures that arise from the female organ after fertilization. The Rhodophyceae are either haploid or exhibit a regular alternation of similar haploid and diploid individuals, the latter bearing characteristic sporangia (tetrasporangia), each producing four spores. An example is *Polysiphonia.*

11. Myxophyceae (Cyanophyceae) – Members with a simple type of cell, containing at the best only a very rudimentary nucleus (central body) and without a proper chromatophore, the photosynthetic pigments being diffused through the peripheral cytoplasm. The pigments present are chlorophyll, carotene, phycocyanin and phycoerythrin, the last two being in varying proportions and the colour of the cells being very commonly blue green. The products of photosynthesis are sugars and glycogen. No motile stages are known and all the members have a membrane around the cell. There is no sexual reproduction. The members of this class are of simple organization and many propagate entirely by simple division or by vegetative means. Most types are filamentous, many of them with a peculiar 'false' branching. They occur very abundantly in freshwaters and in terrestrial habitats and are not common in the sea. An example is *Spirulina.*

But in 1950, Smith proposed seven divisions of algae in his system of classification as follows:
1. Chlorophyta
2. Euglenophyta
3. Chrysophyta
4. Phaeophyta
5. Pyrrophyta
6. Cyanophyta
7. Rhodophyta

The divisions were characterized by the following basic characteristics:
1. *Chlorophyta* – The grass-green algae with the major pigments chlorophyll a and b together with carotenes and xanthophylls. Photosynthetic reserves are usually stored in the form of starch. It is always in association with pyrenoid. Motile stages have flagella of equal length with a few exceptions. The zoospores and motile gametes have two or four flagella. Sexual reproduction is a phenomenon of wide occurrence within the group and in various orders it ranges all the way from isogamy to oogamy. This group also shows a wide range in vegetative structures (*Chlorella*).
2. *Euglenophyta* – All the members are unicellular and most of them are naked free-swimming cells with one, two or three flagella. Many of the genera have grass-green, discoid band-shaped or stellate chloroplasts, with or without pyrenoids. The chloroplasts contain the same chlorophylls as Chlorophyceae, beta-carotene and xanthophylls unlike Chlorophyta. Food reserve is paramylum; nutrition may be holophytic, holozoic or saprophytic. There are one or two contractile vacuoles at the anterior end of the cell, which are connected with a reservoir, which in turn is connected with the cell's exterior by a narrow gullet (*Euglena*).
3. *Chrysophyta* – The members have yellowish-green to golden-brown pigment because of the predominance of carotenes and xanthophylls. The food reserves include a complex carbohydrate leucosin and oils. Some members are with cell wall made up of silica and are composed of two overlapping halves. Cells may be flagellated or non-flagellated, solitary or united in colonies of definite or indefinite shape. Sexual reproduction is usually isogamous by a union of flagellated and non-flagellated gametes, e.g. members of present-day Xanthophyta (*Vaucheria*) and Bacillariophyta (*Nitzschia*).
4. *Phaeophyta* – The Phaeophyta or brown algae have many celled complex type of plant body that is usually of macroscopic size and distinctive shape. The chromatophore or pigment-bearing organelles are yellowish brown in

colour due to the presence of xanthophylls in greater amount than that of chlorophyll and carotenes. The two principle reserve foods are laminarin, a polysaccharide, and mannitol. Zoospores or gametes are pyriform with two laterally inserted flagella of unequal length. Reproductive organs are of two kinds – the one celled or unilocular reproductive organ is always a sporangium and born on a diploid thallus. The other kind of reproductive organ is many celled and with each cell containing a single gamete or single zoospore. Most of the members of Phaeophyta have a life cycle in which there is alternation of two independent multicellular generations, haploid and the other is diploid. The two generations may be identical in size and structure, in others they are dissimilar in both size and structure (*Ectocarpus*).

5. *Pyrrophyta* – Members of this division are greenish to golden brown. The pigments are Chl *a*, Chl *c*, beta-carotene and four xanthophylls. Photosynthetic compounds are reserved as starch and also oil. The nucleus is distinctive in which chromatin lies in numerous bead-like structures on thread. Cell wall when present contains cellulose.

6. *Cyanophyta* – The Cyanophyta or blue-green algae are a distinctive group sharply delimited from other algae (prokaryotic algae). Their pigments are not localized on chromatophores; rather they are present in the peripheral portion of the protoplast and include chlorophyll *a*, carotenes and distinctive xanthophylls. In addition, there is a blue pigment (C-phycocyanin) and a red pigment (C-phycoerythrin). The unique feature of Cyanophyta is the presence of primitive type of nucleus within the cell (central body) which lacks a nucleolus and a nuclear membrane. They lack any flagellated structure and devoid of sexual reproduction (*Oscillatoria*).

7. *Rhodophyta* – The Rhodophyta or red algae have multicellular thalli of microscopic or macroscopic size and often of distinctive shape. Red algae differ from all other algae in structure of their sexual organs, in mode of fertilization followed by formation of a spore-producing structure, the so-called cystocarp. Pigments are localized in chromatophores. In addition to chlorophylls, carotene, xanthophyll and R-phycoerythrin and R-phycocyanin are present.

Prescott (1984) first classified the algal kingdom into seven phyla like other groups of biological kingdom. Each phylum is again divided into different classes and orders as follows:

I. Phylum Chlorophyta
   (i) Class – Chlorophyceae (17 orders)
   (ii) Class – Charophyceae (1 order)
II. Phylum Euglenophyta
III. Phylum Chrysophyta
   (i) Chrysophyceae
   (ii) Bacillariophyceae
   (iii) Heterokontae
IV. Phylum Pyrrophyta
   (i) Desmokontae
   (ii) Dinokontae
V. Phylum Phaeophyta
   (i) Isogeneratae
   (ii) Heterogeneratae
VI. Phylum Rhodophyta
   Subphylum – Bangioideae (4 orders)
   Subphylum – Florideae (6 orders)
VII. Phylum Cyanophyta
   Subphylum – Coccogoneae
   Subphylum – Hormogoneae

Among the old classical algal taxonomy, *Bold and Wynne's* (1985) system of classification is the most well-accepted one. He divided the algal kingdom into nine divisions and introduced a new division Charophyta, which is considered as progenitor of land plants.

Divisions
I. Cyanophyta and Prochlorophyta
II. Chlorophyta (16 orders)
III. Charophyta
IV. Euglenophyta
V. Phaeophyta (13 orders)
VI. Chrysophyta (6 class)
   Chrysophyceae
   Prymnesiophyceae
   Xanthophyceae
   Eustigmatophyceae
   Raphidophyceae
   Bacillariophyceae

 VII. Pyrrophyta
VIII. Rhodophyta
  IX. Cryptophyta

Charophyta

Commonly known as stoneworts, small plantlike, basal rhizoidal part rootlike and upper region differentiated into nodes and internodes. At the nodal region primary and secondary laterals are present. Branching is also prominent. Small leaflike stipules and bracts are present. Reproduction is oogamous type. Male reproductive structure antheridia and female reproductive structure oogonia are covered by sterile jacket, shield cell and tube cell, respectively. They share many characters with land plants. They possess unilateral type of flagellar root – in contrast to cruciate types in the members of Chlorophyta. Mitosis – open type, i.e. they lack nuclear membrane in late prophase, whereas it is closed types in other members of Chlorophyta (*Chara, Nitella*).

Bold and Wynne (1985) mentioned about Prochlorophyta together with Cyanophyta in their system of classification. Prochlorophyta were considered as a new division by Lee (1980, 1989, 1999) with the prokaryotic members having Chl *b* (*Prochloron*). But later on, other characters are also considered including molecular markers and it was found that those are nothing but Chl *b*-bearing cyanobacteria.

1.3.2   Modern System of Algal Classification

In modern approach, the classification is based on the evolutionary process of the biological kingdom. The entire kingdom or individual groups are divided into several kingdoms or classes considering different characters, reflecting the evolution and phylogeny. Together with morphological parameters, other characters, like biochemical and molecular data, are also considered.

Whittaker's (1969) system of biome classification is one of such example, where the entire biome is divided into five kingdoms, viz. Monera,

Protista, Mycota, Metaphyta and Metazoa, as follows:

1. Kingdom: Monera (prokaryotic organisms)
2. Kingdom: Protista (primitive eukaryotic organisms)
3. Kingdom: Mycota (exclusively fungi)
4. Kingdom: Metaphyta (advanced eukaryotic plants)
5. Kingdom: Metazoa (all multicellular animals)

In this classification, all the cyanobacterial genera or prokaryotic algae are placed in 'Monera', together with prokaryotic bacteria. All unicellular members are included in 'Protista', including protozoa of animal kingdom and unicellular algae of plant kingdom. Multicellular higher plants including algae are placed in the kingdom 'Plantae' together with bryophytes and pteridophytes.

According to this classification, Monera represent the most primitive group of organisms. The Monera are thought to have given rise to Protista from which the three other kingdoms of organisms, namely, the fungi, plants and animals, evolved along separate lines. Fungi are thought to first to appear from Protista. Later, about a billion years ago, some protists must have evolved into primitive multicellular animals. Still later, probably about 350 million years ago, some protists must have evolved into higher forms of plants.

Like all systems of classification, the five-kingdom classification has also certain merits and demerits. However, it is largely the most accepted system of modern classification mainly because of the phylogenetic placing of different groups of living organisms.

This system of classification looks more scientific and natural because of the following considerations:

1. All the prokaryotes are placed into an independent kingdom. It is justifiable because they differ from all other organisms in their general organization.
2. The kingdom Protista contains all the unicellular eukaryotes. It solved many problems, particularly related to the position of some unusual organisms like *Euglena*.
3. Separation of the group fungi to a separate kingdom is justifiable since fungi totally differ

from other primitive eukaryotes like algae and protozoans.

4. The five-kingdom classification gives a clear indication of cellular organization and modes of nutrition.

However, the five-kingdom classification has some demerits also, particularly with reference to the lower forms of life:

1. The kingdoms Monera and Protista include both photosynthetic (autotrophic) as well as non-photosynthetic (heterotrophic) organisms and organisms which have cells with cell wall as well as without cell wall.
2. The three higher kingdoms or multicellular lines have originated from Protista several times (polyphyletic).
3. Unicellular or colonial green algae like *Chlamydomonas* and *Volvox* have not been included under Protista because of their resemblance to other green algae.
4. Slime moulds are different from other members of Protista.
5. Viruses have not been given proper place in this system of classification.

Nevertheless, the five-kingdom classification has found a wide acceptance with biologists all over the world.

Status of Viruses

The position of viruses in the biological kingdom is one of the unsolved mysteries. Due to the absence of a cellular organization, viruses cannot be placed with either prokaryotes or eukaryotes. They are considered as intermediate between living and nonliving systems. Viruses are active and show reproduction only inside the host cell. In the free state, they are totally inactive. They may even be purified and crystallized like chemical substances. Viruses have a genetic material represented by either DNA or RNA, surrounded by a protein sheath. Viruses reproduce by using the metabolic machinery and raw materials of the host cell. Because of these peculiarities, viruses do not fit into any of the five kingdoms of life.

From 1975 onwards, with the advent of electron microscopy and other sophisticated instruments like high-resolution SEM, TEM, HPLC and HPTLC, fine characters of algal cells like

ultrastructural and biochemical and more recently the molecular data are also considered for algal classification together with the morphological characters of algal thallus. Since then the science of phycology has sustained major conceptual changes. The increased resolution of the electron microscope revealed the presence and structure of flagella, flagellar hairs, flagellar roots, eyespots, chloroplast, endoplasmic reticulum, etc., which were found to be important in basic systematics of algae especially the green algae. Important observations were made by Pickett-Heaps (1967, 1969, 1972a, b, 1975), which revealed that different types of microtubular arrangements are involved in cytokinesis of green algae. In some orders of Chlorophyta, cell divisions are characterized by the collapse of the interzonal spindle apparatus after mitosis, which give rise to a 'phycoplast' with the microtubules oriented in the plane of cell division, viz. Volvocales, Tetrasporales, Chlorococcales, Oedogoniales and Ulotrichales. On the other hand, some members together with land plants have a persistent spindle and develop a cleavage and furrow (Klebsormidiales) or a 'phragmoplast' in which the microtubules are oriented perpendicular to the plane of cytoplasmic division (Coleochaetales, Charales and Conjugales). At the same time, biochemical analysis also clarified the presence and structure of algal pigments, storage products and cell wall constituents. Considering all these parameters, Stewart and Mattox (1975) classified the green algal division Chlorophyta into five classes, considering comparative cytology, viz. Chlorokybales, Zygnematales, Klebsormidiales, Coleochaetales and Charales.

1.3.2.1 Algal Chloroplast in Classification

Mereschkowski (1905) first studied about the nature and origin of chloroplast in eukaryotic algae and the evolutionary pattern among them. In 1905, he published the most extensive paper on the origin of chloroplast based on the idea that eukaryotic algal cell originated by the process of endosymbiotic events between the cyanobacterial cell and the primitive eukaryotic phagocytotic protozoa. He was with the opinion,

as he observed many characters of unicellular photosynthesizing motile algae similar to that of heterotrophic protozoa like, cell structure, their movement, flagellar structure. On the other hand, chloroplast also has its own DNA and self-replication process. But at that time this hypothesis was not accepted. Later on, with the advent of electron microscope and other sophisticated instruments, some evidences, especially the peptidoglycan wall surrounding the glaucophycean chloroplast, proved the endosymbiotic events in chloroplast evolution. The hypothesis was accepted almost after 75 years of Mereschkowski's original hypothesis, and Lee (1980) first accepted this hypothesis in his system of classification.

Lee (1980) also adopted the endosymbiotic theory and proposed that chloroplast evolution took place in three lines of evolution.

In the first line of evolution for chloroplast development, a prokaryotic algal cell was captured in a food vesicle by a phagocytotic non-photosynthetic protozoan. The protozoans instead of digesting the algal cells started it maintaining as endosymbiont. The endosymbionts are used to get shelter from the host, whereas the host is used to get the supply of photosynthetic products from the endosymbiont. In the course of evolution, the endosymbiont turned into the photosynthetic cell organelle or chloroplast – modifying the photosynthetic protozoa to eukaryotic algal cell. Eventually, in the process of evolution, the plasma membrane of the endosymbiont became the inner membrane of the chloroplast and the food vesicle membrane of the host became the outer membrane of the chloroplast envelope (chloroplast of Glaucophyta represents the intermediate stage). This process is termed as primary endosymbiosis.

In the second line of evolution, a chloroplast of a eukaryotic alga was taken up into a food vesicle by a phagocytotic protozoa. Eventually, the food vesicle membrane of the host became the single membrane of chloroplast endoplasmic reticulum surrounding the two chloroplastic envelope and the process is known as secondary

endosymbiosis, where the two-membrane chloroplast evolved by primary endosymbiosis and the three-membrane algal chloroplast by secondary events (Group III of Lee's classification).

In the third evolutionary line, the phagocytotic protozoan took up a red alga into a food vesicle. The nucleus of red alga reduced to a nucleomorph. This protozoan along with its algal symbiont was taken up by a second phagocytotic protozoan into a food vesicle. The nucleus of the first protozoan took over the functioning of the cellular apparatus, and the nucleus of the second protozoan was lost. Also the food vesicle membrane of the second protozoa and the outer nuclear envelope of the first protozoa were also lost. Ultimately the four-membrane chloroplast evolved. The outer membrane of the chloroplast endoplasmic reticulum was the plasmalemma of the first protozoa and the inner membrane of chloroplastic endoplasmic reticulum was derived from the food vesicle membrane of the first protozoan.

Therefore, Lee (1980) first brought the revolutionary changes in algal classification and proposed four distinct evolutionary groups within algae on the basis of cell structure (prokaryotes and eukaryotes) and chloroplast ultrastructure, and it was accepted by all. Lee's classification was further revised on 1989, 1999 and 2008. According to this classification there are four distinct evolutionary groups.

According to Lee's classification the groupings are mainly done on the basis of evolutionary pattern of algal chloroplast and flagellar ultrastructure and mainly divided into four groups as follows:

The members of the first group are prokaryotic in nature and lack membrane-bound chloroplast having only free thylakoids embedded in cytoplasm. All the cyanobacteria are included in this group.

In the second group, the chloroplasts with basic structure, i.e. double membrane-bound (chloroplast envelope) organelle enclosing the ground substance stroma and the membrane-bound saclike

structure thylakoids embedded in it, are present in three divisions of algae, viz. Glaucophyta, Rhodophyta and Chlorophyta (group II). These algae evolved through primary endosymbiosis.

Among these three algal divisions, in chloroplast of Glaucophyta, thylakoids are arranged equidistantly at peripheral region of chloroplast (like cyanobacterial cell). There are similarities between chloroplast of Glaucophyta and cyanobacterial cell as follows:

- They are about the same size.
- They evolve oxygen in photosynthesis.
- They have 70S ribosomes.
- They have circular prokaryotic DNA without basic proteins.
- They have peptidoglycan wall surrounding the chloroplast envelope.

For this reason chloroplast of Glaucophyta is termed as 'cyanelles' or the incipient chloroplast.

The chloroplast of Rhodophyta (rhodoplast) is also surrounded by two chloroplastic membranes with no chloroplast ER. Inside the chloroplast, thylakoids occur singly and the DNA molecule occurs as microfibrils and the phycobilin pigments are localized into phycobilisomes on the surface of the thylakoids (similar to Cyanophyceae). Chl a and d are present inside the thylakoids. Among the carotenoids zeaxanthin is found in the greatest quantities. Phycobiliproteins include R-phycocyanin, allophycocyanin and three forms of phycoerythrin in maximum amounts.

In Chlorophyta, chloroplasts are highly evolved like higher-plant chloroplast, with two membranes of chloroplast envelope; thylakoids are stacked to form grana which are embedded in the matrix called stroma. Chloroplast pigments are also similar to higher plants. Chlorophylls a and b are present and the main carotenoid is lutein. Extraplastidic carotenoids are sometimes present (haematochrome).

The chloroplastic DNA is partially looped and ribosome is of 70S type. Starch is formed in the chloroplast in association with pyrenoid. The starch is similar to that of higher plant and is composed of amylose and amylopectin. A pyrenoid is a differentiated region within the chloroplast that is composed of polypeptides with enzymatic properties of ribulose-1,5-bisphosphate carboxylase that are capable of fixing carbon dioxide. Storage products are frequently associated with pyrenoids. The pyrenoid is denser than the surrounding stroma and may or may not be traversed by thylakoids.

The chloroplast of group III algal divisions, viz. Euglenophyta, Dinophyta and Apicomplexa, is surrounded by two membranes of the chloroplast envelope and one membrane of chloroplast endoplasmic reticulum, which is not continuous with nuclear membrane. The thylakoids are grouped in bands of three. Major pigments present are Chl a and b (Euglenophyta); Chl a and c2 with peridinin as major xanthophylls (Dinophyta); and rudimentary chloroplast (Apicomplexa).

In addition, some accessory chloroplasts are present in Dinophyta (originated from further endosymbiotic process between dinoflagellate cell and Cyanophyta or Bacillariophyta or Rhodophyta) giving characteristic colour.

The membranes of the fourth evolutionary group Heterokontophyta contain chloroplast having four membranes (two chloroplast envelopes and two chloroplastic endoplasmic reticula).

The chloroplast of Phaeophyta is known as phaeoplast. Phaeoplast is a four-membrane-bound structure having three thylakoids per band. Membrane-bound structures are also present between chloroplast envelope and chloroplast ER. The chloroplast contains Chl a, c1 and c2 with major carotenoid, fucoxanthin. Pyrenoids of Phaeophyceae are stalklike structures which set off from the main body of chloroplast containing granular substances not traversed by thylakoids. Surrounding the pyrenoid is a saclike structure containing the reserve food matters, generally present (laminarin as major component).

Mitochondria
Animals
Fungi
Select protists

Primary endosymbiosis

Photosynthetic bacterial endosymbiont

nucleomorph

Plastid (2membranes)

Cryptophytes

Red algae
Green algae/ plants
Glaucophytes

Secondary endosymbiosis

Heterokonts

Haptophytes

Plastid (4 membranes)

Tertiary endosymbiosis

Secondary endosymbiosis

Secondary endosymbiosis

Dinoflagellates (3 membranes)

nucleomorph

Plastid reduction (remnant plastid)

Apicomplexa

Plastid (3 membranes)

Plastid (4 memb-ranes)

Euglenoids

Chlorarachniophytes

Tertiary endosymbiosis

Schematic diagram of Endosymbiotic process

1.3.2.2 Outline of Lee's (2008) Classification with Basic Characters of Different Groups

In this system of algal classification, the entire algal kingdom is classified into four distinct groups:

I.   Prokaryotes
II. Eukaryotic algae with chloroplast with two membranes
III. Eukaryotic algae with chloroplast with one chloroplast ER (total three membranes)
IV. Eukaryotic algae with chloroplast with two chloroplast ER (total four membranes)

Group I:
1. Cyanobacteria

Group II:
1. Glaucophyta
2. Rhodophyta
3. Chlorophyta

Group III:
1. Euglenophyta
2. Dinophyta
3. Apicomplexa

Group IV:
1. Cryptophyta
2. Heterokontophyta
3. Prymnesiophyta

Cyanobacteria: Prokaryotic members containing chlorophyll *a* and phycobiliproteins. Some members contain chlorophyll *b* and are known as green cyanobacteria (Prochlorophyta). Cell wall is similar to Gram-negative bacteria containing peptidoglycan layer outside the cell membrane. Naked circular DNA present at the central portion of the cell. Cyanophycin, the polymer of arginine and aspartic acid; carboxysome; polyphosphate bodies; and polyglucan granules are the other cellular inclusions. Gas vacuoles, containing a large number of gas vesicles, are present.

Glaucophyta: Members unicellular with primitive type of chloroplast, showing many characters similar to cyanobacterial ancestor and are known as cyanelle. Pigments are similar to cyanobacteria. Members are unicellular flagellates.

Rhodophyta: Both marine and freshwater in habitat. Unicellular to huge thallus, especially for marine seaweeds. Chloroplast with one thylakoid per band and no chloroplast ER, floridean starch grain synthesized in the cytoplasm, no flagella, pit connections between the cells. Reproductive unit spermatia and carpogonia. Post fertilization change prominent.

Single class – Rhodophyceae

Chlorophyta: Members have chlorophylls *a* and *b* and starch is the reserve food matter formed within the chloroplast. Chloroplast with two membranes only, thylakoids form the grana. Both freshwater and marine in habitat with wide range in morphology. Flagella isokont type with fine hairs if present. Flagellar root cruciate type or unilateral type. Eyespot present.

Four classes: Prasinophyceae, Charophyceae, Ulvophyceae and Chlorophyceae

Euglenophyta: Euglenoid flagellate, unicellular, surrounded by pellicle. Chloroplast with two chloroplastic membranes and one chloroplastic endoplasmic reticulum containing Chl *a* and *b*. Marine or freshwater in habitat. Cytosome or gullet-like structures are present at the anterior region of the cell.

Single class: Euglenophyceae

Dinophyta: Unicellular with two halves, epicone and hypocone, made up of thecal plates. Chloroplast with two chloroplastic membranes and one chloroplastic endoplasmic reticulum with Chl *a* and *c*2 and the carotenoids peridinin and neoperidinin as major pigments. Storage product is starch. Two flagella – one longitudinal and one transverse.

Single class: Dinophyceae

Apicomplexa

Unicellular having reduced colourless plastid called *apicoplast*. Apicoplast and dinoflagellate plastids originated from red algae by a single endosymbiotic event. The apical complex consists of a *polar ring* and a *conoid* formed of spirally coiled microtubules. Apicomplexa are *endoparasites* that cause some of the most significant tropical diseases like malaria or diarrhoea. The parasite attaches to the host cell with the conoid protruding to produce a *stylet* that forms a tight junction with the host cell. The apicomplexan cell is taken up into the host cell in the *parasitophorous* vacuole.

Cryptophyta

Cells with chlorophylls *a* and *c*, phycobiliproteins and nucleomorph present between inner and outer membranes of chloroplast ER starch grains stored between inner membrane of chloroplast ER and chloroplast envelope, periplast inside plasma membrane and tripartite hairs on flagella.

Single class: Cryptophyceae

Heterokontophyta

Cells are with tripartite hairs; anterior tinsel flagellum and posterior whiplash flagellum. Pigments are chlorophylls *a* and *c* and fucoxanthin. Storage product usually chrysolaminarin present in vesicles of cytoplasm.

These divisions include 12 classes:

1. Chrysophyceae
2. Synurophyceae
3. Eustigmatophyceae
4. Pinguiophyceae
5. Dictyochophyceae
6. Pelagophyceae
7. Bolidophyceae
8. Bacillariophyceae
9. Raphidophyceae
10. Xanthophyceae
11. Phaeothamniophyceae
12. Phaeophyceae

Prymnesiophyta (Haptophytes)

Two whiplash flagella, haptonema present, chlorophylls *a* and *c*, fucoxanthin, scales common outside cell, storage product usually chrysolaminarin in vesicles in cytoplasm.

Single class: Prymnesiophyceae

McFadden (2001) introduced another division of algae in his classification, where the members possess four-membrane chloroplast with Chl *a* and *b* as the major pigments.

1.3.2.3 Other divisions of Algae

Chloroplast derived from a green alga, chlorophylls *a* and *b* present, nucleomorph between inner and outer membrane of chloroplast ER. Chloroplast with four membranes – two chloroplastic membranes and two chloroplastic endoplasmic reticula. Vegetative cells are naked, uninucleate with amoeboid projections. An example is *Chlorarachnion*.

Bremer (1985) combined charophytes and embryophytes into a single division *Streptophyta*, based on ultrastructure and molecular characters as they share many similar characters and also consider charophytes as progenitor of land plants.

Cavalier (1981) proposed the term *Viridiplantae* to comprise the true green plants including green algae and higher plants as an arguably monophyletic group based on ultrastructure of flagella (stellate structure in flagellar transition region) and plastid characters (Chl *a*, Chl *b*).

Members of phytoplankton belonging to different groups of algae and cyanobacteria contain different types of pigments in different compositions, which are important in algal taxonomy. These pigments play an important role in oceanographic research as they act as tracers to elucidate the composition and fate of phytoplankton in the world's ocean and are also associated with important biogeochemical cycles like carbon dynamics. Pigments of phytoplanktons often change the colour of the water indicating the biomass growth rate, which are also used in their estimation in situ *and in remote-sensing application.* By analysing these pigments using HPLC or HPTLC, presence or absence of picoplanktons can be determined. These techniques have allowed identification of many new pigments. Therefore, pigment analysis of phytoplanktons is very important in oceanographic research especially for chemotaxonomic purpose. From 1997 onwards HPLC-linked mass spectrometry is used for marine plankton analysis.

Phytoplankton biomass of the ocean is generally determined by measuring the ocean colour from space; therefore, in situ pigment measurements have become high-priority areas for oceanographic research (Jeffrey et al. 1997a; Nair et al. 2008).

In recent years to develop the map of microalgal population, the major pigments of a particular group are considered for field study. Many new algal genera have been identified on the basis of pigment composition (e.g. members of Herptophyton) (Zapata et al. 2004). They recovered many new members of chlorophyll *c* and fucoxanthin families from different phytoplankton genera. Jeffrey et al. (1997b) published a very

important book, *Phytoplankton Pigments in Oceanography: Guidelines to Modern Methods* (SOR-UNESCO volume). They listed 12 micro-algal classes as common members of phyto-planktons, viz. diatoms, dinoflagellates, haptophytes, chrysophytes, rhodophytes, raphi-dophytes, cryptomonads, chlorophytes, eugleno-phytes, eustigmatophytes, cyanobacteria and prochlorophytes.

The use of advanced HPLC and ultrahigh-performance liquid chromatography (UPLC) helps to identify different phytoplankton taxa in addition to it considering culture code and gene bank references.

A new system of classification of eukaryotes (including only photosynthetic microalgal groups) from a protistan perspective has been proposed by Adl et al. (2005), which is mainly used in oceanographic literature. According to them the traditional 'kingdoms', such as Metazoa, Fungi and Plantae, are recognized as deriving from monophyletic protist lineages. The authors grouped the molecular phytogenies into six clus-ters as follows:

1. Opisthokonta: animals, fungi, choanoflagellates and Mesomycetozoea
2. Amoebozoa: traditional amoebae, slime moulds, etc.
3. Rhizaria: foraminifera, radiolarian, heterotro-phic flagellates, etc.
4. Archaeplastida: red algae, green algae, Glaucophyta and Plantae

Classification scheme of Adl et al. (2005)

Super groups	First rank	Second rank (examples of photosynthetic eukaryotes)
Rhizaria	Cercozoa	Chlorarachniophyta, Paulinella
Archaeplastida	Glaucophyta	Glaucophyceae
	Rhodophyceae	Subdivisions uncertain according to Adl et al. (2005)
	Chloroplastida	Charophyta[a], Chlorophyta, Mesostigma, Prasinophyta
Chromalveolata	Cryptophyceae	Cryptomonadales
	Haptophyta	Pavlovophyceae, Prymnesiophyceae
	Stramenopiles	Bacillariophyta, Bolidomonas, Chrysophyceae, Dictyochophyceae, Eustigmatales, Pelagophyceae, Phaeophyceae[a], Phaeothamniophyceae, Pinguiochrysidales, Raphidophyceae, Synurales, Xanthophyceae
	Alveolata	Apicomplexa, Dinozoa
Excavata	Euglenozoa	Euglenida

[a]Clades with multicellular groups

1.4 Classification of Phytoplanktons

1.4.1 On the Basis of Size Variations

Phytoplanktons show a wide range of size varia-tions. The earliest work on phytoplankton classi-fication on the basis of size variations was proposed by Schütt (1892). During the 1950s, development of different types of nets, filters and screens with different pore sizes leads to identification of micro-, nano- and ultraplanktons. Picoplanktons are the smallest in cell size with a diameter of 0.2–2.0 µm, followed by nanoplankton (2.0–20 µm), microplankton (20–200 µm), mesoplank-ton (0.2–2.0 mm) and macroplankton (2–20 mm).

Interestingly, in earlier studies picoplanktons were referred only to 'heterotrophic picoplanktons' that are presently known as 'bacterioplankton' (Sieburth 1978). In later periods, chroococcoid cyanobacteria were observed in oceanic samples along with other eukaryotic taxa that are presently referred as 'picoplankton' (Johnson and Sieburth 1979; Li et al. 1983). Several other terms have also been introduced like 'ultrananoplankton' that referred to algae that were less than 2 µm (Dussart and Roger 1966) and 'ultraplankton'. The use of this term was mainly dependent on the discretion of the author and the size which ranged from 0.5 to 15 µm (Hutchinson 1967; Reynolds 1984). Some scientists used the term 'net plankton' for those planktons that were >45 µm in size (Throndsen 1978).

Picoplanktons have gained considerable interests among plankton biologists in the later part of the twentieth century. Several studies have indicated that in oligotrophic waters, picoplanktons are the primary population that constitutes 50–70 % of the total productivity of oceanic ecosystems (Caron et al. 1985). Thus, based upon their pigment composition and genetic diversity, picoplanktons have been categorized as 'prokaryotic picocyanobacteria' and 'eukaryotic phototrophs'. Unfortunately taxonomic identification of picoplanktons on the basis of morphological variations is very difficult to enumerate. Thus, pigment composition and analysis by molecular methods are increasingly been used as possible tools to understand picoplankton populations.

Table showing the classification of planktons on the basis of size variations

Group	Size range	Examples
Megaplankton	(20+ mm)	Metazoans, e.g. jellyfish, ctenophores, salps and pyrosomes (pelagic Tunicata), Cephalopoda
Macroplankton	(2–20 mm)	Copepods, amphipod, polychaete
Mesoplankton	(0.2–2 mm)	Protozoa, Foraminifera, Hydrozoa
Microplankton	(20–200 μm)	Dinoflagellates (e.g. *Dinophysis*, *Gymnodinium*, *Ceratium*), diatoms (e.g. *Biddulphia*, *Thalassiosira*, *Coscinodiscus*)
Nanoplankton	(2–20 μm)	Flagellates (*Distephanus*, *Thalassomonas*, *Tetraselmis*)
Picoplankton	(0.2–2 μm)	Cyanobacteria (*Synechococcus*)
Femtoplankton	(<0.2 μm)	Mostly viruses

1.4.2   On the Basis of Habitat

Phytoplanktons are widespread in their distribution in different aquatic habitats around the world. They live in freshwater, brackish and salt water, ice, moist soil and other damp places.

The freshwater lentic ecosystems like lakes and ponds can be divided into different zones (Fig. 1.1):

1. The *supralittoral zone* which is above the edge of the standing water that gets wet only due to wave actions and splash during windy seasons. Here, algal populations remain sparse due to the drying nature of the habitat along with other deterrents like the abrasive effects of sand and gravel.

2. The *littoral zone* which extends to about 6 m in depth from the water edge into the water body. This zone is a highly productive area in lotic systems in terms of productivity with dominance of periphytic algae like diatoms and desmids.

3. The *sublittoral zone* which extends down to the compensation point.

4. The *profundal zone* which occurs below the compensation depth where the phytoplankton population is mainly composed of colourless heterotrophic algal cells and resting spores of photosynthetic algae.

In lotic ecosystems like oceans and seas, there are two main divisions:

1. *Pelagic* species are those that live near the surface of the ocean during all or most part of their life cycle. The pelagic diatoms are further divided into *oceanic* and *neritic* species.

    (a) *Oceanic* species are those capable of living and reproducing entirely in the open ocean. Oceanic taxa are mostly reported from depth in excess of 200 m. Thus, the oceanic province can be subdivided into two distinct zones:
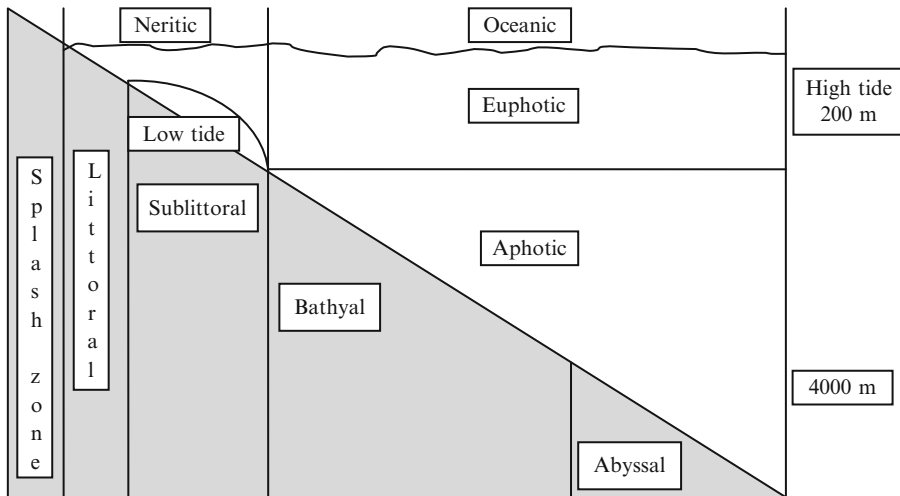
Fig. 1.1 Zonation of marine ecosystem

(i) *Euphotic* or *epipelagic zone* which extends from the surface to a depth of 200 m. Photosynthetic activities occur mainly in the upper portion of this zone.

(ii) *Aphotic zone* which extends from a depth of 200 m. Here light is insufficient to support planktonic photosynthetic activity.

(b) *Neritic* species are those which have their origin near the coast and reproduce most efficiently under coastal conditions. It is not easy to clearly distinct between neritic and oceanic species.

2. *Benthic* environment that represents the ocean bottom. This environment can be further categorized as:

(a) *Littoral* region which extends from high tide to low tide zone

(b) *Deep-sea* region which includes the entire ocean beneath the low tide mark. This region can be further subdivided into three distinct zones:

(i) *Sublittoral* zone which extends from the low tide mark to a depth of 200 m. This zone mainly consists of large seaweeds belonging to Rhodophyta and Phaeophyta. The availability of these seaweeds at different depth depends on the turbidity and light penetration along the water column.

(ii) *Bathyal* zone which extends from a depth of 200–4,000 m, corresponding to the continental slope, the geomorphic province beyond the continental shelf.

(iii) *Abyssal* zone which represents depths beyond 4,000 m.

Both oceanic and neritic species may be further divided into three main groups according to the latitude in which they are most commonly found or have had their origin. Thus, we speak of arctic, temperate and tropical oceanic species and arctic, temperate and tropical neritic species. Subdividing these again, we have boreal (northern but not arctic species), north temperate, south temperate and subtropical species. Some species are ubiquitous, others restricted within rather definite regions. There are a number

of species which it is still impossible to place in any definite group. The boundaries of the regions are variable and the flora of each locality is continually changing with seasonal changes and movements of the water.

Most of the coastal or neritic species have a special adaptation, the resting spores, which serve as protection against changing conditions (e.g. diatoms). The spores sink into deeper water and may be found there for several months after the species has disappeared from the surface. The majority remains on the bottom in shallow coastal water until conditions favour their germination (Gross 1937). Resting spores must be the means by which many species continue in coastal waters in spite of the fact that conditions are more variable there than in the open ocean and may be favourable to diatoms for only a limited part of each year (members of Biddulphiales).

1.5   Algal Pigments

Algae are photosynthetic organisms and they possess chlorophyll in their chloroplasts. The primary photosynthetic pigment of algae is chlorophyll and is the light receptor in photosystem I of light reaction. There are different types of chlorophyll like Chl *a*, *b*, *c* (*c*1, *c*2), *d* and *e* present in algal cells. Among them Chl *a* is universal and present in all members of autotrophic algae (with a few exception of heterotrophic algae). Due to presence of Chl *a*, members of cyanobacteria are also considered as prokaryotic algae by algologist. Chlorophyll a is soluble in alcohol, diethyl ether, benzene and acetone but insoluble in water. Chlorophyll is composed of a porphyrin ring system that is very similar to that of haemoglobin but has a magnesium atom at the centre instead of an iron

atom. Chlorophyll content ranges from 0.3 % of the dry weight among different algal genera of different classes. Chlorophyll has two main absorption bands in the red light region at 663 nm and the other at 430 nm.

Unlike chlorophyll *a*, other types of chlorophylls have a more limited distribution and function as accessory photosynthetic pigments. Chlorophyll *b* is found in the Euglenophyta, Chlorophyta and Chlorarachniophyta. Chlorophyll *b* functions as a light-harvesting pigment transferring absorbed light energy to chlorophyll *a*. Chlorophyll *b* has two main absorption maxima in acetone or methanol, one at 645 nm and the other at 435 nm.

Chlorophyll *c* has two components which are spectrally different, viz. chlorophyll *c*1 and *c*2. The ratio of chlorophyll *a* to chlorophyll *c* ranges from 1.2:2 to 5:1. Chlorophyll *c* probably functions as an accessory pigment to photosystem II. Chl *c* is soluble in ether, acetone, methanol and ethyl acetate but is insoluble in water and petroleum ether. Chlorophyll *c*1 has main absorption maxima at 634, 583 and 440 nm in methanol, whereas chlorophyll *c*2 has maxima at 635, 586 and 452 nm.

Chlorophyll *d* is a minor component present in many members of Rhodophyta. It is soluble in ether, acetone, alcohol and benzene and very slightly soluble in petroleum ether showing three main absorption bands at 696, 456 and 400 nm.

Carotenoids are yellow, orange or red hydrocarbons present in algal members as accessory pigments and usually occur inside the plastid but may be outside in certain cases. Carotenoids can be divided into two classes: (1) oxygen-free hydrocarbons, the carotenoids, and (2) their oxygenated derivatives, the xanthophylls. The most common algal carotene is the β-carotene.

Chla

Chlb

Chld

Chl c$_1$

Chl c$_2$
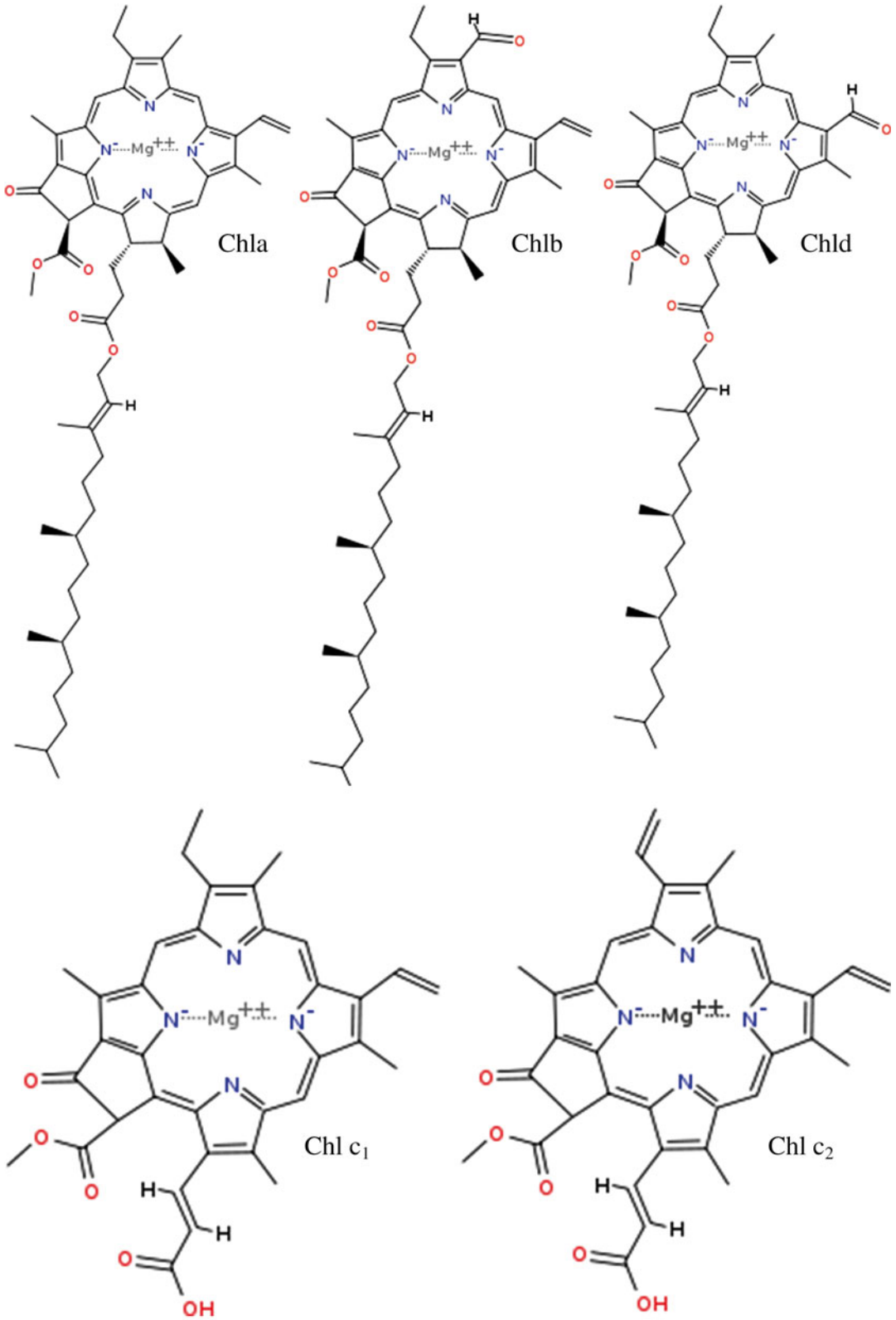
Chemical configuration of algal pigments

β-carotene

COOH   COOH
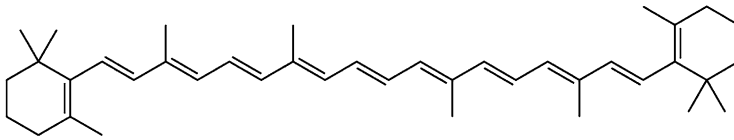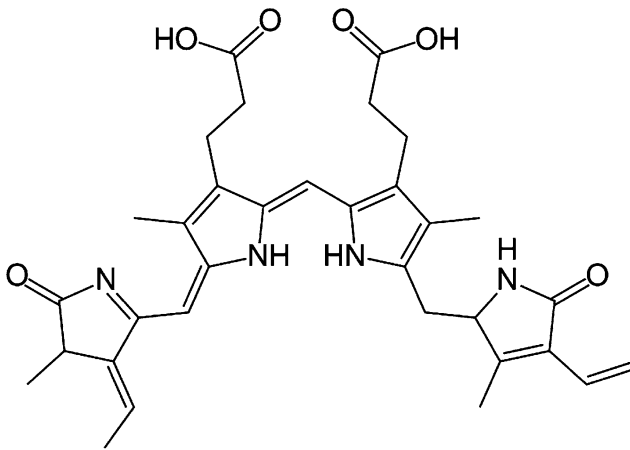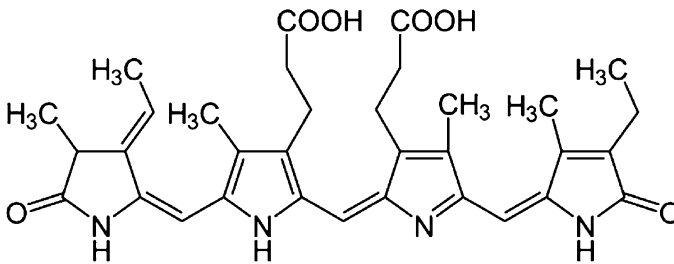
Phycoerythrobilin   Phycocyanobilin

Chemical configuration of few major pigments of algae

There are a large number of different xantho-phylls present in different groups of algae. Fucoxanthin is the principal xanthophylls in the golden-brown algae (Chrysophyta, Bacillariophyta, Prymnesiophyta and Phaeophyta), giving these algae their characteristic colour. Like the chloro-phyll, the carotenoids are also fat-soluble pigment being soluble in alcohols, benzene and acetone but insoluble in water.

Among all the algal pigments, phycobilipro-teins – present in Cyanobacteria, Rhodophyta and Cryptophyta – are water-soluble blue or red pigments. They are located on (Cyanophyta, Rhodophyta) or inside (Cryptophyta) the thylakoids of algal chloroplasts. They are associated with macromolecular protein and are known as chro-moproteins (coloured proteins). They have the prosthetic group (nonprotein part of the molecule) or chromophore. Chromophore is a tetrapyrrole (bile pigment) known as phycobilin and is tightly bound by covalent linkages to its apoprotein (protein part of the molecule). As the pigment is tightly bound to the apoprotein, the term phyco-biliprotein is used. The apoproteins are again of two types, α and β, which together form the basic unit of the phycobiliproteins. The major 'blue' chromophore is called the phycocyanobilin and is present in phycocyanin and allophycocyanin, and the major 'red' chromophore phycoerythrobilin is present dominantly in phycoerythrin.

Each phycobiliprotein usually consists of a basic aggregate of three molecules of α-apoprotein and three molecules of β-apoprotein and the chromophores attached to the apoproteins. The basic aggregate is designated as $(\alpha\beta)_3$. In some cases the basic aggregate is double of this along with a linker polypeptide and can be designated as $(\alpha\beta)_6$. Different linker polypeptides interact with the same phycobiliprotein to give complexes with physical properties determined by the linker polypeptides (Yu et al. 1981). A third apoprotein, γ, is present in B- and R-phycoerythrins. The core of the phycobilisome is probably composed of allophycocyanin, with the peripheral rods containing phycocyanin and phycoerythrin. The length of the peripheral rods varies, being dependent on the wavelength of light under which the cells are grown. This phenomenon is a form of chromatic adaptation (Bryant 1994).

Two classes of phycobilisomes exist: (1) the hemi-ellipsoidal phycobilisomes and the hemi-discoidal phycobilisomes in the red algae, blue-green algae and the cyanelles (endosymbiotic blue-green algae).

It is believed that the light energy transfers in the following pathway during photosynthesis:

$$\text{Phycoerythrin} \rightarrow \text{phycocyanin} \rightarrow \text{allophycocyanin} \rightarrow \text{allophycocyanin B} \rightarrow \text{chlorophyll } a$$
$$(\lambda\max = 565) \quad (\lambda\max = 620-638) \quad (\lambda\max 650) \quad (\lambda\max = 670)$$

$$\text{or}$$
$$\text{Phycoerythrocyanin}$$
$$(\lambda\max 568)$$
$$(\text{Glazer et al. 1985})$$
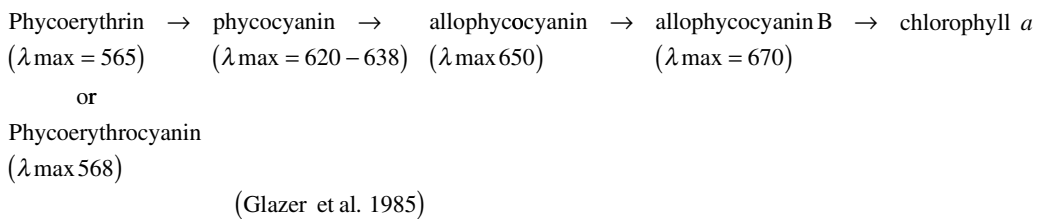
The efficiency of energy transfer from the phycobilisome to chlorophyll a in the thylakoids exceeds more than 90 % in intact cells (Porter et al. 1978).

Table showing different pigment compositions of various groups of algae with thallus organization

Division/class	Thallus organization	Pigments
Cyanobacteria	Members of Cyanobacteria are in the form of unicells, or colonies, up to 2 mm in size. Picoplanktonic forms are 1–2 μm in diameter; filamentous forms are unbranched, pseudobranched or branched	Chl a, Chl b (in Prochlorophyta, now called green cyanobacteria) and traces of MgDVP[a]
		Phycobilins: phycocyanin, phycoerythrin, allophycocyanin.
		Carotenoids: β-carotene, myxoxanthophyll, zeaxanthin, echinenone, canthaxanthin, oscillaxanthin, nostoxanthin, aphanizophyll, 4-keto-myxoxanthophyll. Jeffrey and Wright (2006) categorized five different types of pigment composition, cyano-1–5
Glaucophyta	Biflagellated unicells, oblong or coccoid, dorsiventral, 10–30 μm diameter; also in palmelloid stage	Chl a
		Carotenoids: β-carotene, zeaxanthin, β-cryptoxanthin
		Biliproteins: phycocyanin, allophycocyanin
Rhodophyta	Coccoid unicells, filamentous, simple or polysiphonous, thalloid leaflike	Chl a
		Carotenoids: β-carotene, zeaxanthin;
		Biliproteins: phycoerythrin, phycocyanin (less amount, allophycocyanin)
Chlorophyta	Small green flagellates, naked, or ovoid in form,10–40 mm in diameter, unicellular, coccoid, colonial, filamentous – simple uniseriate to branched form	Chlorophylls a and b, MgDVP; Carotenoids: lutein, violaxanthin, neoxanthin, antheraxanthin, β-carotene, β,ε-carotene, zeaxanthin, β,ψ-carotene (trace), astaxanthin and two pigment types are recognized: CHLORO-1 and CHLORO-2 (Jeffrey and Egeland 2008)

(continued)

(continued)

Division/class	Thallus organization	Pigments
Euglenophyta	Unicellular, ovoid or fusiform; most species have a flexible pellicle, which allows movement by deformation; other species have a rigid lorica	Chl *a* and *b*, MgDVP; Carotenoids: eutreptiellanone, diadinoxanthin, diatoxanthin, 9′-cis-neoxanthin, β,β-carotene, β,ε-carotene (Jeffrey and Wright 1997)
Dinophyta	Mostly unicellular (5–200 μm), with a transverse girdle groove into an upper epicingulum and a lower hypocingulum; unarmoured or armoured with cellulose plates	Chlorophylls: Chl *a*, *c*2, MgDVP; Carotenoids: peridinin, diadinoxanthin, diatoxanthin, dinoxanthin, peridininol, pyrrhoxanthin and β,β-carotene
		Five combinations of pigments: the major dinoflagellate carotenoid peridinin containing DINO-1 or with their endosymbiont pigments, e.g. haptophytes (DINO-2), diatoms (DINO-3), cryptophytes (DINO-4) or prasinophytes (DINO-5) (Jeffrey and Wright 2006)
Heterokontophyta (Bacillariophyceae – diatoms)	Unicellular or colonial forms.	Chlorophylls: Three combinations of pigment are distinguished on the basis of Chl *c* derivatives (Zeffry et al. 2011)
	Cells are covered by characteristic siliceous frustules with two overlapping halves.	DIATOM-1: Chl *a*, Chl *c*1, Chl *c*2, MgDVP
	Morphology of diatoms is based on radial (centric) or bilateral symmetry (pennate)	DIATOM-2: Chl *a*, Chl *c*2, Chl *c*3, MgDVP
		DIATOM-3: Chl *a*, Chl *c*1, Chl *c*2 *c*2, Chl *c*3, MgDVP(trace)
		Carotenoids: fucoxanthin, diadinoxanthin, diatoxanthin, β,β-carotene, 19′-butanoyloxyfucoxanthin, violaxanthin, antheraxanthin, zeaxanthin
Bolidophyceae	Picoplanktonic cells: round or heart shaped	Chl *a*, *c*3
Chrysophyceae	Colonial with coccoid or ovoid cell, flagellated or amoeboid	Chl *a*, *c*1, *c*2
		Carotenoids: β,β-carotene, fucoxanthin, violaxanthin, antheraxanthin, zeaxanthin
Dictyochophyceae	Picoplanktonic or larger, unicellular, naked or inside a siliceous skeleton	Chl *a*, *c*2, *c*3
		Carotenoid: β-carotene, fucoxanthin, diatoxanthin, diadinoxanthin
Eustigmatophyceae	Unicellular, coccoid or ovoid, flagellated	Chl *a*, MgDVP
		Carotenoids: β,β-carotene, antheraxanthin, vaucheriaxanthin, violaxanthin, zeaxanthin
Pelagophyceae	Unicellular or colonial. Cells coccoid or ovoid, filamentous, palmelloid	Chl *a*, *c*2
		Carotenoids: diadinoxanthin, diatoxanthin, fucoxanthin, beta-carotene, gyroxanthin diester
Haptophyta	Unicellular, 5–20 μm in diameter; almost exclusively flagellates, cells elongated	HAPTO-1
		Chlorophylls: Chl *a*, *c*1, *c*2, MgDVP
		Carotenoids: fucoxanthin, diadinoxanthin, diatoxanthin, β-carotene
		HAPTO-2
		Chlorophylls: Chl *a*, *c*1, *c*2, MgDVP
		Carotenoids: fucoxanthin, diadinoxanthin, diatoxanthin, β-carotene
Cryptophyta	Ovoid asymmetrical unicells (6–20 μm), often flattened A unique cell covering or pellicle is made up of a ridged periplast superimposed on an inner layer of thin proteinaceous plates; no microtubular cytoskeleton	Chlorophylls: Chl *a* and *c*2, MgDVP
		Carotenoids: alloxanthin, crocoxanthin, monadoxanthin, β,ε-carotene lipoproteins, red or blue phycobiliproteins

[a]Mg**DVP** – Mg-3,8-divinyl-pheoporphyrin a5 monomethyl ester

1.6   **Ecological Significance**

Phytoplanktons play an important role in aquatic ecosystems, both in freshwater and in marine environment. They are the primary producer organisms, therefore, supporting zooplanktons, fishes and other members of aquatic fauna. Thus, they are placed at the base of the trophic strata or at the bottom of the aquatic food web. Phytoplanktons also play a major role in global carbon dioxide fixation. In marine environment they fix almost 48 Pg C. year^{-1} [1 Pg $= 1 \times 10^{15}$ g], which is almost 48 % of the total fixed carbon on the earth's surface (Geider et al. 1997). Phytoplanktons also maintain the oxygen level of the water body, which is designated as dissolved oxygen or DO.

The phytoplankton population, controlling the life cycle of each species, is again controlled by several factors, like the availability of nutrients, degree of thermal stratification, algal movements relative to the water current, zooplankton grazing, intra-algal competition and parasitism by protozoans, fungi, bacteria or viruses. It is observed in many places that the chlorophyte, chrysophyte, cryptophyte and euglenophyte algae often dominate and form in the summer peak due to an ability to take up nutrients at low level and to maintain their positions by swimming. In some lakes, they also exist below the thermocline and at greater depths.

Different genera of phytoplanktons evolved various strategy to overcome the nutrient depletion and grazing. They generally produce different types of enzymes, some of which are directly involved in nutrient uptake and others responsible to secrete some chelators or siderophores which form complex with the nutrients and make them available for uptake. Due to diatom bloom the nutrient level becomes depleted especially silica (SiO_2) – required for diatom frustule growth. Phytoplanktons can move directly or float through water current. Movement by swimming or a change in cell density may allow them to reach new sources of nutrients actively or passively. In adverse environmental conditions, some algae produce resting spores, remain active at the junction of epilimnion and hypolimnion region of thermocline. To protect themselves from grazing also, many species produce protective spores, gelatinous coats, or grow fast to produce a large population. Grazing rate of zooplanktons may be reduced due to thick growth of algae or sometimes due to production of unpalatable species such as blue-green algae.

1.6.1   **Phytoplankton Bloom**

A rapid increase or accumulation in the population of algae (typically microscopic) in an aquatic system is regarded as an 'algal bloom'. Many of the planktonic genera form the blooms.

Phytoplankton population generally grows in a series of pulses or blooms. Blooms occur when cell numbers exceed their annual average or background concentration manifolds or when a certain high cell number is reached, for example, 5×10^6 cells/L. A bloom can colour the water.

In temperate region, the first bloom is initiated in spring due to increased sunlight; subsequently, the growth is terminated in autumn when light decreases in water. On the other hand, in tropical regions growth may be nearly continuous when sufficient nutrients are available. In polar region only a short period of growth can be observed mainly of diatoms as the sunlight and ice-free periods are very brief.

In productive lakes of temperate regions, holoplanktons, i.e. the algae which always remain in planktonic form, flourish more during spring time, like the diatom genera – *Asterionella, Fragilaria* and *Tabellaria* – forming the spring blooms. Excessive growth of chytrid fungi, zooplankton grazing or protozoans interference may affect the algal bloom.

Meroplanktonic genus *Melosira,* which is only sometimes in planktonic form, appears in large number in winter. Actually due to resuspension of live cells of *Melosira*, i.e. germination of resting spores from the sediments in favourable season, resulted in changes in population pattern and the bloom appeared. *Melosira* has a slow growth rate, but they are quite able to take the advantage of the high nutrient levels and benefits from low levels of competition and grazing.

The other meroplanktonic cyanobacterial taxa like *Aphanizomenon*, *Anabaena* and *Microcystis* flourish more in warm lakes in summer and falls, but the diatoms grow at a faster rate in winter of a tropical country. They produce the resting spore or thick-walled cell during winter to withstand the unfavourable season. Moreover, cyanobacteria can regulate their buoyancy by their minute gas vesicles and are able to adopt themselves in thermocline of different seasons at different depths. Many cyanobacteria and eukaryotic algae have an ability to take up nutrients like phosphate and ammonia at low levels. A few of them can also fix atmospheric nitrogen gas. All other algal groups as well as many other cyanobacteria lack this ability. Therefore, cyanobacterial blooms appear in comparatively low nutrient level even at nitrogen-depleted condition. Among the algal divisions cyanobacteria and dinoflagellate members produce bloom very frequently in different ecological conditions and are also ecologically significant.

1.6.2   Cyanobacterial Bloom

Cyanobacteria grow profusely, congregate and make the lake water coloured soup. This phenomenon is called 'cyanobacterial bloom'. Due to huge growth of buoyant cyanobacteria, the lake and ocean water turned coloured and the transparent water suddenly became soupy in appearance often turned into bright blue, grey, tan or even red in colour.

Generally chlorophyll production of bloom is 10 mg μm^{-3} (ca 20,000 cells mL^{-1}). Bloom formation is mainly the function of the environment; both freshwater ecosystem and the oceanic surface are suitable for cyanobacterial bloom formation.

Marine planktonic cyanobacteria control the biogeochemical cycle and the trophic status of marine environment. They control the marine production and nutrient cycling in two main ways – firstly they fix CO_2 to a greater extent at blooming condition, therefore controlling the C-cycling, and secondly some of them can fix atmospheric N_2; as a result the level of soluble bioavailable nitrogen in ocean water is increased. Nitrogen-fixing cyanobacteria generally form the surface bloom and supply the nitrogen to N-depleted ocean water. Ocean water is generally unproductive and can be called as oligotrophic in nature. In the early times, it was believed that marine cyanobacteria are very few in numbers. But since the 1970s with the advent of high-resolution fluorescence microscopy, electron microscopy, HPTLC, etc., it is proved that the oceanic primary productivity is mainly maintained by pico (≤ 5 μm)- and nanoplanktonic (5–20 μm) cyanobacteria together with comparatively less microplanktonic (≥ 20 μm) cyanobacterial members. Marine planktonic cyanobacteria are represented by unicellular (*Synechococcus*, *Prochlorococcus*, *Synechocystis*, *Aphanothece*), colonial (*Merismopedia*), filamentous non-heterocystous (*Lyngbya*, *Oscillatoria*, *Phormidium*, *Spirulina*, *Trichodesmium*) and heterocystous taxa (*Anabaena*, *Aphanizomenon*, *Nodularia*, *Richelia*). Picoplanktonic genera of *Synechococcus*, *Prochlorococcus* and *Synechocystis* constitute 30–50 % of phytoplankton biomass and therefore control the primary productivity by fixing CO_2. Cyanobacterial taxa grow in different ecological conditions forming bloom. The free-floating *Trichodesmium erythraeum*, the non-heterocystous taxa, forms a dense colony, ensheathed with polysaccharidic sheath, therefore producing an O_2-free microenvironment on sea surface and fixing atmospheric N_2. Another N_2-fixing filamentous genus *Richelia* grows inside the diatom *Rhizosolenia* and fixes atmospheric N_2 in ocean water. Heterocystous planktonic genera, *Nodularia*, *Aphanizomenon*, etc., grow in estuarine entropic environment and fix considerable amount of atmospheric nitrogen.

The cyanobacterial taxa having gas vesicles form the surface bloom like planktonic filamentous *Anabaena* and *Aphanizomenon* or colonial form *Microcystis*, etc. Cyanobacterial blooms form the surface scum at early morning, as the internal carbohydrate is generally consumed at night. During daytime when photosynthetic rate is increased and carbohydrate is accumulated within the cell, the gas vesicles collapsed due to the increased turgor pressure. As a result the

organisms descend out of the surface scum and the bloom disappeared. Afterwards they reappear the next morning, when the stored carbohydrate is consumed. Due to some physiological damages like photoinhibition, photo-oxidation and dehydration, persistent surface blooms can appear which indicate the failure of buoyancy regulation. According to Pearl and Ustach (1982), the surface blooms are a part of an ecological strategy for optional use of photosynthetically active radiation and atmospheric carbon dioxide. Surface bloom also affects light penetration through the water column, not only by covering the water surface but also by scattering the light by the gas vesicles. Due to light scattering by cyanobacterial gas vesicles, the planktons of euphotic zone have an advantage of intercepting more light.

1.6.2.1 Cyanobacterial Bloom Control

Bloom formation can be controlled by nutrient concentration and/or controlling the light and temperature. Mixing is another process by which the turbulent environment of lakes or streams can be initiated which affect the natural phenomenon of bloom formation. The following are few practiced process by which bloom can be controlled:

1. By collapsing gas vesicles: To prevent buoyancy, if the cyanobacterial population is exposed to a hydrostatic pressure of 0.4 MPa, a significant proportion of gas vesicles would be collapsed; therefore, the bloom would disappear. Circulation of water containing surface scum of cyanobacteria up to a depth of 90 m can destroy the gas vesicles – therefore, the surface water would be free of cyanobacterial scum.

2. Artificial mixing: Cyanobacterial members prefer stable water column together with high nitrate and phosphate level for bloom formation. Artificial mixing of water column is the effective process for controlling cyanobacterial bloom. After the removal of the cyanobacteria, other members of diatoms or dinoflagellates may appear in blooming condition in turbulent environment with high nutrient levels.

3. Application of biological control: Inoculation of cyanophage (virus that infects cyanobacterial cell) for controlling cyanobacterial bloom is a common phenomenon.

4. Use of different algicides like copper sulphate for bloom controlling is a regular phenomenon for common people. But the toxic effects of chemicals also hamper the total ecological balance. Application of $CaCO_3$ in fish pond to control algal bloom is a common practice.

5. Light shielding: Light is the major factor for bloom formation. Light shielding is therefore an easy process for bloom control. Shielding can be done by covering with some dark sheet or by floating angiospermic plants like *Eischornia* and *Lemna*.

1.6.3   Dinoflagellate Bloom

Occasionally large populations of dinoflagellate, i.e. dinoflagellate blooms, appear on the surface of lakes, estuaries and ocean as red covering of the water body and are visible in the naked eye. Dinoflagellate blooms are usually known as 'red tide', e.g. bloom of *Peridinium* in alpine lake. Most of the members of dinoflagellates can quickly regulate their position by swimming. They are comparatively larger and can move fast and are phototactic in nature. They generally swim to the surface of water in the morning for photosynthesis and then swim down again in late afternoon.

Dinoflagellate members like *Peridinium* and *Ceratium* generally grow fast in summer and autumn and are quite able to swim actively to get the positions of favourable light and nutrients. The algae are positively phototactic and may form reddish-brown surface patches, called red tides. Nutrient requirements of dinoflagellate members are complex and may include organic substrate due to their heterotrophic nutrition. Dinoflagellate's population may decline due to heavy zooplankton grazing, competition from other algae and possibly nutrient depletion. The growth cycles of different algae actually depend on both physical and chemical factors and therefore is a complex phenomenon. Large colonies

rise or sink faster than unicellular or filamentous form. Large size and unpalatability prevent serious loss to zooplankton grazing.

Recently, harmful algal blooms (HABs) have become a cause of concern due to their toxic nature mainly composed of dinoflagellate members and a few other algae including cyanobacteria. A *harmful algal bloom* (HAB) is an algal bloom that causes negative impacts to other organisms via production of natural toxins above the permissible level, mechanical damage to other organisms or by other means. HABs are often associated with large-scale marine mortality events and have been associated with various types of shellfish poisonings. Harmful algal blooms have been observed to cause adverse effects to varying species of marine mammals and sea turtles, with each presenting specific toxicity-induced reductions in developmental, immunological, neurological and reproductive capacities.

Dinoflagellates constitute approximately 50 % of all red tide species and 75 % of all HAB species (Sournia 1973; Smayda 1997); therefore, research related to dinoflagellate ecology is essential for understanding the red tide and HAB phenomena. The well-known 'Florida red tide' that occurs in the Gulf of Mexico is an HAB caused by *Karenia brevis* that produces brevetoxin, causing neurotoxic shellfish poisoning. Bloom of *Karenia brevis* is a recurrent phenomenon in the West Florida Shelf as well. This increase in the population mainly originates in the oligotrophic offshore water which is subsequently transported to the West Florida Shelf via winds and tidal currents (Steidinger and Haddad 1981). These thermal fonts not only act as a barrier but also as transport mechanism to concentrate *Karenia brevis* population in the shelf waters. Thus, the resultant bloom is not due to the excessive productivity but the concentration process. A study on this phenomenon from October 1998 to January 2002 showed that the cell density ranged from 1 to 5.4 million cells/L under an N-limited but P-enriched condition (Vargo et al. 2001). It was reported that during these periods, wind mixing as well as upwelling favouring

winds allowed onshore transport of water. This accounted for transportation of estuarine waters into the coastal zone that led to the breakdown of vertical stratification and promoted horizontal stratification with the formation of thermal and salinity fonts. Thus, it can be said that development of 'blooms' is not only a nutrient-regulated phenomenon but also involves physical processes as well.

Similar algal blooms occur in freshwater as well as in marine environments. Typically, only one or a small number of phytoplankton species are involved in bloom formation, and some blooms may cause characteristic discolouration of the water resulting from the high density of pigmented cells. If the algal bloom results in a high enough concentration of algae, the water may become discoloured, varying in colour from purple to almost pink, normally being red or green (Fig. 1.2).

HABs occur in many regions of the world, and in the USA, these are recurring phenomena in multiple geographical regions. The Gulf of Maine frequently experiences blooms of the dinoflagellate *Alexandrium fundyense* that produces saxitoxin, the neurotoxin responsible for paralytic shellfish poisoning. California coastal waters also experience seasonal blooms of *Pseudo-nitzschia*, a diatom known to produce domoic acid, responsible for amnesic shellfish poisoning. Off the west coast of South Africa, HABs caused by *Alexandrium catanella* occur in every spring. These blooms used to cause severe intoxication of filter-feeding shellfish which affects the entire food chain (Fig. 1.3).

At the end of the growing season, the dead and decomposed planktonic biomass depletes the oxygen from the water together with the increased loading of organic matter into the water body. This causes massive death of aquatic animals due to suffocation and intoxication, which ultimately produce the dead zone. Dead zones are hypoxic (low-oxygen) areas in the world's oceans – the observed incidences of which have been increasing as oceanographers recorded since the 1970s. These occur near inhabited coastlines, where aquatic life is most

Fig. 1.2 A red tide off the coast of La Jolla, San Diego, California (Source: www.wikipedia.com)
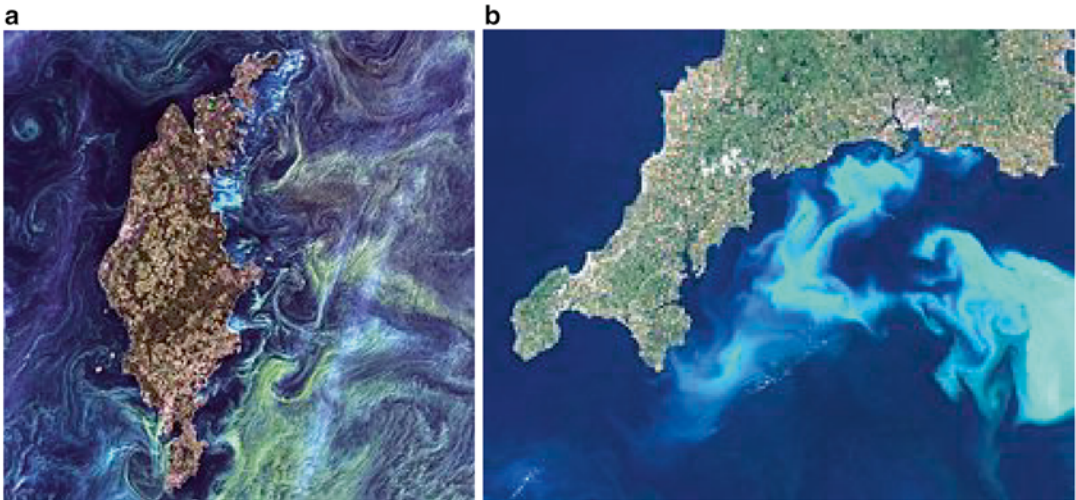
Fig. 1.3 (**a**) Satellite image of phytoplankton swirling around the Swedish island of Gotland in the Baltic Sea, in 2005, and (**b**) an algae bloom off the southern coast of Devon and Cornwall in England, in 1999 (Source: www.wikipedia.com)

concentrated. In March 2004, when the recently established UN Environment Programme published its first Global Environment Outlook Year Book (*GEO Year Book 2003*), it reported 146 dead zones in the world's oceans where marine life could not be supported due to depleted oxygen levels. Some of these were as small as a square kilometre (0.4 mi^2), but the largest dead zone covered 70,000 km^2 (27,000 mi^2). A recent study counted 405 dead zones worldwide.

1.6.4 Algal Toxins

The toxicity of some algal genera including cyanobacteria has been known since early times. Most of these taxa are planktonic causing deleterious effect on marine and freshwater fauna and flora. Generally the concentration of these toxins, viz. cyanotoxin, paralytic shellfish poison (PSP) or domoic acid (DA), increase when the secreting taxa appear in blooming condition,

causing intoxication or death of other organisms especially the mammals.

1.6.4.1 Cyanotoxin

The toxins secreted by cyanobacteria or the cyanotoxins are the most common toxins of both freshwater and marine habitat. Different types of cyanotoxins have been recorded with varied chemical structure. The most commonly occurring toxins are anatoxin-a, saxitoxin, microcystin, scytophycin, cyanobactrin, lyngbyatoxin, etc. Depending on the toxic effect of the cyanotoxins, it can be categorized into different types like neurotoxins, hepatotoxin and cytotoxins.

Neurotoxins are chemically nitrogen-containing compounds of low molecular weight, for example, anatoxin and saxitoxin. They generally block the signal transmission from neurone to neurone and neurone to muscle. The neurotoxic amino acid L-beta-*N*-methylamino-l-alanine was shown to be produced by diverse cyanobacterial taxa. In acute intoxication it may be fatal due to respiratory arrest. Cyanobacterial taxa like *Anabaena flos-aquae*, *Aphanizomenon flos-aquae*, *Oscillatoria* and *Trichodesmium* produce neurotoxins.

The most common hepatotoxin is microcystin secreted by *Microcystis aeruginosa*. It is a chemically cyclic hepatic peptide. A total of seven peptides are involved to form the structure of a microcystin, and the molecular formula is (2S,3S, 8S,9S,4E,6E)-3-amino-9-methoxy-2,6,8-trimethyl-10-phenyl-4,6-decadienoic acid. It contains D-alanine (D-ala) and D-METHYL-ASPARTATE (Masp). *Microcystis* poisoning was first reported about 1,000 years ago in southern China, when a Chinese general reported the death of his troops who drank green-coloured water from a river. Another hepatotoxin is nodularin, secreted by other cyanobacterial taxa including *Nodularia*.

A large number of cyanobacterial taxa produce cytotoxic compounds which are active against cell tissue line and have antitumor activities.

1.6.4.2 Dinoflagellate Toxins

Toxins produced by marine dinoflagellates are among the most potent nonproteinaceous lethal materials known. The most notorious of the dinoflagellate toxins are neurotoxins. These toxins act either as depolarizing agents or as non-depolarizing agents in membranes of excitable cells. Dinoflagellate toxins are a matter of public health concern as they infect many marine products through the food chain especially during red tide formation.

The water-soluble toxins, saxitoxins, are produced by members of *Gonyaulax*, a tetrahydropurine composed of two guanidinium moieties. These toxins are categorized as follows:

1. Neosaxitoxin – 1(*N*)hydroxysaxitoxin (class I paralytic shellfish poison)
2. Sulfated 11 hydroxyl substitution (class II) – gonyautoxins 1,2,3 and 4
3. *N*-sulfoconjugation on the carbamoyl position (class III) – gonyautoxins 5 and 6
4. Dual sulfoconjugation at the 11 hydroxyl and carbamoyl positions (class IV)

Lipid-soluble toxins (Florida red tide toxin) are produced by:

1. *Ptychodiscus brevis* – brevetoxins
2. *Gymnothora javanicus* – ciguatoxin
3. *Prorocentrum lima* – okadaic acid
4. *Dinophysis fortii* – methyl okadaic acid

The dinoflagellate toxins act predominantly by altering transmembrane fluxes of cations, primarily sodium. Only maitotoxin acts in a sodium-independent manner. They block the inward flow of sodium ions without affecting the potassium channel. Ciguatoxin enhances the inward flow of sodium ions. Saxitoxin binds to specific receptors in the nerve membrane, whereas maitotoxin possesses a specific calcium-dependent transport.

1.7 Algae in Wetlands

Wetlands are waterlogged ecosystem with a periodic fluctuation in water depth. Most of the wetlands are with a depth of less than 2 m (<2). Wetlands occur in every continent except Antarctica. According to Mitsch and Gosselink (1993), wetlands comprise as much as 6 % of global land area. It is also reported that 14 % land area of Canada is wetland – most of which are confined to northern peatlands.

Wetlands are important for their high productivity as they are considered as nutrient sinks (Dolan et al. 1981; Reeder 1994), flood control buffers and the breeding ground of different aquatic animals like waterfowl and others (Batt et al. 1989). Wetland research is carried out in different countries by various scientists (Barica et al. 1980; Hanson and Butler 1994; Moss 1983).

1.7.1   Role of Phytoplanktons in Wetlands

In wetland ecosystem, phytoplanktons are one of the fundamental players of physical, chemical and biological processes that characterize the wetland ecosystems. They mostly act as primary producer, therefore placed in the wetland food web. Pinckney and Zingmark (1993) calculated the relative primary production of different types of algal community of wetlands and obtained as much as 22–38 % of epipelagic algae, 10–17 % for macroalgae and 30–59 % for vascular plants. The average C fixation rate of freshwater marsh phytoplanktons varied from 3 to 16 μ L^{-1} h^{-1} as estimated by different authors (Kotak and Robinson 1991; Mitsch and Reeder 1991). Whereas in peat bogs, it was 5–32 μg L^{-1} h^{-1} (Henebry and Cairna 1984); in salt marsh it was recorded as 100 g m^{-2} year^{-1} (Vernberg 1993), and in tundra ponds, it was at minimum level of 0.6–0.9 g^{-2} year^{-1} (Stanley 1976).

The importance of wetland phytoplanktons as a resource of food to herbivores depends on their availability throughout the year. Their variation in size, species composition and productivity support the zooplankton and other aquatic fauna as continuous food source.

Generally the levels of phytoplankton chlorophyll in wetlands varied from 50 to >200 μg L^{-1} during periodic cyanobacterial bloom (Barica 1975).

1.7.2   Nutrient Status of Wetland Ecosystem

In a wetland ecosystem, nutrient efflux from different sources enriches the nutrient level; therefore, high entropic condition resulted in periodical phytoplankton bloom. Efflux from the sediments is a major source of nutrients to the water column. Significant water input from the adjacent lake, river or streams is the main source of nutrients and algal inocula for lakeshore and riverside wetlands. Nutrient efflux due to various anthropogenic factors is another source of nutrients for wetlands; waste water from different sources like industrial waste and municipal waste also increases the nutrient level in wetland ecosystem, especially in stagnant wetlands.

Limnologists are of the opinion that freshwater wetlands are generally P limited, though there are exceptions also. In north temperate wetland of North America, the N–P ratio in the water column is mostly >10 (Barica 1990). The nutrient deficiency of northern wetlands is due to the variation in phytoplankton population there. Murkin et al. (1991) estimated the alkaline phosphatase activity, ammonia uptake rate and the ratios of P–Cl, N–P, N–C and chlorophyll–C composition ratio and found severe N and P deficiency in summer due to insufficient nutrient loading. But other wetlands enriched by cattle feedlot effluent did not have any nutrient-deficient symptoms. Campeau et al. (1994) studied the ecological effect of the addition of N and P to a nutrient-poor marsh and observed the stimulation in biomass production of phytoplanktons together with epiphyton and metaphyton but not the epipelon. Generally shallow wetlands are dominated by phytoplanktons (Barica et al. 1980), but some wetlands with deepwater levels have abundant macrophytes and associated epiphytes. Physicochemical parameters and allelopathic effects of different organisms also play a major role in wetland ecology and phytoplankton abundance together with water depth.

Sometimes there is a direct role of fluctuating water depth on wetland nutrient status. It is already reported that exposure of sediments during draughts promotes the decomposition of organic matter and the nutrients are liberated during subsequent reflooding (Kadlec 1986; Schoenberg and Oliver 1988). van der Valk (1994) reported that in late stage of flooding, macrophytes are killed by flood stress and their

decomposed biomass releases N and P (Murkin et al. 1989). Moreover, both algae and higher plants of wetland ecosystem release a diverse type of soluble organic substances into the water column during their growth and decompositions (Hall and Fisher 1985; Briggs et al. 1993). Therefore, due to abundance of organic N and P species, the algal community may also continue their heterotrophic nutrition. Pip and Robinson (1982) experimented with radiolabelled mixture of glucose, fructose and sucrose and observed that most of the algal genera including cyanobacteria can also utilize the organic carbon sources.

1.7.2.1 Physical Factors Affecting Wetland Ecosystem

I. Light: Light penetration in water column of shallow wetlands is affected greatly by wind-driven sediment resuspension which also increases the productivity of shallow wetlands (Klarer and Millie 1992). The bottom sediments are also subjected to regular disturbances by the benthivorous carp fishes (*Cyprinus carpio*) and other macrophytes (Meijer et al. 1990). Sometimes floating algal mats or *Lemna* mats disrupt light penetration; therefore, the population productivity of wetland flora is greatly affected, where it becomes light limited rather than nutrient limited.

II. Temperature: In wetland ecosystem differences in temperature with depth are minor, as the wetlands are shallow and the wind-driven mixing minimizes the temperature gradient of wetland water column. Sometimes the thick algal mats or floating mat of duckweed may increase the temperature variation in water column reducing the temperature.

1.7.3   Types of Wetlands

Based on the depth and duration of the water-logged condition of the wetland and their respective algal flora, the limnologists classified wetlands into different types.

1.7.3.1 Dry State
In dry state wetland, water levels occur at very low level after a long period of draught, i.e. draw

down in existing wetland or the low level of water by early flooding of a new wetland. Epipelic algae are predominant in this type forming a crust on the bottom sediment.

1.7.3.2 Open State
An open state wetland is with deep and turbulent water column. This type of wetland may arise by two ways: by gradual filling of dry state wetland or by biomanipulation of phytoplankton-dominated lake state wetland. Open state wetlands are dominated by macrophytes, and with abundant epiphyton biomass on them, comparatively phytoplanktons and epipelic algae are less.

1.7.3.3 Sheltered State
In some wetland areas, nutrient load is very high, but the area is shady due to bordering vegetations and excessive growth of macrophytes. These metaphytes remain covered by epiphytic growth. These epiphytic algal mats sometimes detach from their substratum and float on the water surface as metaphytons. Whitton (1970) recorded high nutrient status, high irradiance, alkaline pH, high calcium and low N–P ratios as the main contributors for metaphyton growth.

1.7.3.4 Lake State
Lake state wetlands are characterized by high water column and nutrient levels, therefore ideal for phytoplankton growth. Due to high depth of water, macrophyte growth is checked together with the epiphytic and metaphyton growth. The water column is turbid due to phytoplankton growth. Lake state wetland may develop by rapid water input to other types of wetlands, by natural process or by anthropogenic manipulation. This leads to the death of macrophytes and epiphytons, leading to a growth of lake state wetlands.

1.8   Key to Identification of Common Phytoplankton Genera

1.8.1   Division: Cyanobacteria

Cells smaller, blue green in colour, cells without membrane-bound cell organelles; pigments

diffused throughout peripheral portion of the protoplast; water-soluble pigments like phycocyanin and phycoerythrin present; photosynthetic storage products are glycogen and glycoproteins; definite nucleus and chromosome absent, mucilage conspicuous, hydrostatic gas vacuoles present, reproduction by fission and by fragmentation, sexual reproduction absent.

1.8.1.1 Class: Cyanophyceae

Unicellular/multicellular without true nucleus or chromatophore; chlorophyll *a* and phycobiliproteins are main pigments that are composed of allophycocyanin, phycocyanin and phycoerythrin; photosynthetic product glycogen or glycosides, no starch; reproduction by division or through fragmentation of thallus, endospores, exospores, hormogones, motile flagellate cells absent; sexual reproduction almost absent.

1.8.1.2 Key to Orders

Thallus unicellular or colonial, sometimes forming pseudofilamentous colony, no trichome organization, no differentiation into base and apex, endospores not formed in sporangia, no exospores, nanocysts present – Chroococcales

1.8.1.3 Key to Family

Cells unicellular or forming colonies, not forming filament-like growth – Chroococcaceae

1.8.1.4 Key to Genera

1. Cells single or few together in a shapeless colony	2
1. Cells generally many in a single colony	8
2. Cells spherical	3
2. Cells elongated	5
3. Without individual mucilage envelopes	*Synechocystis*
3. With distinct envelope	4
4. Vesicular sheath	*Gloeocapsa*
5. Cell division transverse, with a firm vesicular sheath	*Gloeothece*
5. Cell division transverse, without such a sheath	6

6. Cells ellipsoidal or cylindrical with round ends	7
7. Cells single or 2–4 together, erect without a common mucilage	*Synechococcus*
8. Cells without any regular or definite arrangement	9
8. Cells with definite arrangement in distinct colonies	14
9. Cells in a general amorphous mucilage, without or with a few distinct sheaths round the individual cells	10
9. Cells with distinct individual envelope or sheaths, colonial mucilage not homogenous	12
10. Cells typically well packed into microscopic colonies of definite shapes, mostly planktonic	*Microcystis*
10. Cells loosely arranged, mostly not planktonic, forming macroscopic colonies	11
11. Cells spherical	*Aphanocapsa*
11. Cells ellipsoidal to cylindrical	*Aphanothece*
12. Individual sheaths vesicular and broad and formed one in another	13
12. Individual sheaths not vesicular, cells spherical	*Chroococcus*
13. Cells spherical	*Gloeocapsa*
13. Cells ellipsoidal to cylindrical	*Gloeothece*
14. Colony with cells arranged in a tabular or cubical or 3D colony	15
14. Colony a hollow sphere with cells arranged along the margin uniformly	16
15. Cells in regular transverse and longitudinal rows, tabular or flat colonies	*Merismopedia*
16. Cells spherical, colonial mucilage homogenous	*Coelosphaerium*
16. Cells pear shaped or weakly spherical, colonial mucilage not homogenous, cells with distinct mucilage sheaths	*Gomphosphaeria*

1.8.2 Division: Chlorophyta

Grass-green chloroplasts, chloroplasts often with pyrenoids, food reserve starch, cell wall composed of cellulose and pectic compounds

1.8.2.1 Class: Chlorophyceae

Unicells (sometimes motile), simple or well-organized colonies, simple or branched filaments, partitioned coenocytes and true coenocytes (filaments without cross walls). Reproduction both sexual and asexual

1.8.2.2 Key to Orders

1. Motile in the vegetative condition; flagella 2 or 4, rarely 8, equal in length; organism 1 celled or colonial	Volvocales
1. Not motile in the vegetative condition	2
2. Cells embedded in copious mucilage (homogenous or lamellated), united in colonies of indefinite shapes or forming gelatinous strands (pseudofilaments) or mucilage invested, some unicellular or forming dendroid colonies which are epiphytic or epizoic, cells often with false flagella (pseudociliates) returning to a motile condition without resorting to reproductive stage	Tetrasporales
2. Cells not embedded in mucilage	3
3. Thallus filamentous, composed of cells adjoined end to end in definite series, sometimes interrupted	4
3. Thallus not composed of cells arranged to form filaments; unicellular or colonial; or if filamentous, occurring as coenocytes without cross walls	15
4. Filaments unbranched; attached or free floating	5
4. Filaments with branches, the branches sometimes closely appressed, forming pseudoparenchymatous masses	13
5. Filaments composed of a single series of cells	6
5. Filaments composed of more than one series of cells; cells adjoined; thallus a hollow tube or ribbon/frond-like expansion	12
6. Chloroplasts 1 to several, large, in the form of spiral bands, stellate masses or broad plates; pyrenoid conspicuous; reproduction by conjugation	Zygnematales
7. Thallus a single cell or a colony of definite or indefinite form; cells with various shapes that range from spherical, pyramidal to polygonal; no vegetative reproduction, reproduction by autospores, zoospores or isogametes	Chlorococcales

1.8.3 Order: Volvocales

Both vegetative and reproductive cells are motile; 2, 4 or rarely 8 flagella, generally a conspicuous pigment spot, cup-shaped parietal chloroplasts; reproduction by cell division, by zoospores, by isogametes or by heterogametes.

1.8.3.1 Key to Families

1. Cells possessing a definite wall and sometimes a mucilaginous sheath; solitary or united in colonies	2
2. Cells solitary	3
2. Cells united in colonies	5
3. Cell wall not bivalved, not flattened	4
4. Cells with protoplasts located at some distance within the cell wall and connected to it by radiating cytoplasmic strands	Haematococcaceae (in part)
4. Cells without radiating cytoplasmic strands	Chlamydomonadaceae
5. Cells united to form flat or globular colonies, evenly dispersed, although sometimes closely arranged within colonial mucilage	Volvocaceae

1.8.4 Order: Chlorococcales

One celled or colonies of definite shapes; cells may be adjoined or merely enclosed by colonial mucilaginous envelope. No cell division in vegetative state. Asexual reproduction by zoospore formation, sexual reproduction isogamous

1.8.4.1 Key to Families

1. Unicellular or colonial; cells varied in shape but not irregular; wall of uniform thickness and not definitely lamellated; free living or attached, rarely subaerial	2
2. Free floating or adherent on soil	3
3. Cells cylindrical and forming a macroscopic network or triangular or polyhedral and united to form either a flat and circular or a globose coenobium (colony)	Hydrodictyaceae

3. Cells not cylindrical and not forming colonies as above	4
4. Unicellular, solitary or sometimes gregarious, free floating (usually on moist soil if adherent), reproduction by zoospores (rarely aplanospores) which do not adhere to one another but which are liberated separately from the parent cell	Chlorococcaceae
4. Colonial or solitary, not reproducing by zoospores	5
5. Thallus not a globose, hollow coenobium	6
6. Cells not in a peripheral arrangement with no coloured mucilage	7
7. Cells solitary or in colonies of definite or indefinite shape; cells variable in form (spherical, ovate, lunate, polyhedral, etc.), not adjoined to one another; reproduction by autospores	Oocystaceae
7. 2–8 cells adjoined together or adherent to form a pattern of definite shape (a linear series, stellate or cruciate); reproduction by the formation of autocolonies within the cells of the parent coenobium	Scenedesmaceae

1.8.5 Division: Bacillariophyta (Diatoms)

1.8.5.1 Order: Centrales

Valves with a concentric or radiating sculpture around a point or points, central or lateral. Without raphe or pseudoraphe. Cells circular, oval or elliptical, sometimes polygonal, rarely crescent shaped or spindle shaped. Processes common

I. Suborder: Discoideae

Cells disc shaped or cylindrical. Valves circular, surface flat or convex, sometimes hemispherical. Spines frequent. Without horns or knobs; when present, small

1. Valves circular. Not divided into definite sectors by ribs, rays or undulating sectors. Sculpturing sometimes arranged in bundles, long spines often present.

Family – Coscinodiscaceae

(a) Cells lens shaped, round or cylindrical. Usually united into more or less long typical chains. Intercalary bands often sculptured. Valve mantle usually strongly developed.

Subfamily – Melosirinae

Common genera – *Melosira*, *Stephanopyxis*

Key to Genera

Cells globose, elliptical or cylindrical, closely united in straight, beadlike chains by the centres of the valves. Valves either simply punctate or punctate and areolate. Intercalary bands none or many and narrow.

Melosira

Cells oblong, oval or nearly circular, with hexagonal areolations. Usually in short chains.

Stephanopyxis

(b) Cells short or elongated–cylindrical, bound into close chains by delicate siliceous projections or gelatinous threads. Cell wall usually weakly siliceous.

Subfamily – Skeletoneminae

Common genera – *Skeletonema*, *Thalassiosira*

Key to Genera

Cells circular, lens-shaped, oblong, or cylindrical. Valves circular, somewhat arched, without distinct structure, with a row of fine spines at the edge of the valve parallel to longitudinal, pervalvar axis. Spines interlock midway between adjacent cells and unite cells into chains.

Skeletonema

Cells similar to those of *Coscinodiscus*, usually drum or disc shaped, united in flexible chains by a cytoplasmic or gelatinous thread or living in formless gelatinous masses or seldom solitary. One or more intercalary bands to each valve. Valves with areolae or delicate radial rows of punctations. Structure often difficult to see. Marginal capsule or little spines present, usually distinct.

Thalassiosira

(c) Cells disc or drum shaped, solitary. Valve surface slightly convex, sometimes nearly flat or slightly concave, with prominent sculptures (commonly hexagonal). Intercalary bands hyaline or rarely very delicately sculptured. Valve mantle not particularly well developed.

Subfamily – Coscinodiscinae

Common genera – *Coscinodiscus*, *Cyclotella, Planktoniella*

Key to Genera

Cells disc or box shaped, single or in twos immediately after cell division. Valves circular, without large knobs or processes, with hexagonal areolae arranged in various ways or fine round puncta.

Coscinodiscus

Cells single, disc shaped, with a hyaline winglike expansion all around consisting of extracellular chambers strengthened by radial rays. The winglike expansion weakly siliceous, an organ of flotation. Valves areolated like those of *Coscinodiscus excentricus.*

Planktoniella

2. Valves circular. Divided into distinct, complete or incomplete sectors by radial ribs or undulations or by wide hyaline rays from a characteristically constructed centrum. Without horns or prominent spines.

Family – Actinodisceae

(a) Valves divided into sharply distinct sectors by radial ridges uniformly running from the margin to the hyaline central area. Small but distinct spines usually at the marginal ends of these ridges. Alternate sectors generally depressed.

Subfamily – Actinoptychinae

Common Genus – *Actinoptychus*

Key to Genera

Cells disc shaped, single. Valves divided into sectors which are alternately raised and depressed. Smooth central area. No intercalary bands.

Cell wall usually of several layers, the individual membranes punctuated; puncta in crossing lines and more or less strongly areolated.

Actinoptychus

3. Valves usually radially waved, eyes or knobs on the elevations or valves flat and then with singly placed wartlike elevations or circle of needles.

Family – Eupodisceae

(a) Valves with knobs. Only one genus.

Subfamily – Aulacodiscinae

Common genus – *Aulacodiscus*

Key to Genera

Cells discoid or box shaped. Valves with a circular outline, flat or slightly lower in the middle or convex, with four or more conical processes symmetrically arranged near the margin. Areolated. Intercalary bands present.

Aulacodiscus

II. Suborder: Solenoideae

Valves oval or circular in cross section. Cells elongated, cylindrical or subcylindrical, with numerous intercalary bands, without internal septa. Valve structure arranged in relation to an excentric pole. Cells united into chains by their valves

As above – Family: Solenieae

(a) Valves flat or raised, with or without marginal spines. Excentric process or asymmetrical spine absent.

Subfamily – Lauderiinae

Common genera – *Corethron*, *Leptocylindrus*

Key to Genera

Cells living singly. Cylindrical with rounded valves having a crown of long thin spines or setae at the margin directed outwards at an angle. Numerous intercalary bands, scalelike, often very indistinct.

Corethron

Cells long, cylindrical, united into chains by whole valve surface. Valves flat, without spines or processes.

Leptocylindrus

(b) Valves with a single often very short spine or process, usually excentrically placed, thus destroying the symmetry of the cell. Valves flat or convex

Subfamily – Rhizosoleniinae

Common genus: *Rhizosolenia*

Key to Genera

Cells cylindrical with greatly elongated pervalvar axis, living singly or in compact or loose chains. Cells usually straight or more rarely curved, forming spirally twisted chains. Cross section elliptical or circular.

Rhizosolenia

III. Suborder: Biddulphioideae

Cells box shaped. Pervalvar axis generally shorter, sometimes slightly longer, than the valvar axis. Valves usually oval, sometimes polygonal, circular or semicircular; unipolar, bipolar or multipolar, each pole represented by an angle or by a horn or spine or by both angles and horns.

Valves with long setae, longer than the cells. Cells united into chains by basal part of the setae. Seldom living as single cells. Intercalary bands only seldom present. Valves circular or oval. All species pelagic.

Family – Chaetocerotaceae

Common genera: *Bacteriastrum, Chaetoceros*

Key to Genera

Cells cylindrical, in cross section circular. Bound into loose chains by the fusion of the more or less numerous setae that are regularly arranged around the margin of the cells. Setae of two adjacent cells are fused for a certain distance beyond the base, farther out divided again.

Bacteriastrum

Cells with oval section to almost or rarely completely circular in valve view; in broad girdle view quadrangular with straight sides and concave, flat or slightly convex ends. Valve with more or less flat end surface or valve surface and a cylindrical part or valve mantle which is bound together without a seam.

Chaetoceros

Horns short and thick or with claws at the end of long horn. Cells united into chains by the ends of the horns. Valvar plane circular or elliptical, usually with one to several poles and multiangled. Intercalary bands and septa often present. Mainly planktonic, partly littoral. Majority of species marine.

Family – Biddulphiaceae

(i) Knobs and horns without claws on the end Valves bipolar. Cell wall weakly siliceous. Plankton forms.

Subfamily – Eucampiinae

Common genus – *Eucampia*

Key to Genera

Valves elliptical in surface view with two blunt processes, without spines or setae. Numerous intercalary bands difficult to see in water mounts. Chains spirally curved. Large apertures between the cells.

Eucampia

Valves tripolar to multipolar, sometimes with bipolar varieties. Angles not bearing domelike protrusions or horns. Intercalary bands frequently present. Marine forms, usually littoral, a few pelagic.

Subfamily – Triceratiinae

Common genera – *Ditylum, Lithodesmium, Triceratium*

Key to Genera

Cells elongated, prismatic to box shaped. Solitary except immediately after division. Valves three to four cornered, seldom bipolar, with a strong central siliceous hollow spine and a marginal ridge strengthened by ribs.

Ditylum

Cells united in usually long, straight chains with concealed apertures. Valves three cornered. Valves with marginal pervalvar- directed membrane by which adjacent cells are joined. Long, thin, hol-

low spine in the centre of valve. Intercalary bands present, collar like.

Lithodesmium

Valves bipolar, tripolar or multipolar. Each angle with a domelike protrusion or a horn. Usually strongly siliceous and forms chains. Predominantly littoral, but sometimes pelagic. A few species are typically planktonic and are then more weakly siliceous.

Subfamily – Biddulphiinae

Common genus – *Biddulphia*

Key to Genera

Cells box shaped to cylindrical. Valves elliptical, with two poles or three- or four sided (rarely five sided). At the corners or at the ends of the apical axis, more or less strongly developed processes or horns may be present.

Biddulphia

Valves unipolar. Cells in broad girdle view rhombic or trapezoid. Large to very large, robust marine forms. Littoral.

Subfamily –Isthmiinae

Common genus – *Isthmia*

Key to Genera

Cells cylindrical–box shaped with elliptical valve surface and usually longer pervalvar axis. Intercalary bands absent.

Isthmia

(ii) Horns with claws on the end

Valves bipolar, tripolar or quadripolar. Each angle with a long vertical horn tipped with a claw.

Family – Hemiaulineae

Common genera – *Cerataulina*, *Hemiaulus*

Key to Genera

Cells cylindrical, usually in chains. Valves slightly arched, with two blunt projections or processes near their margin, attached to adjacent cell by means of a fine, small, curved, hairlike process which fits into the valve of the adjacent cell. Intercalary bands numerous, annular.

Cerataulina

Cells single or united in chains. Valves elliptical in section, with two narrow, pointed, more or less long processes at the ends of the apical axis, parallel to pervalvar axis.

Hemiaulus

Cells without horns. Valves without internal septa. Valves semicircular, broader than long. Intercalary bands very seldom present. Cells in girdle view cuneate.

Family – Euodieae

Common genus – *Hemidiscus*

Key to Genera

Cells shaped like a sector of a sphere, in girdle view wedge shaped, narrowing from the dorsal towards the ventral side. Valve semicircular to asymmetrically elliptical. Valves flat with short valve mantles. Intercalary bands and septa absent, pervalvar axis not particularly elongated.

Hemidiscus

1.8.5.2 Order: Pennales

Valves elongated, bilaterally symmetrical. Outline generally boat shaped or rod shaped, sometimes oval, cuneate, crescent shaped or sigmoid; markings generally pinnate or transverse. True raphe, or hyaline median line (pseudoraphe), or raphe obscured by lateral wings or keel (cryptoraphe) always present. Processes absent. Cell capable of spontaneous movement if a true raphe is present.

1. Raphe absent. Pseudoraphe usually present.

Suborder – Araphidineae

Cells in general rod shaped to tabular prism shaped, in valve view usually more or less linear, seldom club shaped. In girdle view linear to tabular rectangular. Intercalary bands and septa frequently present. Valves with transapical striae or ribs, sometimes areolated–punctated, often with mucilage pores. Without a true raphe, but usually with a median pseudoraphe. Chromatophores usually more or less numerous small platelets, seldom a single large plate.

Family – Fragilarioideae

Cells in valve view usually linear, more seldom wedge shaped, frequently with transapical inflations or constrictions. In girdle view usually linear to tabular, seldom wedge shaped. Intercalary bands and septa always present and distinct. Valvar plane not bent in the pervalvar direction, the two valves of a cell usually entirely alike. Cells usually united into bands. Marine and freshwater forms.

Subfamily – Tabellarieae

Common genera – *Rhabdonema, Grammatophora*

Key to Genera

Cells in girdle view rectangular with rounded corners, usually united into zigzag chains.

Grammatophora

Cells with poles of apical axis unlike. In girdle view, as in valve view, wedge shaped. Intercalary bands and septa present. Cells stalked and often united into strongly branched colonies. Marine.

Subfamily – Licmophorinae

Common genus – *Licomophora*

Key to Genera

Cells with wedge-shaped girdle band side and wedge- or club-shaped valve. Two intercalary bands in resting cells, with a more or less long penetrating septum on the head pole. Valves with transapical punctated striae, seldom with weak transapical ribs and extremely delicately punctated intercalary space.

Licomophora

Cells usually rod shaped. Usually linear in both valve and girdle view, seldom wedge

shaped or with tabular girdle view. Intercalary bands sometimes present, but always without or with only very rudimentary septa.

Subfamily – Fragilariieae

Common genera – *Fragilaria, Synedra, Thalassionema, Thalassiothrix, Asterionella*

Key to Genera

Cells united into more or less long bands by the whole valve sides, occasionally with regular apertures between the cells. Connection of the cells with one another often assisted by tiny spines on the valve margin.

Fragilaria

Cells single or united into fanlike to clustered starlike colonies, seldom in short bands. In general with greatly elongated apical axis, rodlike, sometimes bent in the direction of the apical axis.

Synedra

Cells forming zigzag bands or star-shaped colonies, adjacent cells united to each other by small gelatinous cushions on one cell end. In girdle view linear.

Thalassionema

Cells living singly or forming star-shaped colonies, zigzag bands or bunches, united to one another by a gelatinous cushion on the end of the cell. In girdle view narrow linear.

Thalassiothrix

Cells united by one end (the larger end) into star-shaped colonies or spirally curved, sometimes straight, comb-shaped bands.

Asterionella

Valves with transapical ribs that are, however, sometimes limited to one valve of a cell or to one single middle rib. Freshwater or marine forms. Cells as a rule united into closed or zigzag bands.

Subfamily – Diatominae

Common genus – *Diatoma*

2. One valve of the cell always with *Navicula-like* raphe, the other without a raphe or with a rudimentary raphe knot.

Suborder – Monoraphideae

Cells with linear, lanceolate or elliptical valvar plane, more or less distinctly bent about the apical or transapical axis. Valves sometimes with polar pseudosepta. The membrane lying between the transapical rows stronger, often thickened, riblike. The two valves of a cell usually considerably differentiated in regard to the structure as well as to the development of the raphe.

Family – Achnanthoideae

Cells bent about the transapical axis, sometimes also about the apical axis; the valve with the raphe, concave; the one without a raphe, convex. One valve always with a developed raphe, the other without, seldom with a very short raphe knot or with a rudimentary raphe. Outline of valve usually linear–lanceolate, seldom elliptical. Intercalary bands sometimes present, true septa absent.

Subfamily – Achnanthaceae

Key to Genera

Cells single or united into ribbon-like bands, with or without a gelatinous stalk to hold the chains to the substrate. Seldom pelagic. Valves usually linear–lanceolate, seldom elliptical; in girdle view in general rectangular, but more or less strongly broken along the transapical axis.

Achnanthes

Cells elliptic to near round, rapheless valve with slightly radial transapical striae, pseudoraphe narrow, valve with raphe with radial punctuate striae.

Subfamily – Cocconeideae

3. Both valves with developed raphe.

Suborder – Biraphideae

Cells of various types as regards to structure of membrane, cell contents and general form. All forms with a similar characteristic raphe system: outer and inner fissures and accompanying end and central knots. Knots often greatly reduced or in many species only slightly developed. Inner and outer fissures often difficult to distinguish from each other. Raphe usually in the valvar plane, generally distinct, not developed as a canal raphe; usually without a keel or strongly developed wings, but when present always without marginal canal and keel puncta.

Family – Naviculoideae

Cells as a rule of symmetrical construction, transapical axis only seldom with unlike ends. In girdle view usually rectangular, valves elliptical, linear or lanceolate, often S shaped, seldom club shaped or crescent shaped. Raphe usually in the valvar plane. Cells usually solitary, sometimes in gelatinous tubes or on a gelatinous stalk.

Subfamily – Naviculeae

Key to Genera

Cells usually free, motile. In plankton species usually united into ribbon-like chains. Valves linear to elliptical, with rounded, capitate or rostrate ends.

Navicula

Valves linear or lanceolate. Usually sigmoid. Axial area very narrow. Central area small. Striae punctate, in transverse and longitudinal rows.

Gyrosigma

Valves linear to lanceolate, usually sigmoid. Raphe usually sigmoid, central or excentric. Striae finely punctate in oblique and transverse lines. Central nodule usually small and rounded.

Pleurosigma

Raphe on a keel or wing that usually lies in the midline of the valve. Cells usually twisted about the apical axis.

Subfamily – Amphiproroideae

Key to Genera

Cells single or in ribbon-like chains. Cells constricted in the middle. Valves lanceolate, convex, with raphe, central nodule and a sigmoid keel. One-half of keel lies on each side of the chain axis. Terminal nodules present.

Amphiprora

Keel with canal raphe lying in the valvar plane, often displaced transapically as far as to the valve margin. Both valves with canal raphe. Keel with puncta.

Family – Nitzschiaceae

Raphe obscured by punctate marginal keel. Markings always transverse.

<div align="right">Sub-family Nitzschieae</div>

Key to Genera

Cells spindle shaped, single or united into colonies. Valves keeled, the keel including a concealed raphe, usually diagonally opposite, either central or excentric.

<div align="right">*Nitzschia*</div>

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

2.1 Physical Factors

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

2.1.1 Light and Temperature

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

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

$$E_d(z) = E_d(0) . e_{d^z}^{-k} \quad [\text{Beer Lambert s Law}]$$

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

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

Fig. 2.1 Specific
zonations on the basis
of light and temperature
variations at different
depths of the water column
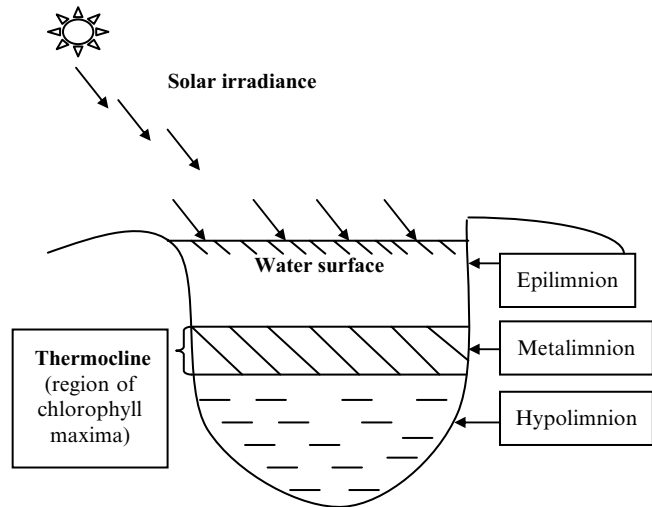
to more than 100 m in the Mediterranean Sea and the Pacific gyre. Many plankton biologists have considered this depth as the lower limit beyond which phytoplankton cells become incapable of photosynthetic activity. Exceptionally, there are reports that picoplanktonic form like *Prochlorococcus* can photosynthesize at 0.01 % of surface irradiance availability (Goericke et al. 2000). With an increase in depth, light availability decreases and the spectral range narrows to the blue region since the blue wavelength is least attenuated in a water column. So it can be said that phytoplankton cells have the ability to acclimatize to depth and light availability by increasing their pigment content and by shifting their pigment composition (e.g. *Prochlorococcus* has the ability to increase their Chl b:Chl a ratio since chlorophyll b absorbs optimally blue wavelength). Under high irradiance (top 20 m in oligotrophic waters), photosynthetic activity of phytoplanktons becomes photoinhibited due to damage of the photosystem core proteins by UV exposure. Cells counteract these detrimental effects by increasing the amount of photoprotective pigments such as zeaxanthin or diatoxanthin. Thus, the diversity in a water column is dependent on the vertical distribution of algal population. On the basis of light variation, vertical distribution can be separated into two different heads: high light, epilimnion, and low light,

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

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

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

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

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

2.1.2 Turbulence

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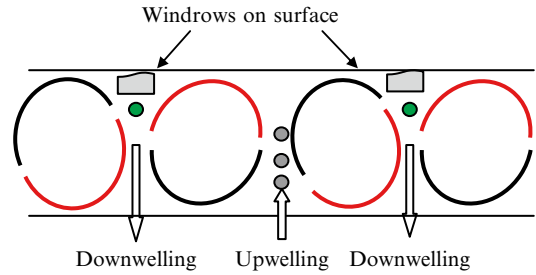

Fig. 2.2 Cross-sectional views of adjacent Langmuir cells which rotate in opposite directions, creating regions of downwelling (where the windrows occur) and upwelling. Accumulation of foam and positively buoyant algae (*green circles*) occurs in the downwelling region, whereas negatively buoyant algae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

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

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

When wind blows in a particular direction, it generates the waves on the water body which move from one side to the other (north to south). But after crushing of the wave on the opposite shore, the force will return again to the north
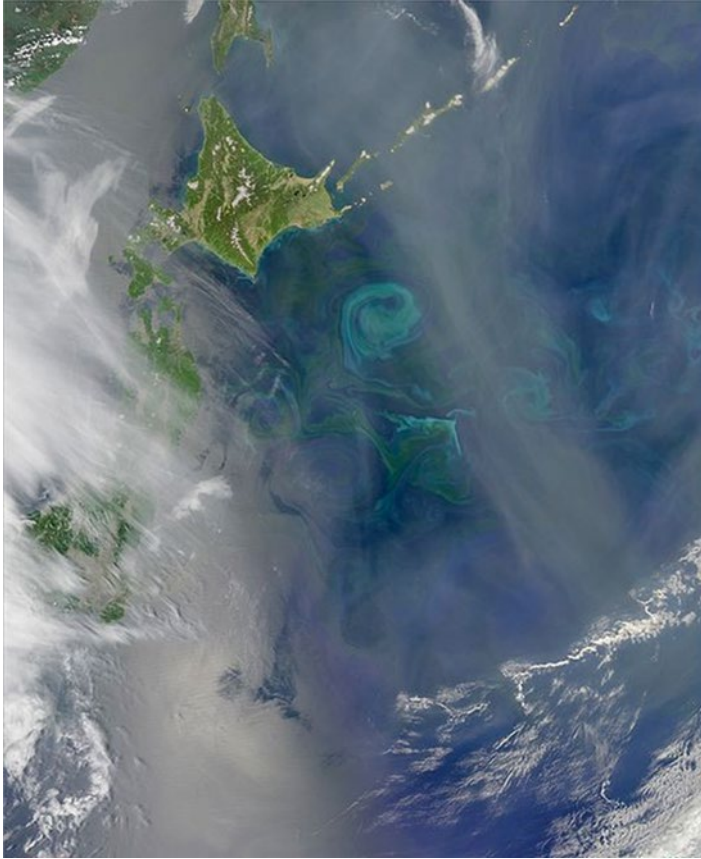
Fig. 2.3 The convergence of the Oyashio and Kuroshio currents. When two currents with different temperatures and densities (cold, Arctic water is saltier and denser than subtropical waters) collide, they create eddies. Phytoplankton growing in the surface waters becomes concentrated along the boundaries of these eddies. The swirls of colour visible in the waters southeast of Hokkaido (*upper left*), show different kinds of phytoplankton that are using chlorophyll and other pigments to capture sunlight for photosynthesis (Source: www.wikipedia.com)

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

In oceanic environment, sometimes by tremendous wind speed along with gravitational and other forces, a special type of water current develops. Due to this current, a portion of the entire ecosystem including phytoplanktons, zooplanktons, fishes and other aquatic organisms is pinched off from the whole system with varying diameters (100–200 km) and forms discrete ecosystems. These wind-driven water currents are called 'eddies' or 'loops'. Besides this, the coastal water is enriched by nutrients by upwelling water together with wave action towards the coast or away from the coast (Fig. 2.3). This is brought about by the combined action of wind and the Coriolis force of the earth's rotation. For these reasons, nutrient statuses of coastal waters vary from place to place, thereby controlling the phytoplankton diversity.

2.2   Major Nutrients

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

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

2.2.1   Redfield Ratio

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

With regard to Redfield ratio, biologists and geochemists interpret it differently. Geochemists use a C:N:P stoichiometry 105:15:1 based on the covariation of nitrate, phosphate and non-calcite contribution to total inorganic C in deep seawater, whereas biologists use a ratio of 106:16:1 based on Fleming's analysis of the average elemental composition of marine organisms (Goldman et al. 1979). The Redfield C:N has its main application in oceanography for calculation of export production and for nutrient-based productivity calculations as well as in models of ocean productivity. The Redfield N:P ratio of 16:1 is often regarded as a standard value to distinguish between N-limited and P-limited habitats among the different water bodies especially with reference to oceans (Behrenfeld and Falkowski 1997; Tyrell 1999). Accordingly, it has often been suggested that if N:P < 16, the system is N-limited, whereas it is P-limited when N:P > 16.

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

2.2.2   Carbon

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

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

$$H_2CO_3 \rightleftarrows H_2O + CO_2;$$
$$H_2O + 2CO_2 \rightleftarrows 2HCO_3^{2-}$$
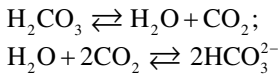
But in marine water, where pH ranges from 7.5 to 8.4, bicarbonate ions become predominant. But above pH 10, carbon exists in the form of insoluble carbonate. Thus, pH level regulates the carbonate–bicarbonate–CO_2/H_2CO_3 equilibrium in freshwater or marine habitats. Therefore, total carbon pool in aquatic ecosystems can be represented as follows:

$$TCO_2 = [CO_2] + [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}].$$

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

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

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

2.2.2.1 CCM in Phytoplanktons

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

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

$$HCO_3^- + H^+ \rightleftarrows CO_2 + H_2O$$
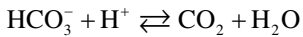
This CO_2 formed by CA rapidly diffuses away from the thylakoid lumen to the chloroplast stroma that inhibits oxygenase activity of RuBisCO and promotes carboxylase activity of RuBisCO initiating the carbon reduction cycle.

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

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

2.2.3 Nitrogen

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

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

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

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

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

2.2.4 Phosphorus

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

DIP is mostly constituted by orthophosphate (PO_4^{3-}) with much lower concentration of monophosphates (HPO_4^{2-}) and dihydrogen phosphate (H_3PO_4). Phytoplanktons primarily utilize DIP as a phosphorus source, but under limiting conditions extracellular alkaline phosphatase (AP) promotes utilization of phosphate bound to organic substances. Thus, level of AP activity is an indication of phosphate limitation in aquatic habitats (Rengefors et al. 2003). Under P-limited conditions, if there is a sudden pulse of soluble reactive phosphorus (SRP), planktonic algal cells have the unique ability to make 'luxury consumption' and develop polyphosphate bodies, thereby creating an internal pool of phosphorus to deal with phosphate shortage.

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

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

2.2.5 Silicon

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

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

Parameters like nitrate, nitrite, ammonia, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP) and dissolved silicate (DSi) contents can be measured spectrophotometrically within 30 min of sample collection following the protocols of APHA (1998). The values thus obtained are fitted to a standard curve prepared for determination of nutrient concentrations of water samples.

The procedures are mentioned below:

Nitrate

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

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

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

Nitrite

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

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

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

Ammonia

Reagents required: Nessler's reagent.

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

Dissolved Inorganic Phosphate (DIP)

Reagents required: Ammonium molybdate solution, stannous chloride solution.

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

Dissolved Silicate (DSi)

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

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

2.2.6   Nutrient Uptake Model

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

2.2.6.1 Michaelis–Menten Model (1913)

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

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

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

2.2.6.2 Droop Model

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

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

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

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

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Phytoplanktons and Primary Productivity

Phytoplanktons have a unique ability to sequester dissolved as well as free carbon dioxide from aquatic ecosystems and convert them as storage product. This phenomenon is regarded as the *primary productivity* of that ecosystem. As proposed by Field et al. (1998), about 50 % of global productivity through carbon sequestration is carried out in aquatic ecosystems due to the comparatively higher solubility of CO_2 than O_2 in natural water. Falkowski opined that about 98 % of productivity in oceans is accounted for phytoplankton populations. Thus, studies on productivity by phytoplankton populations in natural lotic habitat of estuaries and coasts have gained considerable attention by the plankton biologists.

The total primary productivity of a population under optimal conditions of light and temperature is regarded as the gross primary productivity (GPP). Although aquatic autotrophs are the only source of primary productivity, yet this production is consumed by the entire microbial floral and faunal populations of aquatic ecosystems. Thus, through respiration, often regarded as community respiration rate (CRR), fixed carbon is utilized as a source of energy which thereby causes a considerable decrease in the total productivity of the entire ecosystem known as net primary productivity (NPP). Thus, it can be represented as

$$NPP = GPP - CRR, or GPP = NPP + CRR$$

The relations between diversity and productivity in planktonic populations are not always cause and effect relationship. Based upon the kind of diversity and productivity, mainly three different mechanisms have been proposed:

1. Complementary use of resources (complementary effect)
2. Facilitation between species in highly diverse communities (facilitation hypothesis)
3. Higher probability that highly diverse communities include a highly productive species (sampling or selection effect)

It is a well-known fact that chlorophyll containing cells can fix CO_2 through light-assisted photosynthetic carbon fixation with the production of oxygen (O_2). Thus, dissolved oxygen content in aquatic ecosystems is actually a measure of the photosynthetic efficiency of phytoplankton populations. Thus, estimation of DO contents under different conditions of light availability can be a possible proxy for estimation of primary productivity of aquatic ecosystems. Based upon this concept, Winkler (1888) proposed a set of procedures and formulae for estimation of DO as well as productivity of aquatic habitats.

Initially, sample waters from specific habitat are collected in specially designed BOD bottles (125 mL/250 mL) below the surface of water at specific depths and are immediately stoppered below the water surface to avoid any external exchanges. The sample thus collected is immediately fixed by addition of manganese sulphate ($MnSO_4$) and alkaline potassium iodide (KI). This method of precipitation is done to stop any biological activity by planktonic organisms that may alter the actual DO content. This bottle is designated as initial bottle (IB). The precipitate on dissolution by

acids is titrated using sodium thiosulphate with starch as indicator. The DO content is subsequently calculated from the following formula:

$$DO(mg/L) = \frac{x \times .025 \times 8 \times 1,000}{\dfrac{V_2(V_1 - v)}{V_1}}$$

where:

V_1 = total volume of sample taken (125 mL)

V_2 = volume taken for titration (100 mL)

v = 2 mL of reagents (1 mL $MnSO_4$ + 1 mL alkaline KI)

x = volume of $Na_2S_2O_3$ consumed for titration

These processes are repeated for two other sample bottles as well and are designated as light (LB) and dark bottles (DB) respectively. LB is incubated in natural light and DB is removed from light and kept in complete darkness for equal periods of time. After incubation, DO contents of both LB and DB are determined in the same way as has been mentioned in the previous section. The different parameters of productivity are determined from the following formulae:

$$GPP = \frac{\left[(O_2LB) - (O_2DB)\right] \times 1,000}{PQ \times t}$$

$$NPP = \frac{\left[(O_2LB) - (O_2IB)\right] \times 1,000}{PQ \times t}$$

$$CRR = \frac{\left[(O_2IB) - (O_2DB)\right] \times 1,000}{t}$$

where:

GPP = gross primary productivity

NPP = net primary productivity

CRR = community respiration rate

O_2 LB = DO content of the BOD bottle after incubation in sunlight for 3 h

O_2 IB = DO content of the BOD bottle immediately after sampling

O_2 DB = DO content of the BOD bottle after incubation in dark for 3 h

PQ = photosynthetic quotient ($\equiv$ 1.2)

t = time period of incubation (light/dark) (in hours)

A combination of factors like light, CO_2 concentration, species composition and chlorophyll content play a well-orchestrated role in the overall primary productivity in aquatic ecosystems. In oligotrophic waters, due to the clear nature of the water column, light penetration is very high that enhances the epilimnion to depths of up to 60 m, as found in the Aegean Sea, Eastern Mediterranean region. In contrast to the general feeling, net primary productivity is not very high in these oligotrophic waters, although the PAR (photosynthetically active radiations) availability is quite high in the water column. This is mainly due to the nutrient status of the habitat where phosphate concentrations often reach nanomolar levels. In these limiting conditions, phytoplankton species that can acquire phosphate from organic sources by using extracellular alkaline phosphatase (AP) constitutes the phytoplankton population. Thus, the plankton population is dominated by nano- and picoplanktonic forms with significantly low chlorophyll a content and low cellular biovolumes. This accounts for the relatively low primary productivity of the Eastern Mediterranean as compared to other eutrophic habitats around the world.

An entirely different scenario is observed for eutrophic waters like the Bhagirathi–Hugli estuary. Although both light and nutrients are optimally present in these habitats, yet the high SPM (suspended particulate matter) load in the water column inhibit PAR availability at different depths of the water column. This low availability of PAR tends to reduce the photosynthetic efficiency of phytoplankton taxa that culminates in reducing the primary productivity of the aquatic ecosystem.

In eutrophic water, the nutrient-enriched habitat promotes diversification of microbial population that includes bacterial population as well. As can be expected for a food web, bacterial population acts as decomposer. For the purpose of decomposition, oxygen acts as a major source for oxidation–reduction reactions. The requirement of O_2 by microbial population for biochemical decomposition of organic matter is regarded as *biochemical oxygen demand (BOD)*. In a eutrophic habitat, the high nutrient status promotes survival of diverse life forms which subsequently add up to the organic decomposable

matter load on course of their death and decay. Thus, eutrophic habitats tend to represent under saturated DO levels with high BOD values with an increase in heterotrophic population.

For determination of biochemical oxygen demand (BOD), the water samples are to be kept under optimum conditions of light and temperature without fixation with addition of 1 mL of each of K_2HPO_4, Na_2HPO_4, $7H_2O$, $MgSO_4$, anhydrous $CaCl_2$ and $FeCl_2$ and $6H_2O$. After 5 days from the day of sampling, DO contents are subsequently measured (Winkler 1888).

BOD values were determined from the following formula:

$$BOD(mg/L) = \left(DO_{0 \text{ days}} - DO_{5 \text{ days}}\right)$$

Thus, a combination of different factors is indicative of the overall trophic status as well as the primary productivity of different study areas at different ecosystems around the world.

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Community Pattern Analysis

Phytoplankton communities in aquatic ecosystems are the most important component that varies significantly on the basis of the available environmental conditions and trophic status of the habitat. Thus, analysis of the phytoplankton community is highly indicative of the condition of the habitat. Interpretation of plankton data from an ecological perspective depends upon the sampling strategy and the area of study. Thus, strategies of phytoplankton sampling may vary depending upon the ecosystem dynamics which is different for standing water (lakes and wetlands) as compared to lotic habitats (rivers and estuaries). For proper and precise data, collection sampling cannot remain restricted to a particular station or site. Several sites/stations should be sampled on the same instance to reduce uneven horizontal distribution (patchiness). Accordingly, sample collection for phytoplankton community analysis is an important aspect for correct community pattern analysis. From time to time the procedures for phytoplankton sample collection have improved significantly. Thus, in this section, we will discuss about the more commonly used phytoplankton sampling methods applicable both in estuarine and marine habitats.

4.1 Phytoplankton Sampling

In an attempt to determine the cell count of phytoplankton populations, different methods have been implemented as follows:

1. Bottle samplers
2. Plankton pumps
3. Plankton nets

4.1.1 Bottle Samplers

Sampling of water by bottle sampler is probably the simplest but well-recommended method to correctly determine the quantitative composition of the phytoplankton. A water bottle sample generally contains all but the rarest organisms in the water mass sampled and includes the whole size spectrum from the largest entities, like diatom colonies to the smallest single cells. Bottle sample method is the simplest method which is mainly used for the collection of water samples from any desired depth of shallow systems like the nearshore water, estuaries and mangroves (Fig. 4.1). The sample volume as well as the depth at which samples are to be collected can be easily controlled as per the discretion of the plankton biologists. Thus, this simple method can be utilized by both inexperienced students and experienced researchers for collection of phytoplankton samples in a water column.

4.1.1.1 Meyer's Water Sampler (Fig. 4.2)
This type of water sampler consists of ordinary glass bottles of 2 L capacities which are enclosed with a metal band. This apparatus is weighted below with a lead weight and there are two strong nylon graduated ropes: one tied to the neck of the bottle and the other to the cork that caps the open

Fig. 4.1 Simple graduated bottles for collection of phyto-plankton water samples. The nozzle in front allows the observer to squeeze out the measured portions of sample for study

Fig. 4.2 A simple Meyer's water sampler

end of the bottle. During sample collection, the corked up apparatus (closed bottle) is brought down to the desired depth where the stopper is jerked

open by a strong pull of the cork rope. Water flows into the bottles and then the cork rope is released to keep the cork closed. Afterwards, using the neck rope, the bottle containing the water sample as well as the biotic variables is taken out of the water columns. This apparatus can only be used up to the depths of 20 m.

4.1.1.2 Friedinger's Water Sampler

This water sampling apparatus is made of Plexiglas or Perspex with two hinged covers. While operation, the sampler is sent down in an open state to the desired depth and can be closed by a drop weight messenger, which falls down inside on sliding rail and closes the covers and makes the bottle water tight. By this way, the water together with the planktonic organisms of the specified column is trapped inside.

4.1.1.3 Niskin Water Sampler (Fig. 4.3)

This is a more sophisticated apparatus that is mainly used for collection of large samples in river systems as well as in oceans. It is employed for taking water samples for phytoplankton enumeration from subsurface levels to various depths. In this apparatus, several non-metallic, free-flushing bottles are used for general water sample collection. These samplers can be individually or serially attached on a hydro cable and activated by a messenger, or placed in any kind of multisampling system (like G.O., Sea Bird, Falmouth Scientific, and small multisampling system), and activated by remote or pre-programmed command.

4.1.2   Plankton Pumps

Plankton pumps are integrating samplers that pump a continuous stream of water to the surface and the phytoplankton can then be rapidly concentrated by continuous filtration. Because the pumps can collect continuously as the tube is lowered through the water column, the samples are integrated from the surface to the desired depth. This method has its disadvantages like breaking up of colonies or large *Chaetoceros* setae or long pennate cells like *Thalassiothrix* spp.
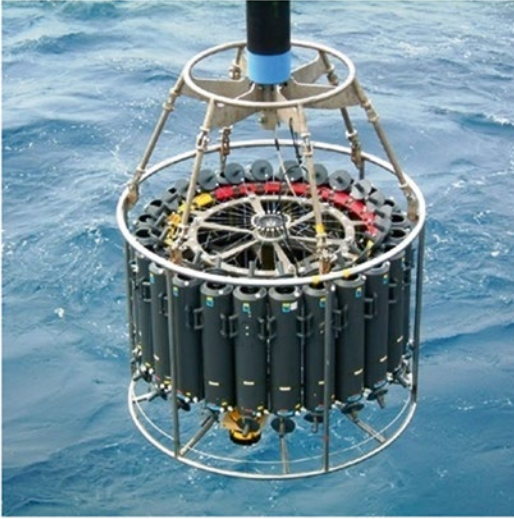
Fig. 4.3 A Go-Flo rosette Niskin water sampler

4.1.3   Plankton Nets

Phytoplankton nets are most popularly used device for sampling. Plankton nets may vary in design that range from basic tow nets (conical or with truncated neck) to more complicated device fitted apparatus for more specific sample collection (Fig. 4.4). Nets permit quantitative studies, since the mesh size will select the type of phytoplankton collected. Sampling by nets is highly selective, depending on the mesh size of the gauze, net towing speed and the species present in the water. *Chaetoceros* setae, for instance, may form a fine network inside the gauze and very small single cells, which in other cases pass through the meshes, are retained. On the other hand, nets with very fine meshes (5 or 10 μm) often filter too little water to provide an adequate diatom sample. The most useful mesh size for collecting diatoms is 25 μm. Net hauls have the advantage of a simultaneous collection and concentration of the plankton providing sufficient for species identification. A typical plankton net usable in the surface layers is conical in shape and has the following constituents: a net ring made up of stainless steel, wrapped and sealed with polythene tubing, present anteriorly. To this, a non-filtering portion made of a coarse khaki cloth is attached using button and hole system. The filtering portion

Fig. 4.4 Image of a typical phytoplankton net being hauled for phytoplankton collection (Image courtesy: www.nearhus.gr)

is made of monofilament nylon material as described earlier and is followed by again a non-filtering portion of khaki cloth. To the latter, a metal net bucket provided with a stopcock is tied with a strong twine. The determination of the volume of water filtered through any plankton net is essential for the estimation of the standing crop. The volume of water traversed by the net is determined as an approximate value by the formula $v = \pi \cdot r^2 d$, where V is the volume of the water filtered by the net, r is the radius at the mouth of the net and d is the distance through which the net is towed. The water collected through the different water samplers is either centrifuged or passed through fine mesh nylon or filter papers to separate the plankton present in it. The smaller the subsample, the fewer number of rare species will be obtained. On the other hand, there is no point in concentrating large quantities of a sample rich in one or a few species. Concentration by settling, concentration by centrifugation and concentration

Table 4.1 Showing net mesh sizes and types of planktons to be harvested

Size of aperture	Approximate open area (%)	Types of planktons
1,024	58	Largest zooplankton and ichthyoplankton
752	54	Larger zooplankton and ichthyoplankton
569	50	Large zooplankton and ichthyoplankton
366	46	Large microcrustacea
239	44	Zooplankton – microcrustacea
158	45	Zooplankton – microcrustacea and most rotifers
76	45	Net phytoplankton –
64	33	macroplankton and
53	–	microplankton
2	–	Nanophytoplankton

by filtration are the most used methods. Plankton concentration is generally used to overcome the damages caused, to certain groups of phytoplankton especially the setoid diatoms and dinoflagellates, by vacuum filtration and centrifugation. The simple plankton concentrator, which is quite gentle in its action, consists of a stiff tube (1.2 cm dia.: 10 cm height) of Perspex or PVC to the bottom of which a filter is attached. A filter paper (Whatman No. 42) or membrane filters supported by monofilament nylon netting which serves as the filter are glued at the bottom of the tube with the aid of ethylene dichloride. While using the tubes are dipped slowly into a beaker containing the phytoplankton sample. Through the filter water flows slowly upwards into the tube and is removed with a large pipette. By forcing the tube downwards, the rate of flow through the filter can be increased. On the basis of mesh size, different types of planktons can be harvested using different plankton nets (Table 4.1).

The phytoplankton net can be hauled horizontally, vertically or obliquely on the basis of sampling requirements. A vertical haul is more appropriate for collection of composite sample of the entire water column, whereas a horizontal haul remains restricted to surface water composite samples only. In case of horizontal haul, the volume of water sampled can be estimated by determining the area of the net aperture and the distance it travelled through a flow meter (Eaton et al. 2003). The basic drawback for this hauling method is that it will accommodate both phytoplanktons and zooplanktons. Thus, phytoplankton biologists often use a zooplankton sampler within a phytoplankton sampler to reduce the number of zooplanktons in the sample, although there remains a risk that larger-sized phytoplankton may get arrested in the zooplankton net. Thus, on completion of the hauling process, samples are collected by unscrewing the end fitting and subsequent collection in sample tubes/containers.

4.1.3.1 Preservation and Fixation of Plankton Samples

Generally 2–5 % formalin is used for preservation and fixation of phytoplankton samples. Commercially available formaldehyde is suitably diluted to desired conditions for fixation. Marine samples are mostly preserved in 5 % neutralized formalin in seawater. Excess seawater is generally removed by filtration for 1–2 days to reduce precipitation of salts from seawater. Eighty percent of pure methyl alcohol was also used as an effective preservative although it often produces shrinkage and discolouration. Formalin–acetic acid–alcohol (FAA) is a good preserving and killing agent for cytological studies of planktonic populations except dinoflagellates. In case of dinoflagellates, it causes loosening of thecal plates that often causes improper fixation of samples. In recent times, Lugol's iodine solution has popularized as a preserving agent for phytoplankton especially of small sizes. The iodine component fixes, preserves and colours the plankton, whereas the other component, acetic acid, preserves the flagella and cilia. This acts as an excellent preservative if the samples are stored in the dark.

4.2   Biomass Estimation

Quantification of phytoplankton biomass is an important aspect as it works as a possible proxy for primary productivity in aquatic ecosystems and gives a measure of the amount of organic

material available for zooplankton consumption. Thus, phytoplankton population can be quantified under two different heads:

Total Biomass

In this measurement, the entire biomass is measured. Chlorophyll *a* estimation has remained as the most preferred method for this estimation as chlorophyll *a* acts as the main light-harvesting pigment in all groups of phytoplankton taxa recorded as in case of higher plants as well.

Species and Group Biomass

Here, indirect estimates of populations are made on the basis of cellular counts and biovolumes. In these cases, determination of group-specific photopigment contents can be an ideal proxy. The importance of such estimates lies not only in assessing the productivity but can also be a possible reference for the determination of the diversity of the study area. For phytoplankton community pattern analysis, different parameters have to be considered to determine the contribution of individual phytoplankton taxa to the entire phytoplankton population. Some of the commonly used parameters are as follows:

4.2.1   Cell Counts

Cell count is an important parameter that is to be investigated to determine the diversity of phytoplankton populations. Earlier plankton biologists implemented this method as it provided data on the abundance as well as density of individual taxa in a population. Furthermore, cell count data of single taxa from a mixed population provide us with the information about the proportion of the population contributed by those taxa. This allows the scientific community to apply different biotic indices to make an assessment of the diversity of the population in question. Thus, such calculations are indicative about not only the species composition but also of the ecosystem functioning. The drawback for this method is that it does not take into consideration the shape and volume of the cell which may significantly affect

the photosynthetic efficiency of the taxa. As an example, spherical cells of pico- and microplankton may have similar cell counts, but due to their dimensions, microplankton will be more productive as compared to picoplankton in a natural ecosystem. In case of cyanobacteria, the *S/V* (surface area–volume) value is an important parameter due to the buoyant nature and hydrographic properties. Thus, although the cell counts may be the same for two different cyanobacterial taxa, the sinking rate in a water column can be significantly different as evident from Stoke's law. Moreover, the pigment composition can also be a determining factor in the overall productivity of the phytoplankton population as it is the primary regulator of photosynthetic efficiency of algal cells with regard to carbon sequestration from aquatic habitats. So a mere calculation of cell counts with inadequate taxonomic identification of phytoplankton taxa may not be a correct representation of the phytoplankton community composition at the species level. Thus, cell counts provide us with data on abundance and density of specific taxa in a population of phytoplankton.

4.2.2   Utermohl Sedimentation Method for Cell Counts

Collected phytoplankton samples are preserved in Lugol's solution so as to make them heavier for easier sedimentation. In this method, a glass tubing of specific length is selected and one end is sealed with a large cover slip using waterproof adhesive (Fig. 4.5). A specific volume of the preserved samples is poured in these chambers and allowed to settle overnight. Once the phytoplankton settles on the floor of the tube, i.e. the cover slip, it is immediately observed under an inverted microscope for enumeration of phytoplankton taxa. This is done by employing an ocular micrometer by standardization with stage micrometer. This measurement technique would allow the estimation of phytoplankton cell counts for a specific area of the sedimentation chamber cover slip. Precautions are to be taken so as to count every representative field of view.
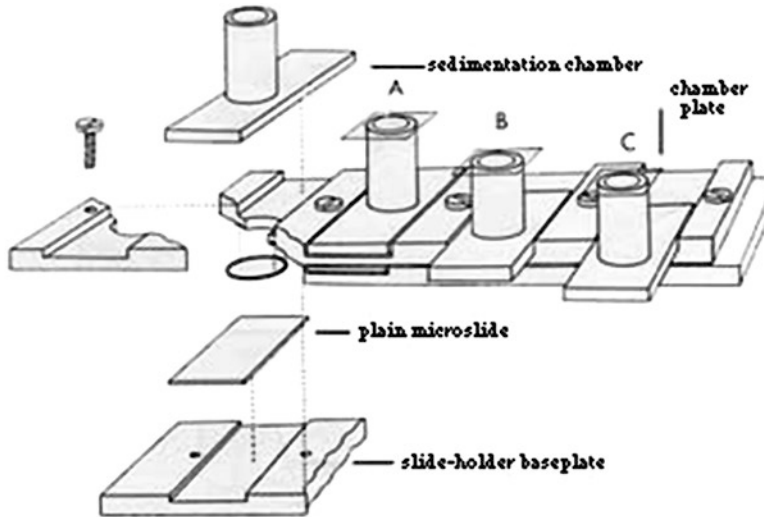
Fig. 4.5 A typical Utermohl sedimentation tube (Image courtesy: www.aquaticresearch.com)

4.2.3 Biovolume

Cellular biovolumes of individual algal taxa as well as phylogenetic group have long been used as an important parameter in determining the species composition of phytoplankton populations at an individual species level. Microalgal biovolume is commonly calculated to assess the relative abundance (as biomass or carbon) of co-occurring algae varying in shape and/or size. This is mainly due to the highly diverse shapes and sizes of algal cells that range from the picoplanktonic prochlorophytes to that of diatoms which measure more than 1 mm in diameter (Reynolds 1984). In natural mixed phytoplankton populations, high numbers of small-sized species might actually contribute only a minor fraction of the overall biomass. Other larger-sized species that are much less abundant in numbers might dominate the overall biomass. Thus, determinations of cell counts are often inadequate as a measure of relative algal biomass (Smayda 1978; Wetzel and Likens 1991). Biovolumes are also calculated for conversion of cell counts to carbon equivalents so as to estimate the fluxes of organic carbon in aquatic communities. Phytoplankton carbon calculation from biovolume eliminates the error due to detrital particulate matter contained in particulate organic carbon (Montagnes et al. 1994).

Although plankton biologists around the world understood the need to estimate biovolumes, yet no standardized formula or calculations were proposed. Afterwards, the formulae were mostly developed at the discretion of the scientists that were working on different populations (Rott 1981). The problem was especially more pronounced for complex-shaped genera like dinoflagellates, diatoms and desmids. Scientists like Kovala and Larrance (1966) used an accurate but complex approach, whereas Edler (1979) applied fairly simple methods that might not have accurately represented cell shape (Hillebrand et al. 1999).

In recent times, more advanced methods like electronic particle counting (Boyd and Johnson 1995), flow cytometry (Steen 1990), microscopic image analysis (Krambeck et al. 1981; Estep et al. 1986) and combined systems (Sieracki et al. 1998) have been implemented to measure phytoplankton cellular biovolumes. However, different drawbacks and expensive equipments do not allow us to recommend a single most accurate technique for the measurement of cellular biovolumes. The flow cytometry method is limited to the level of easily discernible groups (e.g. algae of different classes or pigment composition). This method often gives erroneous results for benthic samples that are often cohesive and contaminated with sediment

Table 4.2 Geometric shapes and equations for the calculation of biovolume (Hillebrand et al. 1999)

Shape	Equation
1. Sphere	$V = 4/3\ \pi \cdot r^3 = \pi/6 \cdot d^3$
2. Prolate spheroid	$V = \pi/6 \cdot d^2 \cdot h$
3. Ellipsoid	$V = \pi/6\ a \cdot b \cdot h$
4. Cylinder	$V = \pi \cdot r^2 \cdot h = \pi/4 \cdot d^2 \cdot h$
5. Cylinder + 2 half spheres	$V = \pi \cdot r^2 \cdot h + 4/3 \cdot \pi \cdot r^2 = \pi \cdot d^2 \cdot (h/4 + d/6)$
6. Cylinder + 2 cones	$V = \pi/4 \cdot d^2 \cdot h + 2 \cdot \pi/12 \cdot d^2 \cdot z = \pi/4 \cdot d^2 \cdot (h + z/2)$
7. Cones	$V = 1/3 \cdot \pi \cdot r^2 \cdot z = \pi/12 \cdot d^2 \cdot z$
8. Double cone	$V = 2/3 \cdot \pi \cdot r^2 \cdot z = \pi/6 \cdot d^2 \cdot z$
9. Cone + half sphere	$V = 1/3 \cdot \pi \cdot r^2 \cdot z + \frac{1}{2} \cdot 4/3\ \pi \cdot r^3 = \pi/12 \cdot d^2 \cdot (z + d)$
10. Rectangular box	$V = a \cdot b \cdot c$
11. Prism on elliptic base	$V = \pi/4\ a \cdot b \cdot c$
12. Elliptic base with transapical constrictions	Same as above, where means of c are considered
13. Prism on parallelogram base	$V = \frac{1}{2}\ a \cdot b \cdot c$
14. Half-elliptic prism	$V = \frac{1}{2} \cdot \frac{1}{4} \cdot \pi \cdot a \cdot 2b \cdot c = \pi/4\ a \cdot b \cdot c$
15. Sickle-shaped prism	$V = \frac{1}{4} \cdot \pi \cdot c \cdot (a \cdot b - a_2 \cdot b_2)$
16. Monoraphidioid	$V = d^2/4 \cdot \left\{ \dfrac{(2b - d + a) \cdot \pi^2}{12} + \dfrac{(2b - d + a)}{2} \right\}$
17. Cymbelloid	$V = 4/6\ \pi \cdot b^2 \cdot a \cdot \beta/360$
18. Prism on triangle base	$V = \frac{1}{2} \cdot l \cdot m \cdot h$
19. Pyramid	$V = 1/3 \cdot l_1 \cdot l_2 \cdot h$
20. Elliptic prism with transapical inflations	$V = \pi/4 \cdot c \cdot (a \cdot b + i^2)$

where V volume, r radius, d diameter, h height, a apical axis (length), b transapical axis (width), c pervalvar axis (height), z height of cone, l length of one side (l_1 and l_2, if sides are unequal), m height of a triangle, β angle between the two transapical sides and i diameter of inflation

particles. Computer-mediated image analysis technique is more applicable for bacterial systems (Psenner 1993) where taxonomic resolution is inadequate. Moreover, for proper measurements, these methods are time consuming and are related to direct microscopic measurements (cf. Krambeck et al. 1981). More recently, Sieracki et al. (1998) proposed a new flow-through analysing system for plankton samples, but this system sacrifices taxonomic information as well.

Hillebrand et al. (1999) worked out and proposed a more conclusive method for the determination of biovolumes on the basis of geometric shapes of algal cells. A standard set of 20 geometric shapes was developed on the basis of the morphology of different microalgal cells. This method proposed that cell biovolumes should be calculated on an individual cell basis even for coenobial, colonial and filamentous forms. In this work, a comprehensive list of individual algal taxa belonging to different phylogenetic groups was prepared and each taxa was given a specific shape. Based upon that, for each shape, specific formulae for measuring the biovolume (V) were recommended. In recent times, this set of formulae has been accepted as the more authenticated method for measurements of cell biovolumes around the world (Table 4.2).

4.2.4 Chlorophyll and Photopigments

Phytoplankton is perhaps the most important component of pelagic ecosystem since it traps almost all the energy used by the ecosystem. Consequently, phytoplankton biomass estimates with respect to algal carbon content are highly important. Unfortunately such estimations are often extremely difficult due to the size variations of phytoplankton taxa. Accordingly,

such estimates are made from other parameters, which require many calculations and/or the use of imprecise conversion factors (Geider et al. 1997). Measurements of photopigment concentrations are widely used to estimate algal biomass (Smayda 1978). Chlorophyll *a* is common to all photosynthetic organisms. Furthermore, it is the most abundant photosynthetic pigment and it is relatively easy and rapid to quantify. Consequently, its concentration is used extensively for estimating phytoplankton biomass. A variety of techniques are at present available, offering varying degrees of accuracy. However, the ratio of chlorophyll *a* to cell carbon depends on external and internal factors, such as phytoplankton taxonomic composition, cellular physiological conditions, temperature, nutrient concentrations and light intensity (Reynolds 1984).

The relationship between chlorophyll *a* and phytoplankton biovolume has been widely studied (Kalchev et al. 1996), where both linear and allometric relationships have been found between these parameters (Tolstoy 1977; Desortová 1981). The spatiotemporal variations among chlorophyll and biovolume mainly depend upon the taxonomic composition of phytoplankton populations, like the life form of the predominant group and their average cell size. Influence of environmental factors like changes in available light intensities, nutrient load or species predominance is some of the other parameters that can influence the 'chlorophyll maxima' in natural aquatic ecosystems.

Earlier, the fluorometric method was mainly used for the quantitative analysis of chlorophyll *a* and phaeopigments. However, the presence of chlorophyll *b* and/or chlorophyll *c* produced erroneous results. Chlorophyll *b* generally not abundant in surface water can be as high as 0.5 times of chlorophyll *a* concentration in the region of deep chlorophyll maxima, causing underestimations of the chlorophyll *a* concentration and overestimations of the phaeopigment concentrations. Divinyl chlorophyll also accounted for such incorrect estimations.

Thus, natural water samples are collected, filtered through specific filters and extracted using different solvents, and absorbance is read at wavelengths from 450 to 700 nm. Different formulae have been developed to estimate different fractions of chlorophyll from natural phytoplankton samples. Some of the more well-known methods are given below.

4.2.4.1 Formulae of Chlorophyll Estimation (90 % Acetone Extract)

Chlorophyll *a*

$$\text{Chl } a \left[\text{mg m}^{-3} \right]$$
$$= \left(11.85 \, D_{663-665} - 1.54 \, D_{647} - 0.08 \, D_{630} \right) v \, l^{-1} \, V^{-1}$$

D = absorbance at wavelength indicated by subscript, after correction by the cell-to-cell blank and subtraction of the cell-to-cell blank corrected absorbance at 750 nm
v = volume of acetone
l = cell (cuvette) length
V = volume of filtered water

Chlorophyll *b*

$$\text{Chl } b \left[\text{mg m}^{-3} \right]$$
$$= \left(-5.43 \, D_{663-665} + 21.03 \, D_{647} - 2.66 \, D_{630} \right) v \, l^{-1} V^{-1}$$

D = absorbance at wavelength indicated by subscript, after correction by the cell-to-cell blank and subtraction of the cell-to-cell blank corrected absorbance at 750 nm
v = volume of acetone
l = cell (cuvette) length
V = volume of filtered water

Chlorophyll *c*

$$\text{Chl } c \left[\text{mg m}^{-3} \right]$$
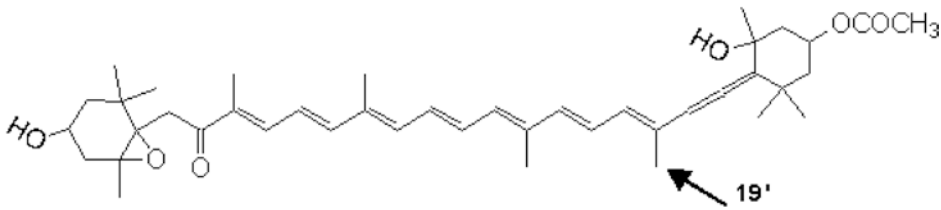$$= \left(-1.67 \, D_{663-665} - 7.6 \, D_{647} + 24.52 \, D_{630} \right) v \, l^{-1} V^{-1}$$

D = absorbance at wavelength indicated by subscript, after correction by the cell-to-cell blank and subtraction of the cell-to-cell blank corrected absorbance at 750 nm
v = volume of acetone
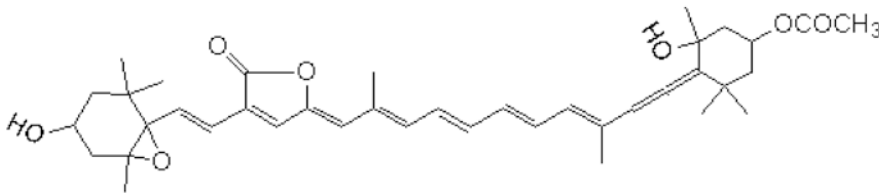l = cell (cuvette) length
V = volume of filtered water
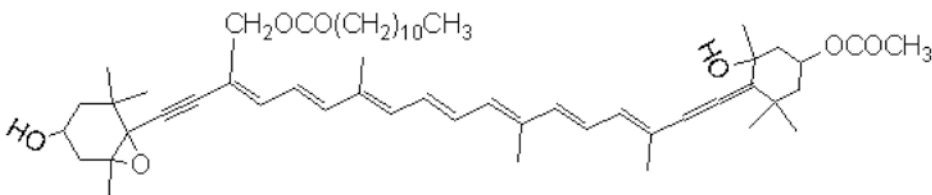
Zeaxanthin (cyanobacteria and a 'bit' in Chlorophytes)

Fucoxanthin (Chrysophytes)

19'-butanoyloxy- and 19'-hexanoyloxy-fucoxanthins (prymnesiophytes)

Peridinin (Pyrrhophyta, Dinoflagellates)

Gyroxanthin diester (Florida Red Tide, Karenia brevis: Pyrrhophyta)

Fig. 4.6 Selected chemotaxonomic biomarker carotenoids

As mentioned before, the interference of phaeopigments and other fractions of chlorophyll often produced incorrect estimates. Thus, in recent times a different approach is implemented where after estimation of chlorophyll *a*, the entire fraction is acidified to convert all chlorophyll to phaeopigments. Subsequent fluorometric readings are taken for phaeopigments and both values are taken for calculations by applying a correction factor for phaeopigment interference (Holm-Hansen and Riemann 1978; Herbland et al. 1985).

In recent times, pigment analyses have not only remained restricted to chlorophyll but other pigments have also been analysed as well as a proxy for biomass estimates with respect to species composition. This method is regarded as 'chemotaxonomy' where class-specific photosynthetic accessory pigments (PAPs) are estimated through HPLC, e.g. chlorophyll *b* (chlorophytes), fucoxanthin plus chlorophyll *c* (chrysophytes, diatoms and relatives), gyroxanthin-diester (Florida red tide, *Karenia brevis*), peridinin (dinoflagellates) and the divinyl chlorophylls *a/b* (prochlorophytes). Additionally, there are many taxon-specific (or abundant, 'zea') photoprotectorant pigments (PPPs), such as zeaxanthin ('zea', cyanobacteria), myxoxanthophyll (cyanobacteria), keto-carotenoids (echinenone, canthaxanthin, cyanobacteria), lutein (chlorophytes) and alloxanthin (cryptophytes), that are estimated as well (Fig. 4.6).

Pigment-based chemotaxonomy has gained increasing favour for rapid spatiotemporal investigations of microalgal communities, such as

phytoplankton distributions in lakes and oceans. It is possible to assign a numerical relationship between the marker pigment and chlorophyll *a*, the biomass marker. The percent composition of the community is calculated by the relative abundance of the taxon-specific chlorophyll *a*.

Pigment-based chemotaxonomy can be extremely advantageous and cost-effective in large-scale ecosystem research and monitoring programs. Recently, uses of CHEMTAX software are in practice, where HPLC data for class-specific photopigments helps in determining the quantitative species composition of the phytoplankton population. Although it is a well-established process, it cannot possibly be a replacement for taxonomic identification and subsequent biovolume or cell count estimates. The drawback of the chemotaxonomy method is that it deals only a class or division level and cannot be applied at a taxon-specific level. Thus, diversity assessment by application of biotic indices cannot be done in this type of community composition study.

4.3   Species Diversity Index

Species diversity index is a statistical measure that indicates the abundance of species in a particular population. This clearly suggests that the population with more number of taxa will show a higher diversity index as compared to another population where the number of individuals for each species may be same but the total number of taxa or species is less as compared to the previous population of similar organisms. The commonly used diversity indices are simple transformations of the effective number of species or taxa, but each diversity index can also be interpreted in its own right as a measure corresponding to some real phenomenon.

The Shannon–Weiner's Index is one of the more commonly used diversity indices in ecological literature, where it is also known as the Shannon diversity index, the Shannon–Wiener index, the Shannon–Weaver index, the Shannon entropy, etc. The measure was originally proposed by Claude

Shannon to quantify the entropy (uncertainty or information content) in strings of text. The idea is that the more different letters there are, and the more equal their proportional abundances in the string of interest, the more difficult it is to correctly predict which letter will be the next one in the string. The Shannon entropy quantifies the uncertainty (entropy or degree of surprise) associated with this prediction. It is calculated as follows:

$$H' = -\sum_{i=1}^{R} p_i \log p_i$$

Here, p_i can be represented as n_i/N – where n_i is the number of individuals of *i*th species in a population and N is the total number of individuals of all species recorded in the population. In ecology, p_i is often the proportion of individuals belonging to the *i*th species in the data set of interest. Then the Shannon entropy quantifies the uncertainty in predicting the species identity of an individual that is taken at random from the data set.

The base of the logarithm used when calculating the Shannon entropy can be chosen freely. Shannon himself discussed logarithm bases 2, 10 and *e* each of which corresponds to a different measurement units, which have been called binary digits (bits), decimal digits (decits) and natural digits (nats) for the bases 2, 10 and *e*, respectively.

Simpson index is used to measure the degree of concentration when individuals are classified into types. The measure equals the probability that two entities taken at random from the data set of interest represent the same type:

$$\lambda = \sum_{i=1}^{R} p_i^2$$

This also equals the weighted arithmetic mean of the proportional abundances p_i of the types of interest, with the proportional abundances themselves being used as the weights. Proportional abundances are by definition constrained to values between zero and unity, but their weighted arithmetic mean, and hence λ, can never be smaller than 1/*S*, which is reached when all types are equally abundant.

Since mean proportional abundance of the types increases with decreasing number of types and increasing abundance of the most abundant type, λ obtains small values in data sets of high diversity and large values in data sets of low diversity. The other popular indices have been the inverse Simpson index (1/λ) and the Gini–Simpson index (1–λ). Both of these have also been called the Simpson index in the ecological literature, so care is needed to avoid accidentally comparing the different indices as if they were the same.

4.3.1 Species Evenness

Species evenness refers to how close in numbers each species in an environment is. Mathematically it is defined as a diversity index, a measure of biodiversity which quantifies how equal the community is numerically. The evenness of a community can be represented by Pielou's evenness index:

$$J' = \frac{H'}{H'_{max}}$$

where H' is the number derived from the Shannon diversity index and H'_{max} is the maximum value of H', equal to

$$H_{max} = -\sum_{i=1}^{S} \frac{1}{S} \ln \frac{1}{S} = \ln S$$

J' is constrained between 0 and 1. The lesser the variation in communities between the species, the higher J' is. Thus, species evenness provides us with an opportunity to determine the contribution of individual taxon to the total population. High species evenness suggests that every taxon in the population has almost a similar number of individual representatives in the population. This also emphasizes that the habitat allows diversification of different populations with different requirements and life strategies. On the contrary, low species evenness is indicative of the fact that the contribution of individual taxon to the total population is variable, thereby ascertaining that the habitat is more suitable for proliferation of selected taxa that have favourable environmental conditions. Thus, under blooming conditions, species evenness shows minimum value as in that period a single species dominates with almost negligible representatives of other taxon.

4.3.2 Species Richness

Species richness is a measure of the number of different species represented in a set or collection of individuals in a natural population. Species richness is simply a count of species, and it does not take into account the abundance of the species or their relative abundance and distributions. The purpose of such estimation can be different on the basis of the quantifying individuals that are taken into consideration. Thus, for correct estimation of species richness, identification of individuals is important. Habitat heterogeneity is another determining factor in calculation of species richness. If samples are collected from different habitats, the build-up in the number of new species in each habitat will be higher as compared to samples collected from the same habitats. Thus, species diversity and richness are a closely knit phenomenon where although they are mutually interdependent, species diversity index is a more authenticated approach as it takes into consideration the number of individuals of each species as well.

Thus, here, the species diversity index (H') is – 2.091923, species evenness (*J'*) is 0.908, and species richness is 10 calculated on the basis of Table 4.3.

In recent times, plankton studies have not remained restricted to morphometric analysis only, but molecular phylogenetic analyses have gained considerable impetus as well. Most of the present works have focussed on picoeukaryotes as they are not very easily detectable under the light microscope. Furthermore, it has been opined by different groups of scientists that due to their low surface–volume ratio, they have the ability to remain

Table 4.3 Calculation for biotic indices

Species	No. of individuals (n_i)	p_i (n_i/N)	$p_i \ln p_i$
A	123	0.134	−0.26933
B	46	0.049	−0.14778
C	72	0.078	−0.198982
D	22	0.024	−0.089513
E	89	0.097	−0.226305
F	182	0.198	−0.32066
G	111	0.121	−0.255547
H	56	0.061	−0.170609
I	19	0.021	−0.081127
J	201	0.218	−0.33207
Total	921	1.001	−2.091923

Species evenness: $H'/\mathrm{Ln}S = -2.091923/\mathrm{Ln}(10) = -2.091923/2.302585 = 0.908$

buoyant, thereby showing greater photosynthetic efficiency. Furthermore, results from different parts of the world have shown that in oligotrophic waters, the majority of planktonic population is accounted by picoeukaryotes. Thus, community composition study on the basis of molecular studies is a well-practiced method. Many of the works available have focussed on 18S rRNA gene for community analysis due to their highly conserved nature through evolutionary timescale with works from the equatorial Pacific Ocean (Staay et al. 2001), the Antarctic Polar Front (Lo'pez-Garcı'a et al. 2001), the Mediterranean and Scotia Sea as well as the North Atlantic Ocean (Dı'ez et al. 2001). The use of target gene sequences for molecular analysis has not remained restricted to 18S rRNA genes only, but other sequences like ITS and rbcL have been exploited as well.

4.4   Multivariate Analysis

Several studies over the years have conclusively established that planktonic populations in natural habitat are not dependent on a single parameter, but a combination of biotic and abiotic variables regulate the spatiotemporal dynamics of phytoplanktons. Thus, a multivariate statistical approach should be taken for this, where interrelationships among

biotic and abiotic variables can be well represented in a single graphical representation. James and McCulloch (1990) also opined that 'It is no longer possible to gain a full understanding of Ecology and Systematics without some knowledge of multivariate analysis'. Thus, here we make an attempt to discuss some of the more commonly used multivariate procedures that are presently being employed for phytoplankton study, which includes data preparation as follows:

4.4.1   Preparation of Data Sets

The initial multivariate data set consists of a table of objects in rows and measured variables for those objects in columns. It is essential to correctly identify as to what are the objects and variables respectively. This distinction among objects and variables is essential to correctly implement multivariate analysis because procedures that analyse relationships among objects or among variables are different. It is assumed that objects are independent, whereas variables are interconnected or interrelated among each other during representation in a multivariate analysis.

4.4.2   Data Transformations

In multivariate data tables, measured variables can be binary, quantitative, qualitative, rank ordered, classes, frequencies or even a mixture of those types. If variables are measured in different ranges, then units of measurements (e.g. environmental parameters) of the variables have to be transformed in an appropriate format before performing further analyses. These transformations will help in developing 'dummy' numerical values for original values of qualitative variables that are subsequently utilized in multivariate procedures. Data transformations can be categorized into two main types:
- *Standardization* is a method mainly used to minimize the effects of magnitude difference

with respect to scales or units. This type of transformation is mainly applied for environmental parameters where range and scale of measurement are often different from each other. A common procedure is to apply the z-score transformation to the values of each variable. For each variable, it consists of:

1. Computing the difference between the original value and the mean of the variable (i.e. centring)
2. Dividing this difference by the standard deviation of the variable

- *Normalization* transformations are mainly implemented to correct the distribution shapes of certain variables, which depart from normal distribution. This would help to obtain more homogenous variances for variables that would allow better application of multivariate procedures. Different mathematical transformations can be used to normalize the x values of a variable like:

The arcsin ($\sqrt{x}$) transformation can be applied to percentages or proportions.

Log($x+c$) to variables departing strongly from a normal distribution.

$\sqrt{(x+c)}$ where c is a constant generally added to avoid mathematically undefined computations. The c constant is generally chosen so that the smallest nonzero value is obtained. The constant should also be of the same order of magnitude as the variable (Legendre and Legendre 1998).

To make community composition (either presence–absence or abundance) data containing many zeros suitable for analysis by linear methods, Hellinger transformation is the preferred method to yield good results of multivariate analysis (Legendre and Gallagher 2001). These transformations are important where samplings are done more randomly with no specific pattern of sample collection and data mining.

4.4.3 Exploratory Analysis

Multivariate exploratory methods are implemented to understand the specific patterns in data

sets, and the possible explanation for those patterns in the data set depends solely on the expertise and discretion of the researcher who is implementing these methods. Thus, care should be taken in regard to data transformation methods as well as the selection of the specific multivariate procedure that the researcher wishes to implement for desired results.

4.4.3.1 Cluster Analysis and Association Coefficients

The basic purpose of cluster analysis is to group the objects on the basis of dissimilarities in a group of variables. In other words, cluster analysis maximizes between group variations and minimizes within group variations, so as to reduce the dimensionality of the data sets only to a few groups or rows (James and McCulloch 1990; Legendre and Legendre 1998). Cluster analysis is mainly used for microbial diversity study or to determine the differences between DNA or amino acid sequences in different group of samples.

Cluster analysis of a data table is mainly carried out in two parts. Firstly, a specific association coefficient is to be found on the basis of which similarity or dissimilarity matrix is to be developed. Secondly, the given data set is analysed accordingly and the calculated matrix is represented either as a horizontal tree (hierarchical clustering) or as a distinct group of objects (*k*-means clustering). The choice of appropriate and ecologically meaningful association coefficients is particularly important because it directly affects the values that are subsequently used for the categorization of objects.

4.4.3.2 Principal Component Analysis (PCA)

PCA has been applied to numerous phenotypic and genotypic (e.g. fingerprinting patterns) data sets, and it is one of the most popular exploratory analyses. The PCA procedure basically calculates new synthetic variables (principal components), which are linear combinations of the original variables. The aim is to represent the objects (rows) and variables (columns) of the data set in a new system of coordinates (generally on two or

three axes or dimensions) where the maximum amount of variation from the original data set can be depicted. PCA plots can be developed either on the basis of variance–covariance matrix or on a correlation matrix. The first approach is followed when the same units or data types are used (e.g. abundance of different species). The aim is then to preserve and to represent the relative positions of the objects and the magnitude of variation between variables in the reduced space. PCA on a correlation matrix is rather used when variables are measured in different units or scales (e.g. different environmental parameters). The two approaches lead to different principal components and different distances between projected objects in the ordination; hence, the interpretation of the relationships must be made with care. Indeed, for correlation matrices, variables are first standardized (i.e. they become independent of their original scales), and so distances between objects are also independent from the scales of the original variables. All variables thus contribute to the same extent to the ordination of objects, regardless of their original variance. PCA results are generally displayed as a biplot (Jolicoeur and Mosimann 1960), where the axes correspond to the new system of coordinates, and both samples (dots) and taxa (arrows) are represented. The direction of a species arrow indicates the greatest change in abundance, whereas its length may be related to a rate of change. Depending on whether a distance or a correlation biplot is chosen, different interpretations can be made from the ordination diagram. The interpretation of the relationships between samples and species differs and is directly affected by the scaling chosen.

PCA is successful when most of the variance is accounted for by the largest (generally the first two or three) components. The amount of variance accounted for by each principal component is given by its 'eigenvalue'. The cumulative percentage of variance accounted for by the largest components indicates how much proportion of the total variance is depicted by the actual ordination. High absolute correlation values between the synthetic variables (principal components)

and the original variables are useful to identify which variables mainly contribute to the variation in the data set, and this is referred to as the loading of the variables on a given axis.

4.4.3.3 Correspondence Analysis (CA)

CA has generally been used in microbial ecology to determine whether patterns in microbial OTU distribution could reflect differentiation in community composition as a function of seasons, geographical origin or habitat structure (Olapade et al. 2005; Edwards et al. 2006; Kent et al. 2007). The overall aim of the method is to compare the correspondence between samples and species from a table of counted data (or any dimensionally homogenous table) and to represent it in a reduced ordination space (Hill 1974). Noticeably, instead of maximizing the amount of variance explained by the ordination, CA maximizes the correspondence between species scores and sample scores. The technique is popular among ecologists because CA is particularly recommended when species display unimodal relationships with environmental gradients.

4.4.3.4 Nonmetric Multidimensional Scaling (NMDS)

NMDS is generally efficient at identifying underlying gradients and at representing relationships based on various types of distance measures. The NMDS algorithm ranks distances between objects and uses these ranks to map the objects nonlinearly onto a simplified, two-dimensional ordination space, so as to preserve their ranked differences, and not the original distances (Shepard 1966). In NMDS ordination, the proximity between objects corresponds to their similarity, but the ordination distances do not correspond to the original distances among objects. Because NMDS preserves the order of objects, NMDS ordination axes can be freely rescaled, rotated or inverted, as needed for a better visualization or interpretation. NMDS is more computer intensive than eigenanalyses such as PCoA, PCA or CA.

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5.1 Studies from Eastern Mediterranean Region: A Review

Several reports are available from different ecological niche. An important example is the Mediterranean region where most of the water bodies represent oligotrophic condition. Many works have concentrated on the Eastern Mediterranean Sea, an extreme oligotrophic environment (Krom et al. 2003) at the far end of a prominent west–east with increasing oligotrophy gradient (Turley et al. 2000). This ultra-oligotrophic condition is testified by high light penetrance (Berman et al. 1984a; Ignatiades 1998); low nutrient concentrations; very low values for phytoplankton; primary productivity and cell abundance (Sournia 1973; Berman et al. 1984a, b; Dowidar 1984; Azov 1986; Bonin et al. 1989; Psarra et al. 2000; Christaki et al. 2001), with a dominance of small-size phytoplankton (Li et al. 1993; Yacobi et al. 1995; Ignatiades 1998; Ignatiades et al. 2002); and outstandingly low bacterial abundance and production (Robarts et al. 1996). Several groups from the Mediterranean countries have worked on the phytoplankton species composition and productivity from the Eastern Mediterranean region. Assessments of the trophic status of habitat by application of empirical indices, statistical analysis and other analytical methods have drawn significant attention from different groups of plankton biologists from this region. Such characterization have been carried out in the Adriatic region using the OECD statistical methodology by Vollenweider and Kerekes (1982) as well as by Vollenweider et al. (1998). Similar assessments were also performed from selected areas of the Aegean Sea (Saronikos Gulf, Island of Rhodes, Mytilini Island) with the use of nutrient and/or phytoplankton species data and the application of statistical analyses (Ignatiades et al. 1992; Stefanou et al. 2000), ecological indices (Karydis and Tsirtsis 1996) and simulation modelling (Tsirtis 1995).

A detailed study was carried out on the chlorophyll a and primary productivity in the Aegean Sea from the northern to the southern open sea environment (Ignatiades et al. 2002) and from inshore to offshore waters (Ignatiades 2005). Although this area primarily represents oligotrophy, due to localized nutrient enrichment, there are mesotrophic as well as eutrophic conditions also developed. Thus, experimental work was carried out from northern and southern Aegean Sea along with inshore and offshore waters of Saronikos Gulf. Samples were collected from depths of 1–120 m (Ignatiades et al. 2002) in the Aegean Sea, whereas samples were collected from 1 to 60 m depth at the Saronikos Gulf. Abiotic variables like salinity, temperature, chlorophyll a and primary productivity were measured in situ for each sampling depth. Samples thus collected for primary productivity estimates were incubated with ^{14}C–$NaHCO_3$, and ^{14}C incorporation were measured in a liquid scintillation counter. Statistical methods were used to establish the relation between Chl *a* and primary productivity.

Results showed that a distinct gradient was evident from the northern to the southern open waters of the Aegean Sea and from inshore to off-shore coastal waters of the Saronikos Gulf. The open water was cooler than the inshore–offshore waters whereas salinity levels in the northern Aegean were lower than in the southern Aegean. As expected, the open and offshore waters were nutrient poor as compared to the inshore waters. Based on the nutrient scaling criteria as proposed by Ignatiades et al. (1992), the nutrient levels of the open waters (northern and southern Aegean) were oligotrophic, whereas those of the offshore (Saronikos) waters were mesotrophic and inshore were eutrophic. Depending upon optical classification of seawater by Jerlov (1997), the habitat waters of the sampling stations were also categorized as oligotrophic (the northern and southern Aegean Sea), mesotrophic (the offshore waters of the Saronikos Gulf) and eutrophic (the inshore waters of the Saronikos Gulf). Analysis of the results of Chl a and primary productivity clearly suggested that the concentration levels of both parameters are related to the origin of the water samples.

In another work, carbon flux of planktonic food web was studied along with oligotrophic gradient (Siakou-Frangou et al. 2002). It has long been proposed that carbon flux in ocean is regulated by the magnitude of primary production and biogeochemical processes within the photic zone. Moreover, the complexity of pelagic food webs and the interactions between its different components are mainly responsible for the regulation of carbon flow. In oligotrophic waters like the Mediterranean region, different studies have established that both carbon and nutrients are remineralized and recycled within a complex microbial community dominated by minute producers and consumers (Caron et al. 1999; Azam et al. 1983; Sherr and Sherr 1988; Roman et al. 1995). Thus, simultaneous estimates of the production and biomass of phytoplankton, bacteria, heterotrophic nano- and microplankton and mesozooplankton are important parameters for the assessment of the carbon flux (Nielsen et al. 1993; Nielsen and Hansen 1995; Richardson et al. 1998; Bradford-Grieve et al. 1999).

Thus, like the previous part, this work was also carried out in the Aegean Sea, an area located between the Black Sea and the other seas of the eastern basin of the Mediterranean region (Ionian and Levantine Seas). Due to the involvement of so many different marine systems with variable salinity and nutrient status, significant variability is observed in regard to the oligotrophic status of the Aegean Sea at different sections. Thus, as a part of the EU project, this work was taken up to assess the organic carbon partitioning between autotrophic and heterotrophic plankters of different sizes and to investigate the carbon flow in the photic zone among the different areas of the Aegean Sea.

Here again, southern and northern Aegean Sea were taken into consideration for sampling that represented different degree of oligotrophy. Samplings were done on board R/V AEGAEO in two contrasting seasons of March and September, when the water column was well mixed and stratified. Total seven stations were selected from North Aegean Sea (N1–N7) and 4/5 stations were selected from South Aegean Sea (S1–S3 and S6, S7). Hydrographic measurements (temperature, pressure, conductivity) were carried out by CTD sampler from Niskin bottles, and inorganic nutrients, phytoplankton biomass and production, bacteria biomass and production, heterotrophic nanoflagellates (HNAN) and ciliates were collected at 2–100 m depths. Inorganic nutrients were measured on board spectrophotometrically. Water samples were size fractionated and chlorophyll concentrations were measured as a proxy for carbon biomass using the conversion factor of Malone et al. (1993). Photosynthetic productivity is also measured in situ by ^{14}C method. Incubation experiments with ^{14}C–$NaHCO_3$ was done and hourly measurements were recorded using a liquid scintillation counter. Epifluorescence microscopy was used to determine heterotrophic bacteria and heterotrophic nanoflagellate population as described by Christaki et al. (1999). Bacterial abundance data were converted into biomass (Lee and Fuhrman 1987), and biovolume–carbon conversion was done for flagellates (Børsheim and Bratbak 1987). Bacterial production (BP) was estimated by the ^3H-leucine method

(Kirchman 1993; Christaki et al. 1999). Similar counts and subsequent biovolume–carbon conversions and productivity measurements were done for ciliates as well. Larger mesozooplankton populations were hauled. Since calanoid copepods dominated the population, grazing of autotrophs were measured from gut fluorescence and gut evacuation rates (Dam and Peterson 1988).

Results from hydrographic studies showed that stratification in the North Aegean was much pronounced as compared to South Aegean Sea. Nutrient concentrations represented a highly contrasting status as compared to the eutrophic status, as observed by the present authors during their study in coastal West Bengal, India. Nitrate concentrations ranged from 0.05 to 2.5 µM and phosphate concentrations ranged from 0.02 to 0.08 µM in the entire area, starting from North to South Aegean Sea, with low seasonal variations. Phytoplankton counts were comparatively higher in March than in September, yet seasonal variations were not very pronounced.

Autotrophic biomass was relatively high $(1,488–2,568$ mg C m^2) with no significant difference between the areas. At all the sampling areas, picoplanktons (<3 µm) dominated the autotrophic component, although there were differences in the population of nanophytoplanktons at the two sampling regions. Whereas in North Aegean Sea they were <10 µm, at South Aegean Sea they were mostly larger than 10 µm. Moreover, the abundance of coccolithophorids was higher in North Aegean as compared to South Aegean Sea.

Among the heterotrophic populations, distinct patterns were observed. Although bacterial component accounted as the largest contributor to the carbon content, their biomass did not vary significantly between regions. On the other hand, although ciliates accounted for a very small proportion of the biomass, the abundance was significantly higher in the south as compared to the northern region. In contrast, mesozooplankton population decreased significantly from northern to southern region.

The carbon partitioning picture in this area did not quite replicate the typical picture, where autotrophic component outnumbers the heterotrophic components. The study area showed a gradual decrease in the autotrophic component with a subsequent increase in the heterotrophic component from northern to southern regions which were probably due to the abundance microheterotrophs. Thus, this work further established the oligotrophic condition for the Aegean Sea as was found for other regions of Eastern Mediterranean as well (Berman et al. 1984a; Krom et al. 1993; Robarts et al. 1996; Mazzocchi et al. 1997) in regard to low nutrient, plankton biomass and productivity. It further establishes an oligotrophic gradient from north to south in the Aegean Sea. Although nutrient concentrations were similar in the entire sampling area, there was a gradual differentiation in plankton community from Northeast to South Aegean. An inverse correlation between nutrient concentrations and autotrophic biomass in the North Aegean can be characterized as 'an anomalous interrelationship' that has been recorded previously in the Gulf of California (Hernandez-Becerril 1987). Experimental studies have shown that there is nutrient inflow from the Black Sea that caused localized enrichment, but due to the high rate of assimilation, nutrient concentrations are often depleted. Abundance patterns of bacteria, ciliates, heterotrophs and microheterotrophs further establish microheterotrophs as an essential component in regulating the spatial and temporal of carbon partitioning in the Aegean Sea.

Thus, from the studies it can be said that lotic aquatic ecosystems around the world represent significant variations with regard to the habitat. It can range from ultra-oligotrophic to highly eutrophic conditions. Moreover, light penetration can be significantly altered due to suspended matter load in the water column. This may in turn result in reduction in the photic zone ratio in the water column. Thus, although the incident radiation may be high, the net reproductivity as well as the dissolved oxygen content in the habitat may not complement the incident radiation. Planktonic populations are highly responsive to such alteration in the habitat including light availability. Thus, sudden shift in abiotic variables like light and temperature can account for major oscillations

in the water column properties which in turn cascades in regulating the phytoplankton population of the study area.

5.2 Case Study I: Phytoplankton Diversity of East Calcutta Wetland: A Ramsar Site

The phytoplankton study in Indian subcontinent extensively started in the mid-twentieth century and was primarily focused on the diversity and taxonomic study. The value of phytoplanktons and other algae as direct or indirect feed for fishes and their usefulness as indicator of water quality has long been well recognized. With the progress of inland fisheries in India, studies on productivity and diversity of phytoplanktons in Inland waters have gained considerable importance. Many aquatic ecosystems especially the sewage-fed ponds are generally affected by eutrophication, which indicates the inorganic nutrient supplies exceeding the phytoplankton growth demands (Fischer et al. 1988; McComb et al. 1995). Bioassay tests were conducted by several authors to determine the relation between nutrient characteristics and phytoplankton abundance (Redfield 1958; Ryther and Dunstan 1971; Pearl et al. 1990; Siep 1994).

The practice of fish culture in shallow waste ponds is quite popular in Indian subcontinent. Different aspects of wastewater ecology and productivity of this type of ecosystem have been studied by a number of authors (Sen 1941). According to Ray Chaudhuri et al. (2008), shallow fish-producing water bodies in West Bengal, India (called Bheris) have distinct architecture, resulting in extensive purification of waste. Such freshwater fish ponds of East Kolkata Wetland Complex (22°27′N 88°27′E) are also declared as a 'Ramsar site', by Ramsar Convention in 19 August 2002. (Ramsar Bureau List was established under the Article 8 of Ramsar Convention.) The Government of India declared this wetland as 'Wetland of International Importance'.

Thus, East Calcutta Wetland can be cited as best example of integrated resource recovery. The utility of Kolkata municipal waste on life and growth of fish was reported by Nayar (1944) and Bose (1944). Roy et al. (1981) further reported the use of Kolkata municipal waste for Bidyadhari–Kulti Fishery complex. The general ecology and biodiversity of Fauna of many ponds have also been recorded by many authors (Mukherjee 1996; Chakraborty 1988; Jana 1998; Mukherjee et al. 2002). Mukherjee et al. (2010) also reviewed that a Bheri is a biological complex system both at quantitative levels as compared to rain water as well as waste water-fed ponds. Pradhan et al. (2008) suggested that phytoplankton growth could be an important factor responsible for greater fish production and could also act as biomonitor for water quality assessment in the Bheris. However, over growth of plankton results in bloom which could be a problem for pond management. Fishes also play a crucial role by maintaining a proper balance of phytoplankton growth, and the planktons convert the nutrients available from waste into consumable form as food for fish (Ghosh 1999). The water and effluent generated form Bheris are used for cultivation of vegetables, which were found to show no harmful accumulation (Ray Chaudhuri et al. 2007). In the present study phytoplankton diversity of waste-fed fish pond and their taxonomic documentation have been done in detail.

5.2.1 Study Area

One such freshwater eutrophic fish pond of the Ramsar site was our study pond – the Captain Bheri. It is situated at eastern region of Kolkata between 88°27′ east latitude and 22°27′ north latitude, at the south of Salt Lake City on Eastern bypass, covering an area of 450 m^2. This pond serves the dual purpose of recycling sewage water of Kolkata metropolitan city and for cultivating fishes extensively. The sewage water includes municipal waste and small-scale industrial effluents of Eastern Kolkata's urban and semiurban areas.

The variation in physicochemical factors recorded throughout the year was also recorded. The temperature of water varied from 15.3 to 31 °C, pH from 7.5 to 8.62. This suggests the alkaline nature of the habitat water. Different nutrients like nitrate, nitrite, phosphate, ammonium

nitrogen, etc., were also measured. Nitrate was found to vary between 0.0775 and 0.286 mg/ml. Nitrite was found to range from 0.885 to 4.4 mg/L. Phosphate ranged from 0.057 to 0.277 mg/L. Ammonium nitrogen concentration varied between 0.45 and 0.187 mg/L.

5.2.2   Results

A total of 55 taxa were recorded during the study period which were found to belong to the groups of Cyanobacteria, Chlorophyta, Bacillariophyta and Euglenophyta. Chlorophyta population was found to comprise of 30 species. On the other hand 9 taxa of Cyanophyta, 8 taxa of Euglenophyta and 8 taxa of Bacillariophyta were also recorded (Table 5.1). From the pie chart of the population, it is evident that chlorophytes were found to be maximum comprising of 55 % of the total population, followed by cyanobacteria with 16 % of the total population, and then euglenophytes and bacillariophytes (15 % and 14 %, respectively) (Fig. 5.1).

Description of few taxa are given below which were restricted to this area only; the rest are given in case studies II and III

Division – Cyanophyta
Class – Myxophyceae
Order – Chroococcales
Family – Chroococcaceae
Chroococcus dispersus (Keissl.) Lemmermann (Plate 5.1, Fig. 1)
Lemmermann 1904 p. 102; Prescott 1982, Pl. 100, Fig. 7

Table 5.1 Showing name of the phytoplankton taxa recorded

S. No.	Name of taxa
	Cyanophyta
1.	*Chroococcus dispersus*
2.	*Coelosphaerium dubium*
3.	*Merismopedia glauca*
4.	*Merismopedia minima*
5.	*Merismopedia trolleri*
6.	*Synechococcus elongatus*
7.	*Planktolyngbya contorta*
8.	*Arthrospira platensis*
9.	*Spirulina subsalsa*

Table 5.1 (continued)

| S. No.	Name of taxa
	Chlorophyta
10.	*Chlorococcum humicola*
11.	*Pediastrum duplex*
12.	*Pediastrum duplex* var. *clathratum*
13.	*Pediastrum tetras* var. *tetras*
14.	*Pediastrum tetras* var. *tetraodon*
15.	*Coelastrum microporum*
16.	*Coelastrum proboscideum*
17.	*Ankistrodesmus falcatus*
18.	*Ankistrodesmus falcatus* var. *tumidus*
19.	*Kirchneriella lunaris*
20.	*Kirchneriella contorta*
21.	*Selenastrum bibraianum*
22.	*Tetraedron minimum*
23.	*Tetraedron muticum*
24.	*Tetraedron trigonum*
25.	*Tetraedron caudatum*
26.	*Crucigenia apiculata*
27.	*Crucigenia quadrata*
28.	*Crucigenia crucifera*
29.	*Crucigenia tetrapedia*
30.	*Scenedesmus abundans*
31.	*Scenedesmus acuminatus*
32.	*Scenedesmus bicaudatus*
33.	*Scenedesmus bijuga*
34.	*Scenedesmus dimorphus*
35.	*Scenedesmus quadricauda* var. *parvus*
36.	*Scenedesmus obliquus*
37.	*Scenedesmus acutus*
38.	*Scenedesmus quadricauda*
39.	*Scenedesmus ecornis*
	Euglenophyta
40.	*Euglena gracilis*
41.	*Euglena viridis*
42.	*Phacus helikoides*
43.	*Phacus nordstedii*
44.	*Phacus tortus*
45.	*Phacus chloroplastes*
46.	*Phacus curvicauda*
47.	*Euglena proxima*
	Bacillariophyta
48.	*Pleurosigma angulatum*
49.	*Cyclotella meneghiniana*
50.	*Amphora coffeaeformis*
51.	*Navicula halophila*
52.	*Navicula microspora*
53.	*Navicula lanceolata*
54.	*Nitzschia actinastroides*
55.	*Aulacoseira granulata*
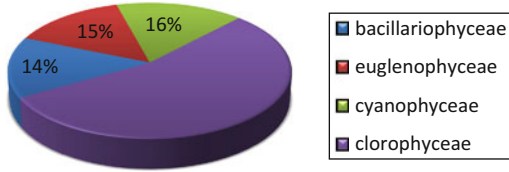
Fig. 5.1 Pie chart showing percentage abundance of phytoplankton population of the study area

Ovate or irregularly shaped colony of 4–6 spherical cells, free floating and flattened; cells are either single or arranged in small clusters, evenly distributed at some distance from one another in the mucilaginous envelop; individual cell sheaths not evident; cell contents bright blue green, cells 3–4.5 μ in diameter
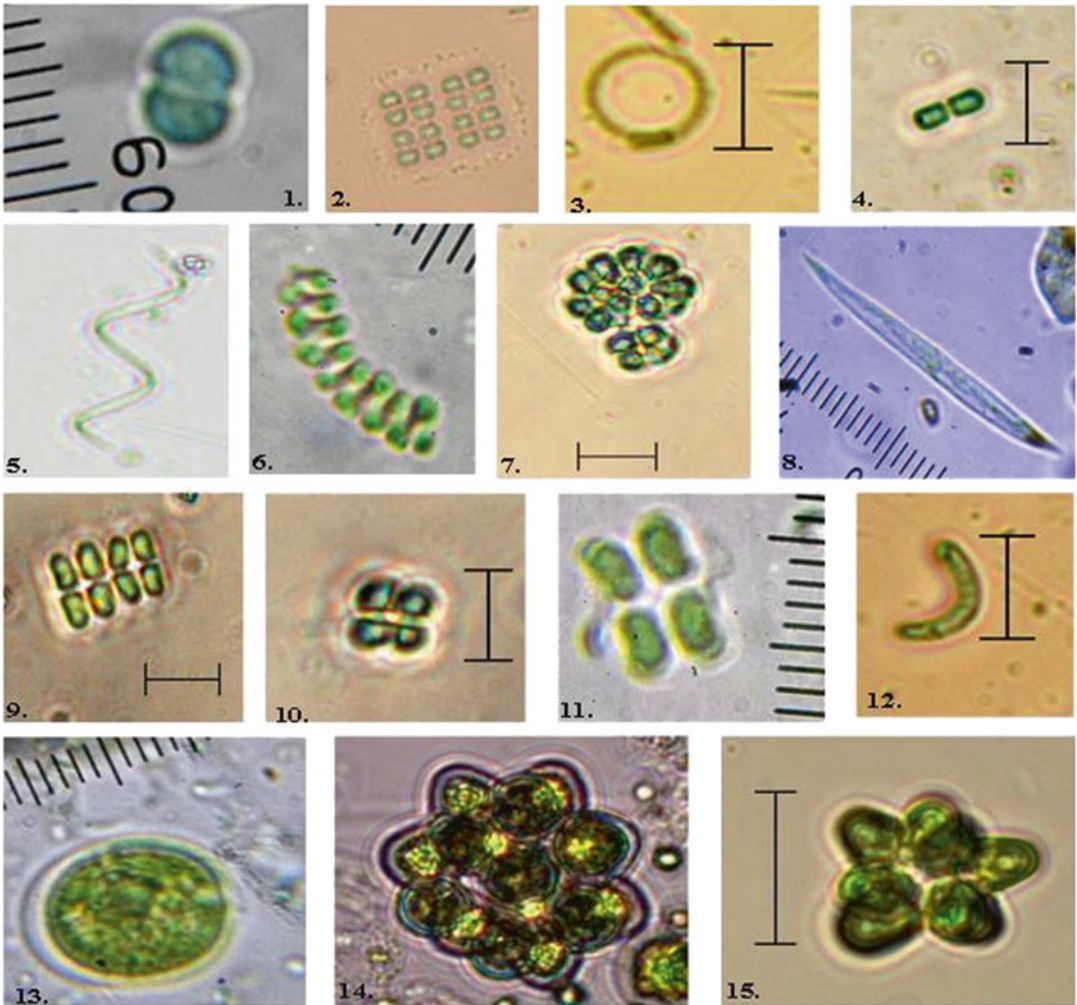

Plate 5.1 (**1**) *Chroococcus dispersus*, (**2**) *Merismopedia trolleri*, (**3**) *Planktolyngbya circumcreta*, (**4**) *Synechococcus elongatus*, (**5**) *Arthrospira platensis*, (**6**) *Spirulina subsalsa*, (**7**) *Coelosphaerium dubium*, (**8**) *Ankistrodesmus falcatus* var. *tumidus*, (**9**) *Crucigenia apiculata*, (**10**) *Crucigenia quadrata*, (**11**) *Crucigenia crucifera*, (**12**) *Kirchneriella contorta*, (**13**) *Chlorococcum humicola*, (**14**) *Coelastrum microporum*, (**15**) *Coelastrum proboscideum*

Coelosphaerium dubium Grunow in Rabenhorst (Plate 5.1, Fig. 7)

Rabenhorst 1865, p. 55; Prescott 1982, Pl. 106, Fig. 1

Spherical or sometimes irregularly shaped colony, cells densely arranged. Cells spherical, free floating, prominent colonial mucilage to form a peripheral layer, cell contents blue green, cells 5–7 µ in diameter; compound colonies as much as 300 µ in diameter

Merismopedia trolleri Bachmann (Plate 5.1, Fig. 2)

Bachmann 1920, p. 350; Prescott 1982, Pl. 101, Fig. 5

Colonial, each cell with a distinct sheath, 8–16 spherical cells evenly arranged within a transparent colonial mucilage; cell contents with pseudovacuoles, appearing brownish or purplish because of light refraction; cells 2–3.5 µ in diameter

Synechococcus elongatus Nag. (Plate 5.1, Fig. 4)

Desikachary, 1959, pl no. 25, fig 7

Cells cylindrical, 1.4–2 µ broad, 1.5–3 times as long as broad, contents homogeneous and light blue green

Order – Oscillatoriales

Family – Oscillatoriaceae

Planktolyngbya circumcreta (G.S. West) Anagnostidis et Komarek (Plate 5.1, Fig. 3)

Kommarek 2005, p. 160, fig 194

Filamentous, solitary, free floating, spirally coiled, 2–2.5 µ wide, coils 33–39 µ broad, making 2–3 turns, sheathes thin, colourless, trichomes light pale blue green

Arthrospira platensis (Nordst.) Gomont (Plate 5.1, Fig. 5)

Desikachary, 1959 pl no. 35, fig 2

Spiral thallus blue green in colour, trichomes slightly constricted at the cross walls, 6–8 µ broad, distance between spirals 8–10 µ, end cells broadly rounded

Spirulina subsalsa Oernst. ex Gomont (Plate 5.1, Fig. 6)

Desikachary, 1959 pl no. 36, figs 3, 9

Spiral thallus, trichomes 1–2 µ broad, bright blue green or yellowish green thallus, irregular spirals, spirals very close to each other, spirals 3–5 µ broad

Division – Chlorophyta

Class – Chlorophyceae

Order – Chlorococcales

Family – Chlorococcaceae

Chlorococcum humicola (Naeg.) Rabenhorst (Plate 5.1, Fig. 13)

Rabenhorst 1868, p. 58; Prescott 1982, Pl. 45, Fig. 1

Unicellular green alga, prominent cell wall, parietal chloroplast, cells spherical, solitary or in small clumps, variable in size within the same plant mass; cells 8–25 µ in diameter

Family – Hydrodictyaceae

Pediastrum duplex var. *clathratum* (A. Braun) Lagerheim (Plate 5.2, Fig. 6)

Lagerheim 1882, p. 56; Prescott 1982, Pl. 48, Figs. 6

Green algal colony, colony with larger perforations than in the typical form; walls with deep emarginations; apices of lobes of peripheral cells truncate; cells 12–20 µ in diameter

Pediastrum tetras var. *tetraedon* (Corda) Rabenhorst (Plate 5.2, Fig. 7)

Rabenhorst 1868, P. 78; Prescott 1982, pl no. 50, Fig 7

Colony 4–8 celled, outer margins of the peripheral cells with deep incisions; the lobes extended into sharp, horn-like process; cells 12–15 µ in diameter, 16–18 µ long

Pediastrum tetras (Ehrenb.) Ralfs var. *teras* (Plate 5.2, Fig. 9)

Ralfs 1844, p. 469; Prescott 1982, Pl. no 50, Figs 3, 6

Colony entire; inner cells (frequently none) with 4–6 straight sides but with one margin deeply incised; peripheral cells crenate, with a deep incision in the outer free margin, their lateral margins adjoined along two third of their length; cells 8–16 µ in diameter

Family – Coelastraceae

Coelastrum microporum Naegeli (Plate 5.1, Fig. 14)

A. Braun 1855, p. 70; Prescott 1982, Pl. 53, Fig. 3

Coenobium spherical, composed of 8–68 sheathed globose cells (sometimes ovoid, with the narrow end outwardly directed); cells interconnected by very short, scarcely discernible gelatinous processes, leaving small
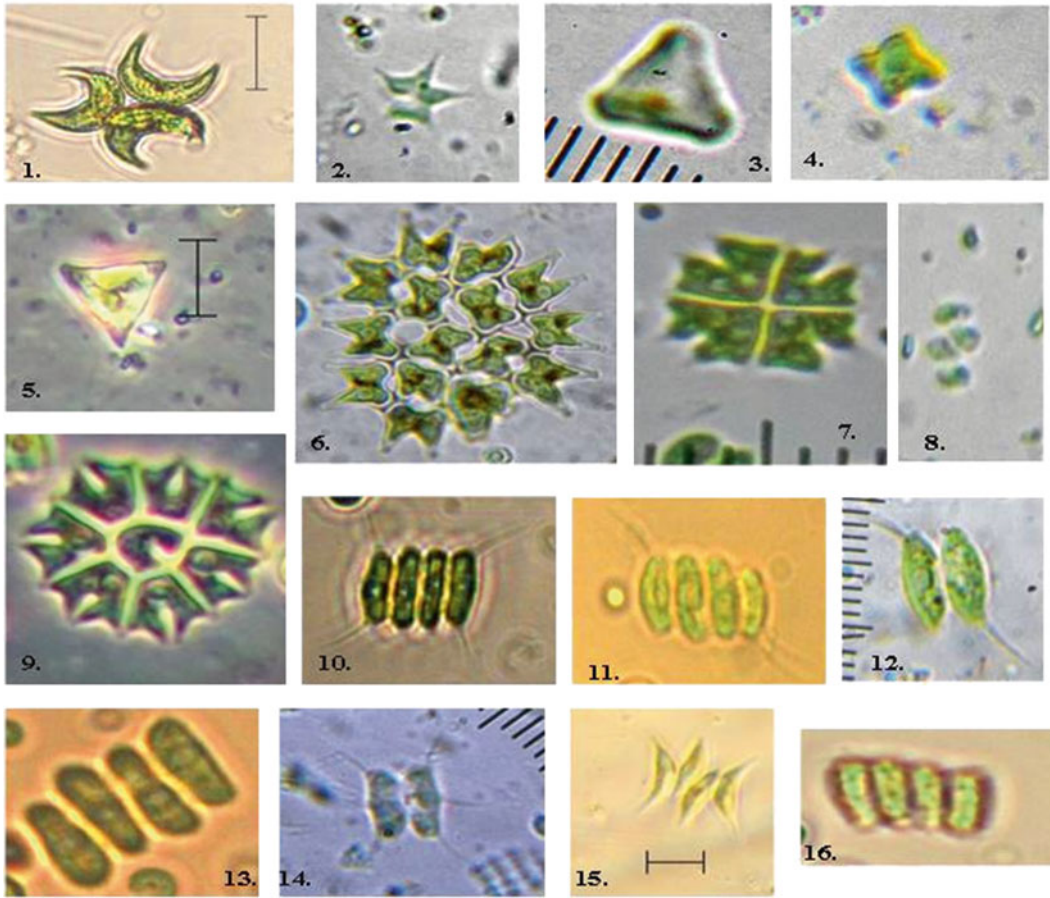
Plate 5.2 (**1**) *Selenastrum bibraianum*, (**2**) *Tetraedron caudatum*, (**3**) *Tetraedron muticum*, (**4**) *Tetraedron minimum*, (**5**) *Tetraedron trigonum*, (**6**) *Pediastrum duplex* var. *clathratum*, (**7**) *Pediastrum tetras* var. *tetraodon*, (**8**) *Scenedesmus acutus*, (**9**) *Pediastrum tetras* var. *tetras*, (**10**) *Scenedesmus quadricauda* var. *parvus*, (**11–12**) *Scenedesmus bicaudatus*, (**13**) *Scenedesmus ecornis*, (**14**) *Scenedesmus abundans*, (**15**) *Scenedesmus acuminatus*, (**16**) *Scenedesmus obliquus*

intercellular spaces; cells 8–20 μ in diameter including the sheath

Coelastrum proboscideum Bohlin (Plate 5.1, Fig. 15)

Bohlin 1897, p. 33; Prescott 1982, Pl. 53, Figs. 4, 5, 8

Coenobium pyramidal or cubical (rarely polygonal), composed of 4-8-16-32 truncate cone shaped cells with the apex of the cone directed outward, the inner or basal wall of the cell concave, the lower lateral walls of the cells adjoined about a large space in the centre of the colony; cells 8–15 μ in diameter; 4-celled colony as much as 35 μ in diameter

Family – Oocystaceae

Ankistrodesmus falcatus var. *tumidus* (West & West) G.S. West (Plate 5.1, Fig. 8)

West 1904, p. 224; Prescott 1982, Pl. 56, Fig. 9

Unicellular, cells lunate or fusiform, the ventral margin decidedly tumid in the midregion, 4.5–6.5 μ in diameter, 61–73 μ long

Kirchneriella contorta (Schmidle) Bohlin (Plate 5.1, Fig. 12)

Bohlin 1897 p. 20; Prescott 1982, Pl. 57, Figs. 7, 8.

Colonial, free floating, usually of 16 twisted, arcuate, cylindrical cells with broad, convex apices, lying irregularly scattered throughout the homogeneous, gelatinous envelope,

chloroplast covering the entire wall of cells, which are 1–2 μ in diameter, 5.8–10 μ long

Selenastrum bibraianum Reinsch (Plate 5.2, Fig. 1)

Reinsch 1867, p. 64; Prescott 1982 pl no. 57, fig. 9

Colony ovate in outline, composed of 4–16 lunate or sickle shaped cells with sharp apices and arranged so that the convex surfaces are apposed and directed towards the centre of the colony; cells 5–8 μ in diameter, 20–38 μ long; distance between apices 16–42 μ

Tetraedron minimum (A. Braun) Hansgirg (Plate 5.2, Fig. 4)

Hansgirg 1888, p. 131; Prescott 1982, pl no. 60, figs 12–15

Unicellular, cells small, flat, tetragonal, the angles rounded and without spines or processes, lobes sometimes cruciately arranged; margins of the cell concave with one frequently incised; cells 6–20 μ in diameter

Tetraedron muticum (A. Braun) Hansgirg (Plate 5.2, Fig. 3)

Hansgirg 1888, p. 131; Prescott 1982, pl no. 60, figs. 16, 17.

Unicellular; cells small, flat, triangular; the angles without spines or furcations; sides of the cell emarginated or slightly convex; cells 6–18 μ in diameter

Tetraedron trigonum (Naeg.) Hansgirg (Plate 5.2, Fig. 5)

Hansgirg 1888, p. 130; Prescott 1982, pl no. 61, figs. 11, 12.

Cells flat, 3-angled, the angles tapering to sharply rounded, spine-tipped apices; margins convex; sides of the cell body concave or straight; cells are 19–29.8 μ in diameter

Tetraedron caudatum (Corda) Hansgirg (Plate 5.2, Fig. 2)

Hansgirg 1888, p. 131; Prescott 1982, pl no. 59, figs. 17, 24, 25.

Cells flat, 5-sided, the angles rounded and tipped with a short sharp spine; the sides between the angles concave, but with one margin narrowly and deeply incised; cells in their longest dimension 8-15-(22)

Family – Scenedesmaceae

Crucigenia apiculata (Lemn.) Schmidle (Plate 5.1, Fig. 9)

Schmidle 1901, p. 234; Prescott 1982, Pl. 65, Fig. 3

Colonial, 4 ovate rhomboidal or somewhat triangular cells arranged cruciately, cells 3–7 μ in diameter, 5–10 μ long; colony 6–12.5 μ wide, 9–8 μ long

Crucigenia quadrata Morren (Plate 5.1, Fig. 10)

Morren 1830, pp. 415, 426; Prescott 1982, Pl. 65, Fig. 10

Colony free-floating, consisting of a circular plate of 4 triangular cells, arranged about a small central place, chloroplasts parietal discs, as many as 4 in a cell; pyrenoids not always present; cells 2.5–6 μ in diameter, 3.7 μ long; multiple quadrate colonies formed by the close arrangement of component quardets

Crucigenia crucifera (Wolle) Collins (Plate 5.1, Fig. 11)

Collins 1909, p. 170; Prescott 1982, Pl. 65, Fig. 4

Colony consisting of 4-sided cells arranged about a central square opening, the outer free walls longer and concave, the outer free angles of the cells rounded, the lateral adjoin other cells, the inner walls colonies resulting from the adherence of quartets of cells by persisting mother cell walls; cells 3.5–5 μ in diameter, 5–7 μ long; colony 9–11 μ wide, 14–16 μ long

Scenedesmus abundans (Kirch.) Chodat (Plate 5.2, Fig. 14)

Chodat 1913, p. 77; Prescott 1982, pl. 62, fig 21

Cells oblong or ovate, in a linear series of 4, the terminal cells with 1 or 2 polar spines and 2 spines on the lateral wall, the inner cells with the spines at each pole, cells 4–7 μ in diameter, 7–12 μ long

Scenedesmus acuminatus (Lag.) Chodat (Plate 5.2, Fig. 15)

Chodat 1902, p. 211, G.W. Prescott 1982, pl no. 62, Fig no. 16

Cells arranged in a curved series of 4 (rarely 8) cells strongly lunate, with sharply pointed apices, the convex walls adjoined inwardly, the concave faces directed outwards; cells 3–7 μ in diameter, 30–40 μ long

Scenedesmus bicaudatus Deuds (Plate 5.2, Figs. 11 and 12)

Jaiswal & Tiwari, p. 94 pl 13, fig 8

Coenobium 2–8 celled, with linear or slightly alternate in arrangement, cells elongated,

outer cells with a long curved spine at alternate poles; inner cells without spines, oval to cylindrical, length 10–12 μ, width 4–6 μ

Scenedesmus obliquus (Turp.) Kuetzing (Plate 5.2, Fig. 16)

Kuetzing 1833, p. 609; Prescott 1982, pl no. 63, Fig 17

Colony composed of 2–8 (usually 4 or 8) fusiform cells arranged in a single series; apices of the cells apiculate; wall smooth; cells 4.2–9 μ in diameter, 14–21 μ long

Scenedesmus quadricauda var. *parvus* G.M. Smith (Plate 5.2, Fig. 10)

Smith 1916a, p. 480; Prescott 1982, pl no 64, Fig 6

Colony composed of 2–16 cylindrical–ovate cells arranged in a single series; outer cells with a long spine at each pole; inner cells with spineless walls; cells 4–6.5 μ in diameter, 12–17 μ long

Scenedesmus ecornis (Ehrenb.) Chodat (Plate 5.2, Fig. 13)

Colonies of 4 cells attached side by side along 3/4 of their side, arranged in a zigzag way; cell body elliptical; cell wall smooth, inner spaces absent, without spiny or dented projections, 7–20 μ long, 4–10 μ in diameter

Scenedesmus acutus Meyen (Plate 5.2, Fig. 8)

Jaiswal & Tiwari, p. 95 pl. 13, fig 12

Colony 4 celled, cells linear or slightly alternate in arrangement, terminal cells with concave outerface, length 20–24 μ and breadth 5–7 μ

Division – Euglenophyta
Class – Euglenophyceae
Order – Euglenales
Family – Euglenaceae

Euglena gracilis Klebs (Plate 5.3, Figs. 1 and 2)

Klebs 1883, p. 303; Prescott 1982, pl no. 85, fig. 17

Unicellular, comparatively larger cell, grass green in colour, cells short fusiform to ovoid; chloroplast many evenly distributed throughout the cell, cell 8–20 μ diameter, 35–50 μ long

Euglena proxima Dangeard (Plate 5.3, Fig. 3)

Dangeard 1902, p. 154; Prescott 1982, pl no. 85, fig. 25

Larger fusiform cells, narrowed posteriorly to a blunt tip, periplast spirally striated, chloroplast numerous, cells 14–21 μ in diameter, 50–95 μ long

Euglena viridis (O.F. Müller) Ehrenberg (Plate 5.3, Fig. 4)

Large cell, 40–65 μm long, 14–20 μm wide; anterior end rounded, posterior end pointed; fusiform during locomotion; highly plastic when stationary; chloroplasts more or less bandform, radially arranged; nucleus posterior

Phacus chloroplastes Prescott (Plate 5.3, Fig. 8)

Prescott 1982, pl no. 87, figs. 15, 16.

Cells broad, pyriform; at posterior end a straight or vey slightly deflected caudus is formed. broadly rounded anterior end with a median papilla; periplast longitudinally striated; margin of cell entire, chloroplasts in parietal bands, cells 20–22 μ in diameter, 29–31 μ long

Phacus curvicauda Swirenko (Plate 5.3, Fig. 7)

Swirenko 1915, p. 333 G.W. Prescott 1982, pl no. 87, figs. 14

Cells broadly ovoid to sub orbicular in outline, slightly spiral in the posterior part, which is extended into a caudus that curves obliquely, chloroplasts numerous, 24–26 μ in diameter, 28–30 μ long

Phacus nordstedtii Lemmermann (Plate 5.3, Fig. 5)

Lemmermann 1904, p. 125; Prescott 1982, pl no. 88, figs. 1

Cells napiform, nearly spherical and with a long straight sharply pointed caudus, broadly rounded anteriorly, periplast spirally striated, cells 18–19 μ in diameter, 35–40 μ long

Phacus tortus (Lemm.) Skvortzow (Plate 5.3, Fig. 10)

Skvortzow 1928, p. 110; Prescott 1982, pl no. 88, figs. 20

Cells broadly fusiform, broadest at the anterior end of the cell, tapering and spirally twisted in the posterior position to form a long straight caudus, cells 38–50 μ in diameter, 85–95 μ long

Phacus helikoides Pochmann (Plate 5.3, Fig. 6)

Pochmann 1942, p. 212; Prescott 1982, pl no. 87, fig. 9

Cells elongate fusiform, twisted throughout the entire length, briefly narrowed anteriorly and bilobed, tapering posteriorly to a spirally twisted long straight caudus, margin entire with two or three bulges, cells 30–50 μ in diameter, 70–120 μ long
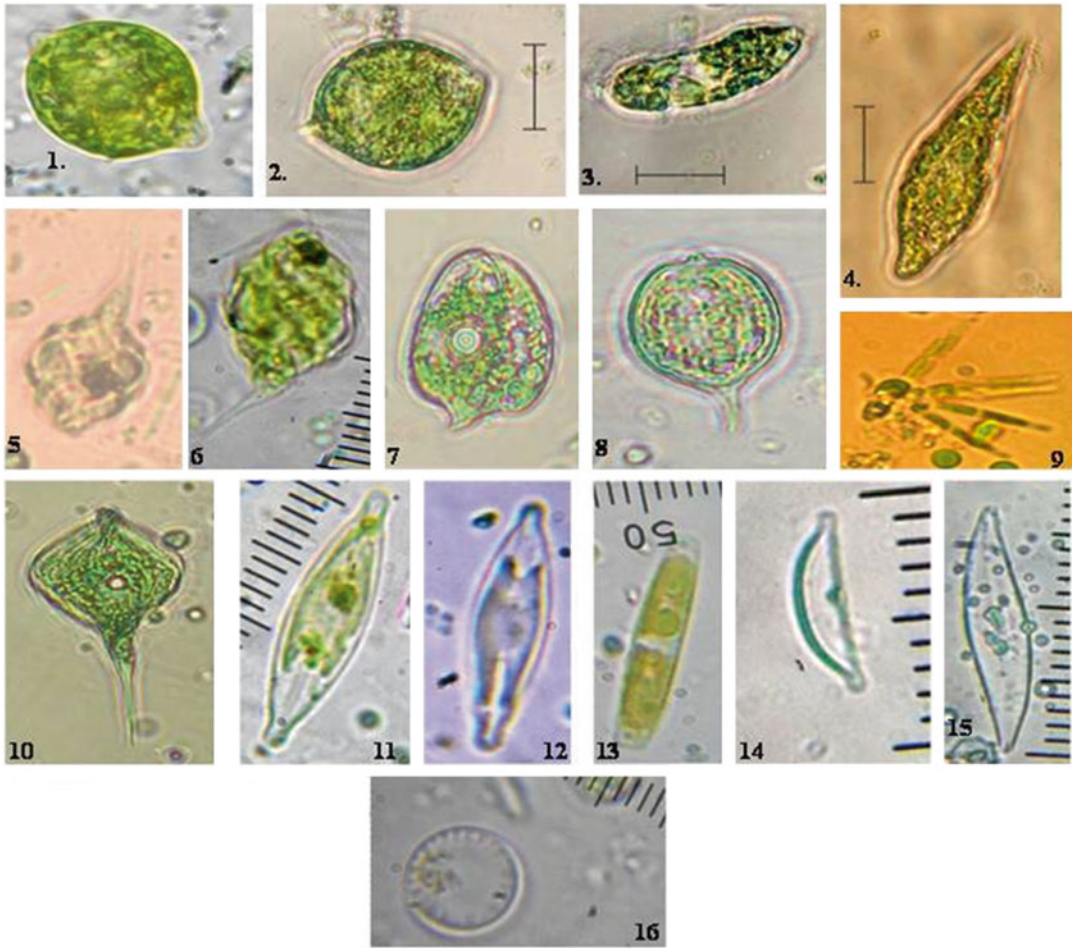
Plate 5.3 (**1–2**) *Euglena gracilis*, (**3**) *Euglena proxima*, (**4**) *Euglena viridis*, (**5**) *Phacus nordstedtii*, (**6**) *Phacus helikoides*, (**7**) *Phacus curvicauda*, (**8**) *Phacus choloroplastes*, (**9**) *Nitzschia actinastroides*, (**10**) *Phacus tortus*, (**11**) *Navicula halophila*, (**12**) *Navicula micropora*, (**13**) *Navicula lanceolata* (*side view*), (**14**) *Amphora coffeaeformis*, (**15**) *Pleurosigma angulatum*, (**16**) *Cyclotella meneghiniana*

Division – Bacillariophyta

Class – Bacillariophyceae

Order – Thalassiophysales

Family – Catenulaceae

Amphora coffeaeformis Agardh (Plate 5.3, Fig. 14)

Frustules in girdle view very prominent elliptic lanceolate, truncate. Valves arcuate on the dorsal margin and straight or slightly concave on the ventral margin. Striae delicate

Order – Thalassiosirales

Family – Stephanodiscaceae

Cyclotella meneghiniana Kutz. (Plate 5.3, Fig. 16)

Venkataraman, 1939, p. 303, fig 11

Frustules discoid in valve view, rectangular and undulated in girdle view; margin well defined, coarsely striated and striae wedge shaped. Diameter 11–30 μ

Order – Naviculales

Family – Naviculaceae

Navicula microspora Kant & Gupta (Plate 5.3, Fig. 12)

Kant and Gupta 1998, p. 27, pl. 127, fig. 12.

Frustules elliptical to lanceolate, rostrate apices, pseudoraphae at the centre, axial area broad, striation not visible in fresh material, longer than broad, 42–54 μ long and 10–14.5 μ broad

Navicula lanceolata (Agardh) Ehrenberg (Plate 5.3, Fig. 13)

Valves linear–lanceolate to lanceolate, with very slightly protracted, bluntly rounded apices. Striae radiate at the centre, becoming convergent at the apices, with a broadly rounded to squarish central area. Length 28–70 μ, width (8)-9-12 μ

Navicula halophila (Grun.) Cleve (Plate 5.3, Fig. 11)

Valves lanceolate with slightly produced and capitate ends. Axial area narrow, linear, central area slightly widened in the middle. Striations parallel and slightly convergent at the ends

Family – Pleurosigmataceae

Pleurosigma angulatum (Quekett) W. Smith (Plate 5.3, Fig. 15)

Valves lanceolate, slightly sigmoid, ends subacute, 116 μ long, 16.5 μ broad; raphae more sigmoid than valve, excentric near the ends

Order – Bacilllariales

Family – Bacillariaceae

Nitzschia actinastroides Van Goor (Plate 5.3, Fig. 9)

Huber – Pestalozii 1942, p. 472, pl. CXXXVIII, fig. 560.

Rustules straight, liner, much longer than broad, 60–90 μ long and 2–4 μ broad, striation not clearly visible in fresh material, 4–5 frustules joined at one end

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5.3   Case Study II: Phytoplankton Diversity of Indian Sunderbans

The Sunderbans mangrove forest is one of the largest mangrove forest in the world (140,000 ha). It is situated in the southeast part of Asia or the southeastern coast of India and Bangladesh, on the delta of the Ganges, Brahmaputra and Meghna rivers on the mouth of Bay of Bengal. The Indian site lies between 21°31′ to 22°53′N and 88°37′ to 89°09′E. Due to its beauty and richness of wildlife, it was declared a world natural heritage site by UNESCO on 1974. The site is intersected by a complex network of small-forested islands and mudflats and some interconnected tidal rivers, creeks and canals, therefore forming a complex network of tidal waterways.

The land is constantly moulded and altered by tidal action, with erosion along estuaries and deposition of silts from seawater. The Sunderbans consist of three wildlife sanctuaries (Sundarbans West, East and South) including the man eater Royal Bengal Tiger.

Sunderbans' beauty lies in its unique natural surroundings. Thousands of meandering streams, creeks, rivers and estuaries have enhanced its charm. Forest areas are dominated by typical mangrove plants, like Sundri and Gewu and patches of Nypa palm. Sunderban is the natural habitat of the world famous Royal Bengal Tiger, spotted deer, crocodiles, jungle fowl, wild boar, lizards, monkey and an innumerable variety of beautiful birds. The entire area is flooded with brackish water during high tides which mix with freshwater from inland rivers. The monsoon rains, flooding, delta formation, and tidal influence combine in the Sundarbans to form a dynamic landscape that is constantly changing. The ecology and the biodiversity of the Sunderban algae have been studied by a very few authors (Prain 1903; Naskar and Mandal 1999; Sen and Naskar 2003). Several authors studied the mangrove ecosystem with reference to human habitation and settlement, development of agricultural fields and brackish water fisheries. The algal flora of Suderbans has extensively studied by the present group from taxonomic point of view and as a potential source for biodiesel (Mukhopadhyay and Pal 2002; Choudhury and Pal 2008; Satpati et al. 2013)

Phytoplankton population of Sunderbans rivers varied to a greater extent with salinity gradient. In present study, phytoplanktons were collected from the different islands of Sunderbans like Basanti, Patharpratima, Bakkhali and Lothian Islands and surroundings river systems like Vidya river, Kholnar khal, Muriganga river, Saptamukhi river, Matla river and Bishalakshi khal. Mid river samplings were done for phytoplankton collection. Sampling section represents from freshwater zone to marine zone. Salinity varies from 0 to 22 psu, temperature profiles were recorded as 22–34 °C and an average pH was measured as 7.98.

Phytoplankton community was dominated by diatoms (Biacillariophyceae) followed by Chlorophyceae, and other algal groups recorded were Cyanophyceae, Euglenophyceae and Dinophyceae. A total of 34 taxa belonging to 5 groups were recorded. Species diversity was found to be maximum in summer (March) and minimum in winter season (November) in all the sample stations.

5.3.1   List of Phytoplankton Genera Recorded from Sunderbans

Cyanobacteria	*1. Merismopedia glauca*
	2. Merismopedia minima
	3. Spirulina platensis
	4. Gloeocapsa punctata
Chlorophyceae	*5. Chlorococcum infusionum*
	6. Pediastrum tetras
	7. Crucigenia tetrapedia
	8. Scenedesmus quadricauda
	9. S. bijuga
	10. S. dimorphus
	11. Closterium tumidium
Euglenophyceae	*12. Euglena gracilis*
	13. E. polymorpha
	14. Phacus longicauda
	15. P. segretii
Bacillariophyceae	*16. Achnanthes hauckiana*
	17. Pleurosigma angulatum
	18. P. normanii
	19. Navicula halophila
	20. N. cincta
	21. N. minima
	22. N. ignorata
	23. N. peregrina
	24. Coscinodiscus excentricus
	25. C. excentricus
	26. Cyclotella meneghiniana
	27. Cyclotella striata
	28. Nitzschia obtuse
	29. N. amphibian
	30. Melosira nummuloides
	31. Fragilaria intermedia
	32. F. oceanic
Dinophyceae	*33. Ceratium hirundinella*
	34. Noctiluca scintillans

5.3.2   Taxonomic Account of a Few Phytoplankton Taxa Recorded from Sunderbans (Rest Are in Case Studies I and III)

Division – Euglenophyta
Class – Euglenophyceae
Order – Euglenales
Family – Euglenaceae
Euglena polymorpha Dangeard (Plate 5.4, Fig. A)
[Dangeard, 1902, p. 175. Pl. 85, Figs. 21, 22; Prescott, 1982, p. 393.]
Cells ovoid to pyriform to subcylindric, narrowed gradually posteriorly to a short blunt tip; periplast with spiral striations; chloroplasts many and disc-like with lacinate margins, with one pyrenoid; cells 20–26 µ in diameter, 80–90 µ long
Phacus segretii var. *ovum* Prescott (Plate 5.4, Fig. B)
[Prescott, 1982, p. 369, pl. 88, fig. 23.]
Cells larger than in the typical form, broadly ovoid, 29 µ in diameter and 40 µ long.
Occurrence, Jharkhali pond (N 22°01.142′, E 088°41.168′), fresh water
Division – Heterokontophyta
Class – Bacillariophyceae
Order – Pennalales
Suborder – Araphidineae
Family – Fragilariaceae
Subfamily – Fragilarioideae
Fragilaria brevistriata Grun. forma *elongata* f. nov (Plate 5.4, Fig. F)
[Venkataraman 1939, p. 305, fig. 25, 26]
Valves linear lanceolate with rounded ends. Striae short and marginal. Pseudoraphae broad. Length 31.20 µ, breadth 4.31 µ, striae 13 in 10 µ
Fragilaria oceanica Cleve. (Plate 5.4, Fig. H)
[Subrahmanyan 1946, p. 165, figs. 336–339]
Frustules in girdle view linear–rectangular, forming a very compact ribbon-like chain. Valves broadly lanceolate with rounded ends, 11.5 µ long, and 6.5 µ broad
Suborder – Monoraphidineae
Family – Achnanthaceae
Subfamily – Achnanthoideae
Achnanthes hauckiana var. *rostrata* (Plate 5.4, Fig. I)
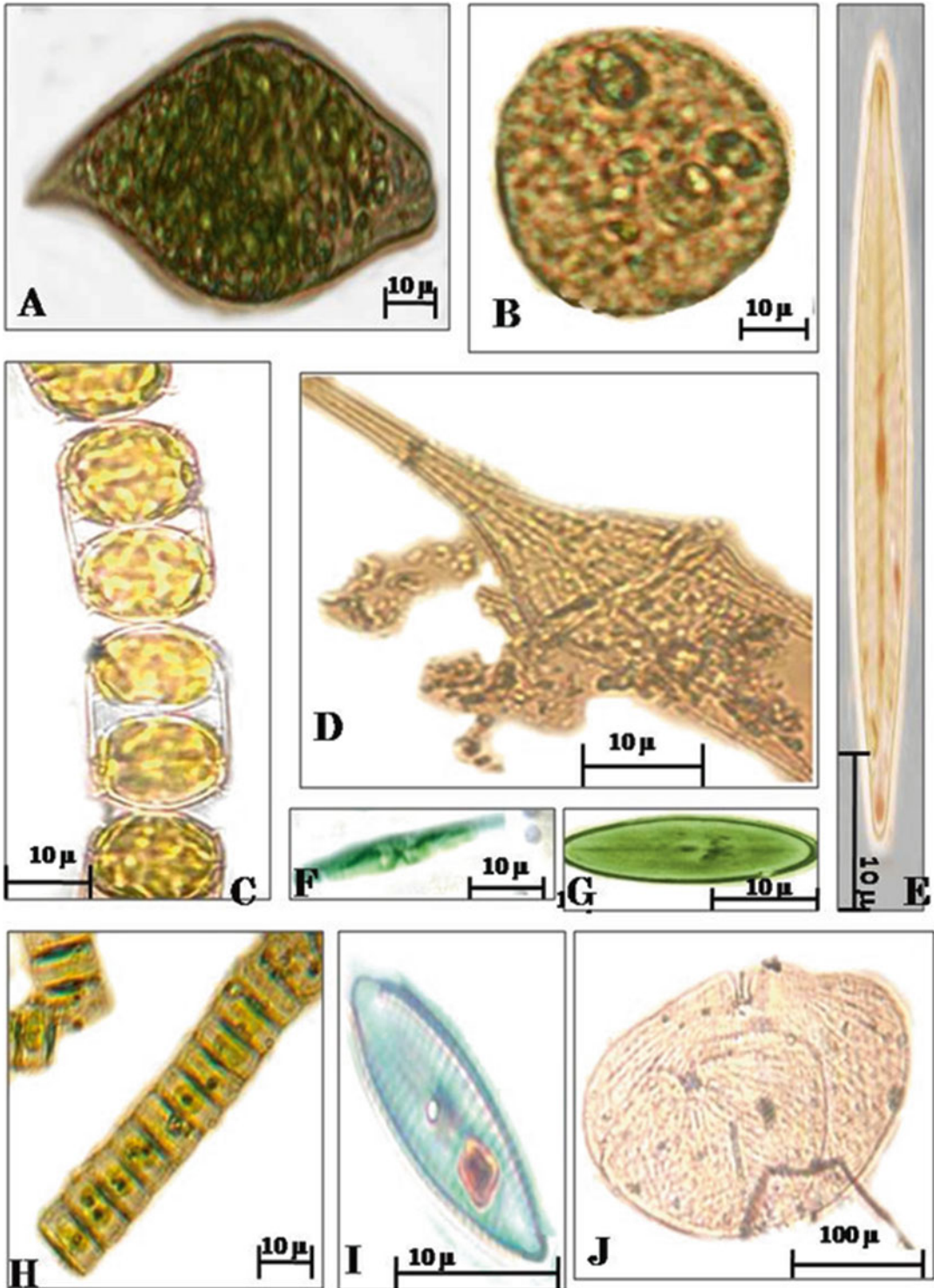[Schulz 1926, p 191, fig. 40]

Plate 5.4 (**A**) *Euglena polymorpha*, (**B**) *Phacus segretii*, (**C**) *Melosira numuloides*, (**D**) *Ceratium hirudinella*, (**E**) *Navicula ignorata*, (**F**) *Fragilaria brevistriata*, (**G**) *Navicula cincta*, (**H**) *Fragilaria oceanica*, (**I**) *Acnanthes hauckiana*, (**J**) *Noctiluca scintillans*

Valves elliptic lanceolate with slightly truncate ends. Raphe thin, thread-like, axial area narrow, central areas somewhat broadened. The length is 20.41 μ and breadth 6.806 μ. Number of striae 20 in 10 μ

Suborder – Biraphidineae

Family – Naviculaceae

Subfamily – Naviculoideae

Navicula cincta (Ehr.) Kutz., var. Heufleri Grun. (Plate 5.4, Fig. G)

[G. Venkataraman 1939, p. 326, Fig 89]

Valves linear lanceolate with obtuse ends. Axial area narrow. Central area small broadened. Striations at the end convergent, 26.56 μ long and 5.81 μ broad, number of striations 10 in 10 μ

Navicula ignorata Krasske (Plate 5.4, Fig. E)

[Hustedt, 1952, p. 442, fig. 819; Foged 1979, p. 87, pl. XLIII, fig. 5]

Valves linear–lanceolate, with somewhat bent ends. The length is 57.44 μ and the breadth is 3.59 μ

Class – Coscinodiscophyceae

Order – Melosirales

Family – Melosiraceae

Melosira nummuloides var. *lesdiana* Pantocsek (Plate 5.4, Fig. C)

[Agardh, 1827, p. 307, fig -312.]

Cells cylindrical to subspherical, forming chains. Valve face flat or domed, covered with small spines or granules; a more or less well-developed corona

Division – Dinophyta

Class – Dinophyceae

Order – Noctilucales

Family – Noctilucaceae

Noctiluca scintillans (Macartney) (Plate 5.4, Fig. J)

Large, round to kidney-shaped cells, with a striated tentacle, one flagellum and a eukaryotic nucleus; cytoplasm may contain photosynthetic symbionts and gametes are gymnodinoid, phagotrophic with food vacuoles containing prey; chloroplasts absent; cells are 200–250 μ in diameter

Ceratium hirudinella (O.F. Muell.) Dujardin (Plate 5.4, Fig. D)

[Prescott, 1982, p. 437, pl. 92, figs. 4, 5]

Cells with polygonal plates, epicone usually larger than hypocone; cells are triangular with horns with prominent transverse furrows; cells are 45 μ long and 15 μ broad

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5.4   Case Study III: Phytoplankton Dynamics of Eastern Indian Coast

5.4.1   Study Area

The Bhagirathi–Hugli estuary, situated at the eastern coast of India, is a deltaic offshoot of the River Ganges and lies approximately between 21°31′–23°20′N and 87°45′–88°45′E. It is a tropical coastal estuary and is associated with the Sunderbans Mangrove Biosphere Reserve which is part of world's largest delta, the Ganges–Brahmaputra delta. The estuary is funnel shaped with the breadth and cross-sectional area at the mouth being 25 km and 156,250 m², which decreases to 6 km and 36,799 m² at the head end. Climatic condition is dominated by NE and SW monsoon where the annual rainfall varied between 188 and 245 cm, with 75–85 % of the total annual rainfall occurring in the monsoon months. The pronounced influence of south west monsoon winds resulted in heavy seasonal precipitation which may be as high as 500 mm in a month. This being a tropical coastline showed a prolonged summer (April–May–June) with an average temperature of 35 ± 5 °C and a long monsoon season (July–August–September) with an average temperature of 35 ± 2 °C. Winter (November–December–January) is comparatively mild in this region of the world with the mean temperature of 12 ± 5 °C. Thus, this region shows a progressive increase in temperature from January to May followed by a decline with the onset of southwest monsoon from June onwards and reaches minimum during the end of the year. From the estuarine and coastal area, we selected four main stations for our study which was mainly based on the salinity gradient of each sampling station (Diamond Harbour, Kakdweep, Junput and Digha). The sampling stations were designated as freshwater zone (Diamond Harbour), estuarine zone (Kakdweep) and marine zone (Junput and Digha).

Diamond Harbour (22°8.78′N and 88°9.0′E) is located at a distance of 56 km from Kolkata, the state capital of West Bengal, India (Fig. 5.2). Just upstream of this coastal station, Rupnarayan River merges with the Hugli River which is further joined by the Haldi River at a distance of 20 km downstream. As this coastal station is located at the upstream region of the Bhagirathi–Hugli estuary, accordingly, salinity was relatively low (0–4.5 psu) and reached as low as 0 psu in the monsoon months. Thus, this station was designated as the freshwater station (Fig. 5.2). Our second sampling station Kakdwip (21°53′0″N, 88°11′0″E) is located at a distance of 36 km from Diamond Harbour and was considered as an estuarine location (salinity, 4–17 psu). At this station, the mixing conditions were more prevalent between the freshwater of Bhagirathi–Hugli and marine waters of the Bay of Bengal, which resulted in the mesohaline conditions of this region (Fig. 5.2).

For our marine samples along a relatively high salinity gradient (26–36 psu), two coastal stations were chosen (Junput, 21°43′N, 87°49′E, and Digha, 21°37′N, 87°31′E) from the confluence of the Hugli River and Bay of Bengal and were together designated as the coastal marine region (Fig. 5.2).

5.4.2   Nutrient and Phytoplankton Dynamics of Coastal West Bengal

Phytoplankton population at coastal West Bengal is in a dynamic state and brought about primarily by interplay of several physicochemical and biological factors. Environmental variables and nutrient concentrations fluctuated significantly both on a monthly as well as on a seasonal basis. Such variability in the nutrient status and physicochemical environment of the habitat brought about fluctuations in the phytoplankton population as well as in the biotic indices. Accordingly, the findings have been represented in different sections as follows:

(a) Phytoplankton diversity of the study area
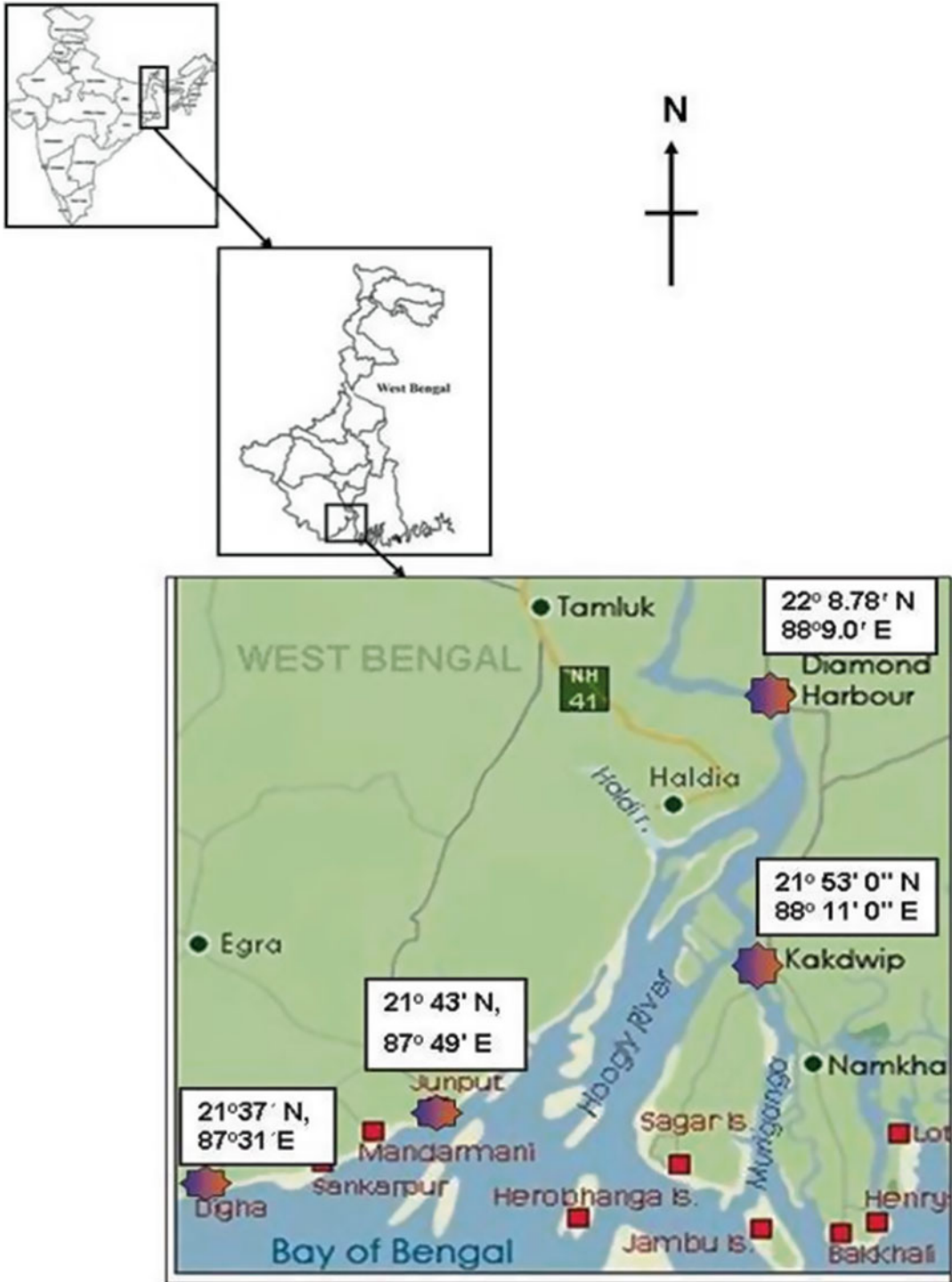(b) Analysis of physicochemical parameters of the study area

Fig. 5.2 Map of the study area at Coastal West Bengal

(c) Phytoplankton population study (cell count) by application of biotic indices

(d) Estimation of Primary productivity (GPP, NPP and CRR) and Oxygen Concentrations (DO and BOD)

(e) Implementation of Multivariate Procedures for community pattern analysis of the study area

5.4.2.1 Phytoplankton Diversity of the Study Area

The phytoplankton population of the study area was represented by 75 taxa belonging to three different algal divisions like Cyanobacteria, Chlorophyta and Bacillariophyta. Among the taxa recorded, 8 species were from Cyanobacteria, 17 species belonged to Chlorophyta and 51 species from Bacillariophyta (Table 5.2). As evident, diatoms

Table 5.2 List of phytoplankton genera recorded from the entire study area (viz. freshwater station, estuarine station and coastal marine region)

S. No.	Name of taxa
1.	*Gloeocaspapunctata*
2.	*Microcystis aeruginosa*
3.	*Merismopedia glauca*
4.	*Merismopedia minima*
5.	*Merismopedia punctata*
6.	*Gloeothece rupestris*
7.	*Spirulina meneghiniana*
8.	*Spirulina platensis*
	Chlorophyta
9.	*Pediastrum duplex* var. *rotundatum*
10.	*Pediastrum simplex*
11.	*Pediastrum simplex* var. *duodenarium*
12.	*Pediastrum tetras*
13.	*Ankistrodesmus falcatus*
14.	*Ankistrodesmus falcatus* var. *stipitatus*
15.	*Dictyosphaerium pulchellum*
16.	*Shroederia judayi*
17.	*Kirchneriella lunaris*
18.	*Scenedesmus bijuga*
19.	*Scenedesmus dimorphus*
20.	*Scenedesmus quadricauda*
21.	*Crucigenia rectangularis*
22.	*Crucigenia tetrapedia*
23.	*Tetrastrum staurogeniaeforme*
24.	*Rhizoclonium riparium*
	Bacillariophyta
25.	*Aulacoseira granulata* var. *angustissima*
26.	*Skeletonema costatum*

(continued)

Table 5.2 (continued)

S. No.	Name of taxa
27.	*Thalassiosira decipiens*
28.	*Cyclotella meneghiniana*
29.	*Cyclotella striata*
30.	*Coscinodiscus granii*
31.	*Coscinodiscus excentricus*
32.	*Coscinodiscus excentricus* var. *fasciculata*
33.	*Actinocyclus normanii* f. *subsala*
34.	*Leptocylindrus danicus*
35.	*Bacteriastrum delicatulum*
36.	*Bacteriastrum varians*
37.	*Chaetoceros curvisetus*
38.	*Chaetoceros diversus*
39.	*Chaetoceros messanensis*
40.	*Chaetoceros wighami*
41.	*Eucapmia zoodiacus*
42.	*Ditylum brightwellii*
43.	*Biddulphia alternans*
44.	*Odontella aurita*
45.	*Biddulphia dubia*
46.	*Biddulphia heteroceros*
47.	*Biddulphia mobiliensis*
48.	*Odontella rhombus*
49.	*Thalassionema nitzschoides*
50.	*Thalassiothrix frauenfeldii*
51.	*Asterionella japonica*
52.	*Cocconeis dirupta*
53.	*Gyrosigma beaufortianum*
54.	*Gyrosigma acuminatum*
55.	*Gyrosigma obtusatum*
56.	*Pleurosigma normanii*
57.	*Pleurosigma salinarum*
58.	*Diploneis weissflogii*
59.	*Diploneis interrupta*
60.	*Navicula minima* Grunow
61.	*Navicula mutica* fo. *cohni*
62.	*Navicula peregrina*
63.	*Navicula quadripartita*
64.	*Amphiprora gigantea*
65.	*Cymbella naviculiformis*
66.	*Bacillaria paradoxa*
67.	*Nitzschia amphibia*
68.	*Nitzschia bilobata* var. *minor*
69.	*Nitzschia ignorata*
70.	*Nitzschia obtusa*
71.	*Nitzschia punctata*
72.	*Nitzschia sigmoidea*
73.	*Nitzschia delicatissima*
74.	*Nitzschia pacifica*
75.	*Surirella fastuosa* var. *recedens*

accounted for the bulk of the phytoplankton population which represented about 69 % of the total population. Although diatom taxa were recorded from all the three sampling areas of freshwater zone, estuarine zone and marine zone, cyanobacterial population was restricted to the freshwater zone, i.e. Diamond Harbour only. On the other hand, green algal genera were recorded from the freshwater and estuarine locations, but none were recorded from the marine coastal region. Among the different members of Bacillariophyta, centric diatoms were more abundant at the estuarine to marine region, whereas pennate diatoms were recorded from freshwater to estuarine region. On an individual site basis, the phytoplankton population at Diamond Harbour was most diverse, in comparison to other two zones, and was repre-

sented by 54 taxa. The population at marine coastal region (Digha and Junput) was represented by 41 diatom genera only. The population at the estuarine location (Kakdweep) was least diverse as it was represented by 25 algal taxa altogether. Each site exhibited distinct seasonal phytoplankton assemblages which varied spatiotemporally in response to different environmental conditions.

The phytoplankton population at freshwater zone (Diamond Harbour) was represented by 54 phytoplankton taxa of which 8 species were blue green, 16 taxa were green algae and 30 genera were of diatoms (Table 5.3). The phytoplankton population showed distinct patterns where green algal population was mostly observed during the warmer summer and monsoon months whereas diatoms were more available in the cooler months of

Table 5.3 Floristic list of phytoplankton genera recorded during the study period from the freshwater station (Diamond Harbour)

Division	Name of genera	Period of availability	Abundance
Cyanobacteria	*Merismopedia minima* (MM)	July to Nov	+
	Merismopedia punctata (MP)	August to Nov	+
	Merismopedia glauca (MG)	June, July	+
	Spirulina platensis (SP)	Apr to Sept	+
	Spirulina meneghiniana (SM)	July, Aug	+
	Gloeocapsa punctata (Glcsp)	Apr to July	+
	Gloeothece rupestris (Glthc)	July	+
	Microcystis aeruginosa (MAero)	Oct to Dec	+ +
Chlorophyta	*Ankistrodesmus falcatus* (AF)	Apr to Sept	+
	Ankistrodesmus falcatus var. *stipitatus*	Apr to June	+
	Kirchneriella lunaris (KL)	Apr to Nov	+
	Shroederia judayi (SJ)	Mar to Aug	+
	Crucigenia rectangularis (CR)	May, June	+ +
	Crucigenia tetrapedia (CT)	May, June	+
	Crucigenia quadrata (CQ)	Rare	+
	Scenedesmus quadricauda (SQ)	Mar to June	+ +
	Scenedesmus bijuga (Sbi)	Mar to June	+ +
	Scenedesmus dimorphus (Sdi)	Mar to June	+
	Pediastrum simplex	June, July	+ +
	Pediastrum tetras (Ptet)	Mar to June	+
	Pediastrum duplex var. *Rotundatum* (Pdro)	Mar to June	+ +
	Pediastrum simplex var. *duodenarium* (Psduo)	Mar to June	+
	Dictyosphaerium pulchellum (Dictyo)	Mar, Apr	+ +
	Rhizoclonium riparium (RR)	Mar to Sept (irregular)	+

(continued)

Table 5.3   (continued)

Division	Name of genera	Period of availability	Abundance
Bacillariophyta	*Odontella aurita* (OAu)	Nov to Feb	+
	Biddulphia dubia (Bdu)	Nov to Feb	+
	Gyrosigma obtusatum (GOb)	irregular	+
	Gyrosigma acuminatum (GAcu)	Aug to Oct	+ +
	Gyrosigma beaufortianum (Gbeau)	Oct to Apr	+
	Pleurosigma salinarum (Psal)	Oct to Mar	+ +
	Cyclotella meneghiniana (CM)	Sept to Oct	+ +
	Cyclotella striata (CS)	Mar and Sept	+
	Coscinodiscus excentricus (CE)	Mar and Sept	+ +
	Actinocyclus normanii f. *subsala* (AN)	Oct to Apr	+
	Stephanodiscus hantzschii (SH)	Nov to Feb	+
	Ditylum brightwellii (DB)	Mar, Apr	+
	Bacteriastrum varians (BV)	Sept, Oct	+
	Bacteriastrum delicatulum (Bdeli)	Aug to Oct	+
	Aulacoseira granulata (Aug)	Aug to Oct	+
	Thalasiothrix frauenfeldii (TF)	Nov to Feb	+ +
	Thalassionema nitzschioides (TN)	Nov to Mar	+ +
	Bacillaria paxillifer (Bpax)	Nov to Feb	+
	Amphiprora gigantea (AG)	Nov to Jan	+
	Leptocylindrus danicus (LD)	Feb to Sept	+ + +
	Cymbella naviculiformis (CN)	Nov to Feb	+
	Navicula peregrina (Nper)	Feb to June	+
	Navicula quadripartita (Nquad)	Oct to Mar	+
	Nitzschia ignorata (Nig)	Nov, Dec	+
	Nitzschia amphibia (Namp)	Rare	+
	Nitzschia obtusa (Nob)	Oct to Dec	+
	Nitzschia punctata (Npu)	Nov to Feb	+ +
	Nitzschia delicatissima (Ndeli)	Nov to Feb	+ +
	Navicula minima (Nmi)	Oct to Feb	+ +
	Navicula mutica (Nmu)	Rare	+ +

$+ = \leq 1 \times 10^4$ cells/L
$+ + = \geq 1 \times 10^4$ to $\leq 5 \times 10^4$ cells/L
$+ + + = \geq 5 \times 10^4$ to $\leq 1 \times 10^5$ cells/L
$+ + + + = \geq 1 \times 10^5$ to 20×10^5 cells/L

post-monsoon and winter. Appearance and abundance of cyanobacterial population was restricted mainly to the monsoon and post-monsoon periods. The most dominant taxon recorded during the entire sampling period was *Leptocylindrus danicus* (Table 5.4). Other abundant phytoplankton genera were *Thalassiothrix frauenfeldii*, *Thalassionema nitzschoides*, *Pediastrum tetras*, *P. duplex* var. *rotundatum*, *P. simplex* var. *duodenarium* and *Scenedesmus* spp. In an analysis of the seasonality of phytoplankton species composition throughout the study period, following trends were noted in the freshwater zone.

Table 5.4   Showing percentage abundance of dominant phytoplankton genera at the freshwater zone (Diamond Harbour)

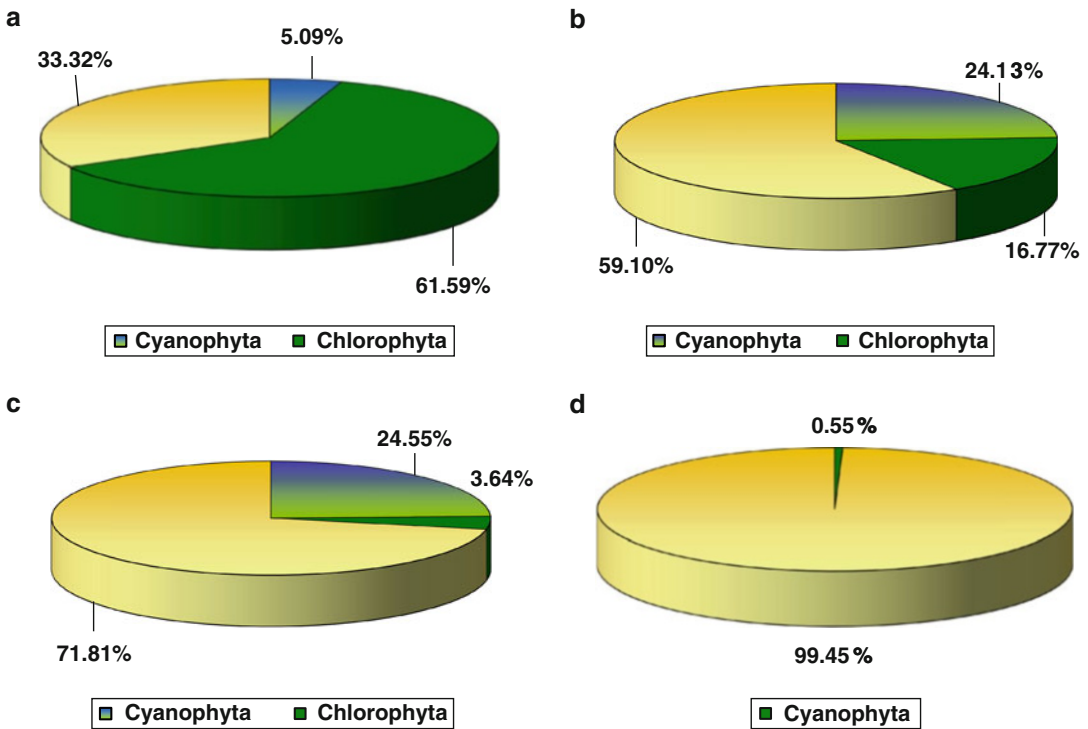| Season	Dominant species	Maximum contribution to total population (%)
Summer	*Leptocylindrus danicus*	9.53
Monsoon	*Leptocylindrus danicus*	18.54
Post-monsoon	*Microcystis aeruginosa*	21
Winter	*Nitzschia delicatissima*	10.07

Fig. 5.3 Percentage seasonal contributions of different algal divisions to the total phytoplankton population: (**a**) summer, (**b**) monsoon, (**c**) post-monsoon and (**d**) winter at the freshwater station (Diamond harbour)

In summer, green algal population was high and made up to 61.59 % of the total phytoplankton population whereas diatom and blue-green algae accounted for 33.32 % and 5.09 % of the population, respectively (Fig. 5.3a). Interestingly, it was observed that the most abundant taxon was the diatom genus *Leptocylindrus danicus* that made up 9.53 % of total population, followed by green algal genera like *Pediastrum duplex* var. *rotundatum, Ankistrodesmus falcatus* and *Pediastrum simplex* var. *duodenarium* contributing to 8.94 %, 8.82 %, and 7.32 % of the total phytoplankton population, respectively.

In monsoon period, dominance of diatoms persisted (59.1 % of the total population), although there was a rise in cyanobacterial population (24.13 % of total population) together with green algae, contributing to 16.77 % of the total population (Fig. 5.3b). On a generic level, dominance of the diatom genus *Leptocylindrus danicus* persisted contributing to 18.54 % of the total population. Among the green algal genera, the most abundant taxon was *Kirchneriella lunaris* that made up

10.54 % of the total phytoplankton population. The cyanobacterial population was composed of taxa like *Spirulina* spp., *Merismopedia* spp., *Microcystis aeruginosa*, etc.

In post-monsoon period, as seasonal precipitation reduced, a further shift in phytoplankton species composition was observed (Fig. 5.3c). The green algal availability decreased further and contributed to only 3.64 % of the population. On the other hand, diatom population continued to increase and made up to 71.81 % of the total population in this period. Cyanobacterial population also flourished in this period and *Microcystis aeruginosa* appeared as the most abundant taxon, contributing 24.55 % of the total population. Diatom population was represented by several genera, among which the more abundant taxa were *Thalassionema nitzschoides*, *Pleurosigma salinarum*, *Nitzschia amphibia* and *Gyrosigma obtusatum* each of which made up more than 5 % of the total population.

As winter appeared, almost the entire population was represented by diatoms (99.45 %), rest

Table 5.5 Floristic list of phytoplankton genera recorded during the study period from the estuarine station

Division	Name of genera	Period of availability	Abundance
Chlorophyta	*Kirchneriella lunaris* (KL)	Mar to Sept	+ +
	Ankistrodesmus falcatus (AF)	Mar to Oct	+ +
	Scenedesmus bijuga (Sbi)	Mar to June	+ +
	Scenedesmus dimorphus (Sdi)	Mar to June	+ +
	Scenedesmus quadricauda (Squa)	Apr to May	+
	Crucigenia tetrapedia(CT)	Apr to Sept (irregular)	+
	Rhizoclonium riparium (RR)		+ +
Bacillariophyta	*Thalassiothrix frauenfeldii* (TF)	June to Feb	+ +
	Cyclotella meneghiniana (CM)	May to Nov	+ +
	Cyclotella striata (CS)	May to Nov	+ +
	Ditylum brightwellii (DB)	May to Nov	+ +
	Gyrosigma obtusatum (GOb)	May to Nov	+ +
	Gyrosigma acuminatum (GAcu)	May to Nov	+ +
	Bacteriastrum varians (BV)	Sept to Oct	+
	Bacteriastrum delicatulum (Bdeli)	Aug and Sept	+
	Stephanodiscus hantzschii (SH)	irregular	+
	Thalassionema nitzschoides (TN)	Oct to Apr	+
	Aulacoseira granulata (AuG)	Oct to Apr	+
	Pleurosigma salinarum (PS)	Oct to Apr	+
	Amphiprora gigantea (AG)	Oct to Mar	+
	Coscinodiscus excentricus (CEx)	Oct to Mar	+
	Nitzschia delicatissima (Ndeli)	Oct to Apr	+
	Odontella aurita (Oau)	Nov to Mar	+
	Biddulphia dubia (Bdu)	Nov to Mar	+

$+ = \leq 1 \times 10^4$ cells/L

$+ + = \geq 1 \times 10^4$ to $\leq 5 \times 10^4$ cells/L

$+ + + = \geq 5 \times 10^4$ to $\leq 1 \times 10^5$ cells/L

$+ + + + = \geq 1 \times 10^5$ to 20×10^5 cells/L

were green algae without any blue green algal members (Fig. 5.3d). Total phytoplankton cell count was significantly higher in this period as compared to other seasons. This was due to increase in cell count of individual taxa. The most abundant taxon was *Nitzschia delicatissima* that contributed to 10.07 % of the population (Table 5.4). Pennate diatom availability tended to be higher and was represented by taxa like *Thalassionema nitzschoides*, *Pleurosigma salinarum*, *Bacillaria paxillifer* (syn. *Nitzschia paradoxa*, www.itis.gov) *Thalassiothrix frauenfeldii*, etc. Each of the taxon accounted for more than 5 % of the population. Centric diatom taxa like *Biddulphia dubia* and *Coscinodiscus excentricus* also made significant contributions to the phytoplankton population.

At Kakdweep, the estuarine coastal station, minimum phytoplankton diversity was recorded

as compared to other sampling stations. The population was represented by green algae and diatoms only with no record of cyanobacterial taxa. The phytoplankton population at the estuarine zone was represented by 25 taxa, out of which 8 species were green algae and 17 genera were diatoms (Table 5.5). Here also, a distinct pattern of phytoplankton population was recorded, where green algae flourished mainly in the summer and monsoon months, but diatoms were more abundant in the post-monsoon and winter periods. Here, unlike other stations, a single genus could not be ascertained as most abundant taxon.

In summer, green algal population was dominant, contributing to 69.46 % of the total phytoplankton population along with diatoms that accounted for 30.54 % of the population (Fig. 5.4a).
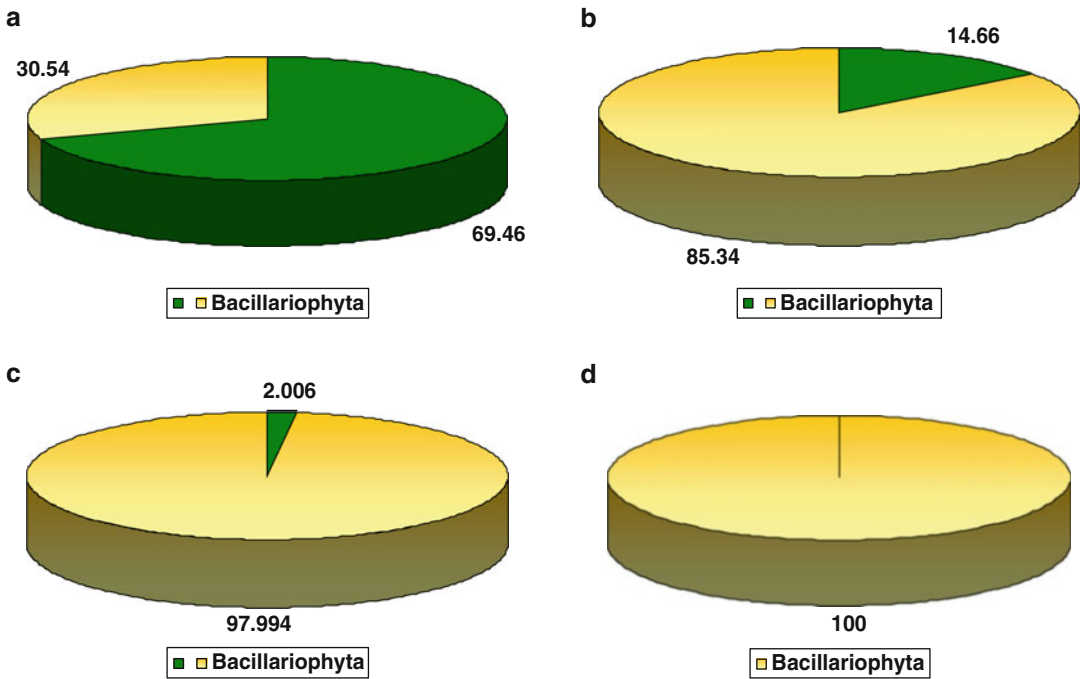
Fig. 5.4 Percentage seasonal contributions of different algal groups to the total phytoplankton population: (**a**) summer, (**b**) monsoon, (**c**) post-monsoon and (**d**) winter at the estuarine station (Kakdweep)

The most abundant taxon was *Kirchneriella lunaris* that made up to 13.81 % of total population. Other dominant taxa were *Scenedesmus brevicauda* and *S. dimorphus* that contributed to 12.53 % and 11.43 % of the population, respectively (Table 5.6).

In monsoon, a shift in phytoplankton species composition was recorded with a drop in green algal population (14.66 %) and a rise in diatom population (85.34 %) (Fig. 5.4b). On a generic level, the most abundant taxon was *Thalassiothrix frauenfeldii* with a contribution of 13.73 % to the total population (Table 5.6). Other major genera that flourished in this period were *Ditylum bright-wellii* and *Stephanodiscus hantzschoides*, each of which accounted for more than 10 % of the population. Green algal population was represented by genera like *Rhizoclonium riparium*, *Kirchneriella lunaris*, *Ankistrodesmus falcatus* and *Crucigenia tetrapedia* although their total counts were much lower as compared to diatoms.

In the post-monsoon period, as seasonal precipitation reduced, phytoplankton species composition changed. The green algal availability decreased further and contributed to only 2.006 %

Table 5.6 Showing percentage abundance of dominant phytoplankton genera at the estuarine zone (Kakdweep)

Season	Dominant species	Maximum contribution to total population
Summer	*Kirchneriella lunaris*	13.81
Monsoon	*Thalassiothrix frauenfeldii*	13.73
Post-monsoon	*Thalassionema nitzschoides*	15.54
Winter	*Thalassionema nitzschoides*	20.49

of the total phytoplankton population. On the other hand, diatom population continued to increase and made up to 98 % of the total population in this period (Fig. 5.4c). Diatom population was represented by several genera, among which the most abundant taxa was *Thalassionema nitzschoides* contributing more than 15 % of the total population. The other dominant genera were *Paralia sulcata*, *Nitzschia delicatissima*, *Aulacoseira granulata* and *Thalassiothrix frauenfeldii*.

As winter appeared, almost the entire population was represented by diatoms (Fig. 5.4d). Total

cell count was significantly higher in this period as compared to other seasons with an increase in cell count of individual taxa. The most abundant taxon was *Thalassionema nitzschoides* that contributed to 20.49 % of the population. Centric diatom abundance tended to be higher as compared to pennate taxa, represented by genera like *Aulacoseira granulata*, *Pleurosigma salinarum*, *Coscinodiscus excentricus* and *Biddulphia dubia*. Each genus accounted for more than 5 % of the population. Pennate diatom taxa like *Thalassiothrix frauenfeldii*, *Nitzschia delicatissima* and *Amphiprora gigantea* also made significant contributions to the phytoplankton population (Table 5.6).

At the coastal marine region, the phytoplankton population was represented by 41 taxa belonging to 26 genera. The phytoplankton flora was represented mainly by diatoms. Only two genera of Dinophyta, namely, *Dinophysis* and *Gymnodinium*, were recorded during the study period (Table 5.7). A few genera like *Bacillaria paxillifer*, *Nitzschia pacifica*, *Amphiprora gigantea*, *Biddulphia heteroceros*, *Aulacoseira granulata*, *Coscinodiscus granii*, *Surirella fastuosa*, *Chaetoceros curvisetus,* *Eucampia zoodiacus* and *Aulacodiscus johnsonii* occurred rarely in the study area. From the present study a distinct seasonal trend in phytoplankton population of this coastal station could be elucidated as follows.

In summer, a total of 12 taxa represented the phytoplankton population. Centric diatom genera (82.69 %) were more abundant as compared to pennate genera (17.31 %) (Fig. 5.5a). The most abundant taxa were *Odontella rhombus* and *Asterionella japonica*, with contributions of 24.06 % and 11.59 % to the total population, respectively (Table 5.8). The population of *Odontella rhombus* gradually increased in the summer months with cell count of > 700 cells/mL in June 2005. *Cocconeis dirupta* appeared in the month of May 2005 that accounted for 25 % of the phytoplankton population. Rest of the diatom genera contributed 5–25 % of the total phytoplankton population and appeared seasonally. The sudden appearance of *Skeletonema costatum* with a high cell count was another major taxon recorded in the month of June 2006 that contributed to 50.31 % of the total plankton population.

In monsoon also, the centric diatom population was high as compared to pennate population (Fig. 5.5b). The population of *Odontella rhombus* continued as dominant genus in monsoon months, accounting for 13.48 % of total population. Other relatively abundant taxa were *Odontella mobiliensis* and *Ditylum brightwellii*, each with cell counts of > 100 cells/mL. Members of *Chaetoceros* spp. appeared only during monsoon period at this zone. Taxa like *C. diversus* (7.64 %) and *C. messanensis* (7.73 %) were quite abundant at this time. During this period, there was a steady rise in abundance of centric diatoms which made up to 80.48 % of total count.

During post-monsoon period, population of centric diatoms (62.4 %) began to recede with a rise in pennate population (37.6 %). The most abundant genus was *Biddulphia alternans* contributing to 16.05 % of population (Fig. 5.5c). Other dominant centric members were *Biddulphia dubia* and *Odontella aurita*. Among pennate members, taxa like *Thalassiothrix frauenfeldii*, *Thalassionema nitzschoides, Diploneis weissflogii* and *Diploneis interrupta* were important members of the total phytoplankton population.

As winter approached, there was a significant drop in freshwater input to the coastal marine waters along with a gradual decrease in temperature as well. This further resulted in shifting of species composition of the population. In this period, there was a sharp rise in pennate diatom population primarily due to a high growth rate of the taxon *Asterionella japonica*. Pennate genera contributed for >80 % of total population with *A. japonica* contributing for 77.35 % of the population (Fig. 5.5d). Centric diatom population was represented by several taxa like *Coscinodiscus* spp., *Biddulphia* spp., *Paralia sulcata*, *Ditylum brightwellii*, *Stephanodiscus hantzschii*, etc.

5.4.2.2 Analysis of Physicochemical Parameters of the Study Area

The eastern coast of India is rich in nutrients and light which is sufficient to support phytoplankton population. Therefore, light and nutrients never acted as limiting factors in the study area although the phytoplankton production was hampered due to the silt contents along with other anthropogenic

Table 5.7 Floristic list of phytoplankton genera recorded during the study period from coastal marine region

Division	Name of genera	Period of availability	Abundance
Bacillariophyta	*Asterionella japonica* (AJ)	Almost throughout the year	+ + + +
	Odontella rhombus (OR)	Apr to Oct	+ + +
	Odontella mobilensis (OM)	Mar to Oct	+ +
	Odontella aurita (OAu)	Oct to Mar	+ +
	Biddulphia alternans (Balt)	Aug to Jan	+ +
	Biddulphia dubia (Bdu)	Oct to Mar	+ +
	Biddulphia heteroceros (BH)	Oct, Nov	+
	Gyrosigma obtusatum (GOb)	Mar to July	+
	Gyrosigma acuminatum (GAcu)	Feb to Apr	+
	Pleurosigma normanii (PN)	Dec to Mar	+
	Cyclotella meneghiniana (CM)	Almost throughout the year	+ +
	Coscinodiscus perforatus (CP)	Almost throughout the year	+ +
	Coscinodiscus centralis (CC)	Nov to Apr	+ +
	Coscinodiscus excentricus (CE)	Apr to July	+ +
	Actinocyclus normanii f. *subsala* (AN)	June to Oct	+ +
	Coscinodiscus granii (CG)	Oct, Nov	+
	Nitzschia delicatissima (ND)	Apr to July	+ +
	Nitzschia sigmoidea (NS)	Apr	+
	Cyclotella striata (CS)	May to Sept	+
	Stephanodiscus hantzschoides (SH)	Nov (2006)	+ +
	Thalassiosira decipiens (TD)	Mar (2007)	+
	Cocconeis dirupta	Aug to Mar	Rare
	Ditylum brightwellii (DB)	May (2005)	+ +
	Chaetoceros curvisetus	Almost throughout the year	+ +
	Surirella fastuosa (SF)	June, July (2005)	Rare
	Bacteriastrum varians (BV)	June, Oct	+
	Chaetoceros diversus (CD)	Mar	+
	Diploneis interrupta (DI)	July to Sept	+ +
	Diploneis weissflogii (DW)	July to Nov	+
	Aulacoseira granulata (AuG)	Oct, Nov	+
	Chaetoceros wighami (CW)	July to Nov	+
	Chaetoceros messanensis (ChM)	July to Oct	+
	Thalassiothrix frauenfeldii (TF)	July to Oct	+ +
	Thalassionema nitzschioides (TN)	Aug to Oct	+ +
	Bacillaria paxillifer (BPax)	Aug to Feb	+ +
	Nitzschia pacifica n. sp. (Npac)	Nov to Jan	+ +
	Amphiprora gigantea (AG)	Mar, Oct	+
	Eucampia zoodiacus	Oct, Nov	+
		Oct, Nov	Rare
	Skeletonema costatum	June (2006)	Rare
		March (2006)	Rare
Dinophyta	*Gymnodinium* sp.	May (2005)	
	Dinophysis sp.	May (2005)	

$+ = \leq 1 \times 10^4$ cells/L

$+ + = \geq 1 \times 10^4$ to $\leq 5 \times 10^4$ cells/L

$+ + + = \geq 5 \times 10^4$ to $\leq 1 \times 10^5$ cells/L

$+ + + + = \geq 1 \times 10^5$ to 20×10^5 cells/L

a

17.31%

82.69%

centric pennate

b

19.52%

80.48%

centric pennate

c

37.60%

62.40%

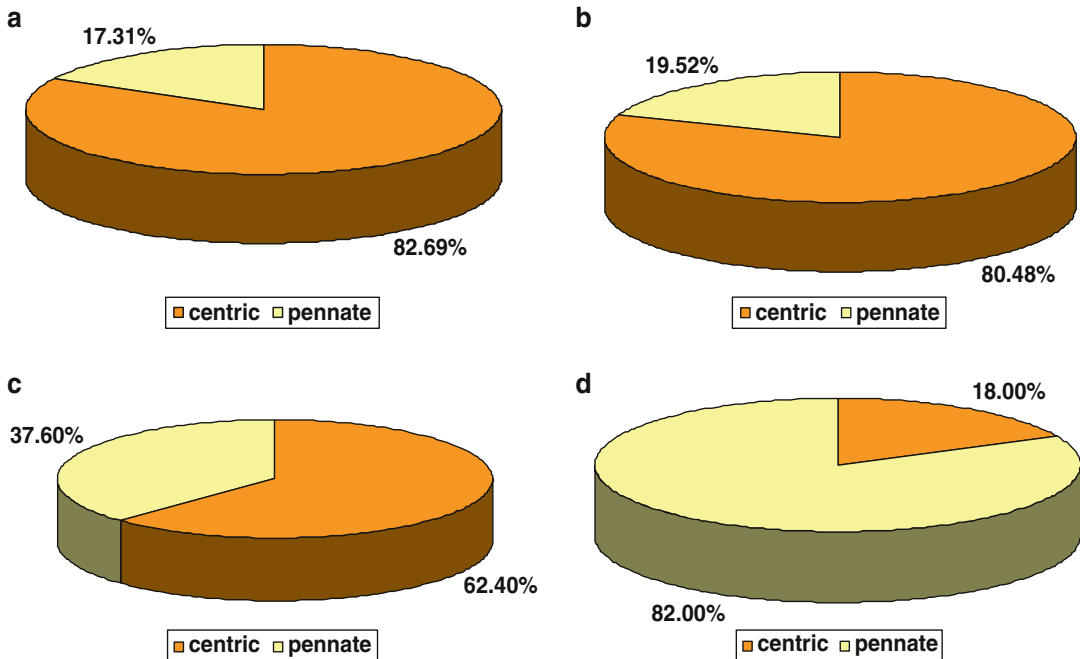centric pennate

d

18.00%

82.00%

centric pennate

Fig. 5.5 Percentage seasonal contributions of centric and pinnate diatoms to the total phytoplankton population: (**a**) summer, (**b**) monsoon, (**c**) post-monsoon and (**d**) winter at the coastal marine region (Junput and Digha)

Table 5.8 Showing percentage abundance of dominant phytoplankton genera at the coastal marine zone (Junput and Digha)

Season	Dominant species	Maximum contribution to total population (%)
Summer	*Skeletonema costatum*	26.63
Monsoon	*Odontella rhombus*	13.48
Post-monsoon	*Biddulphia alternans*	16.05
Winter	*Asterionella japonica*	77.35

factors. Salinity variations were pronounced that varied from 0 to 36 psu. Seasonal precipitation and heavy riverine inflow especially in the monsoon months played an important role in lowering the salinity levels at all stations. This being a tropical coastline, there is a prolonged summer (April–May–June) with an average temperature of 35 ± 5 °C and a long monsoon season (July–August–September) with an average temperature of 35 ± 2 °C. Winter (November–December–January) is comparatively mild with a mean temperature of 12 ± 5 °C. The pH level varied

from 7 to 8.3 in the entire study area. The nutrient content especially with respect to dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP) were comparatively higher in the freshwater station and estuarine station than at the marine region. On the contrary, dissolved silicate (DSi) contents showed an opposite trend with higher values at the marine region in comparison to the other stations.

Results showed that the habitat water of the freshwater station was weakly alkaline with the pH ranging from 7.0 to 8.3 with the mean pH of 7.57 (Fig. 5.6a). During the drier months of summer and winter, the pH was relatively high, ranging from 7.5 to 8.3 showing pH maxima in summer for both 2005 and 2006. As expected, water temperature was also maximum in summer and minimum in winter. Salinity was relatively low with a mean of 2.2 psu which reached as low as 0 psu in monsoon period due to high influx of freshwater from perennial rivers, along with heavy seasonal precipitation (Fig. 5.6c). Maximum salinity at this hypo saline station was recorded in winter, reaching as high as 5 psu in January 2006, when seasonal precipitation as
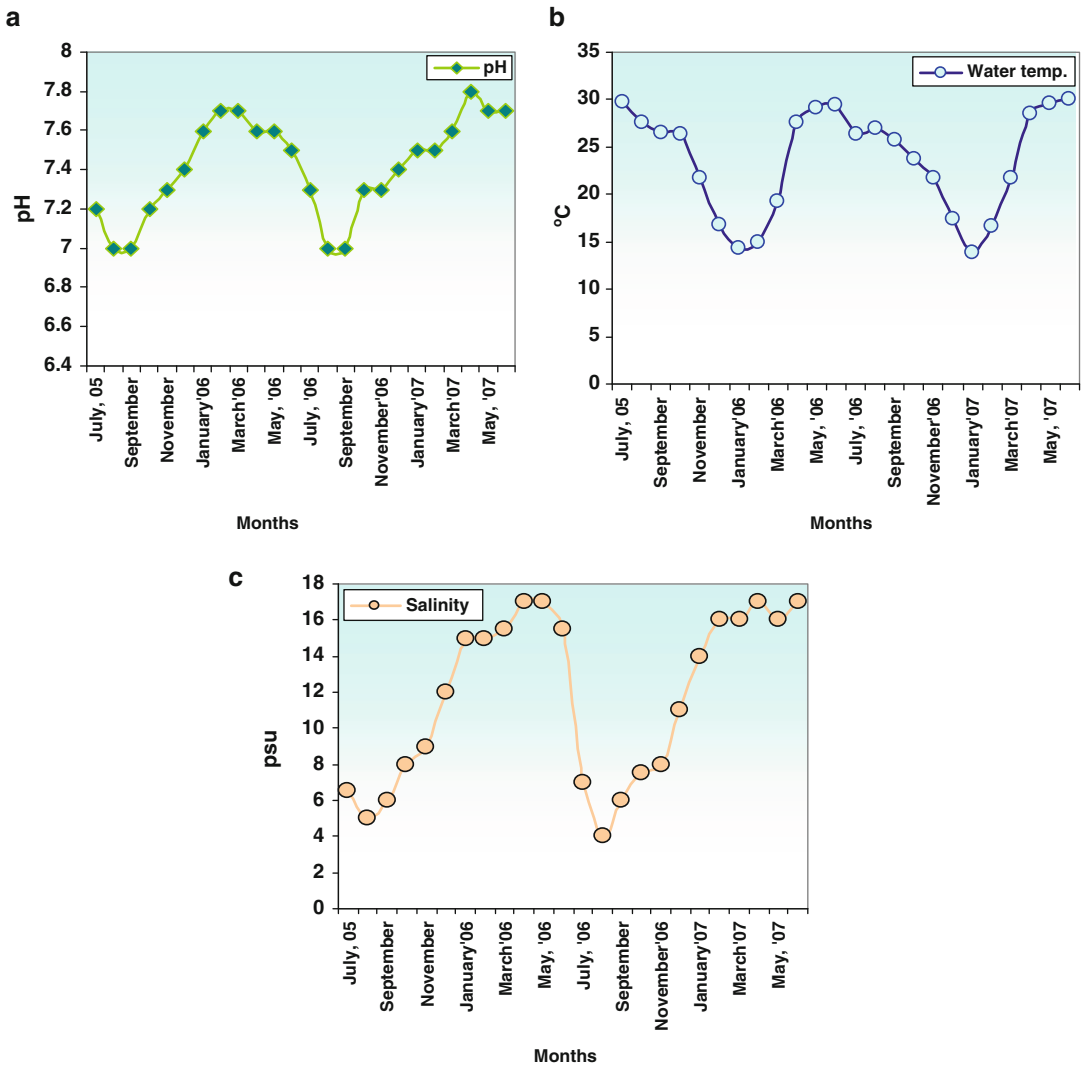
Fig. 5.6 Monthly variations in (**a**) pH, (**b**) water temperature and (**c**) salinity at the freshwater station (Diamond Harbour)

well as riverine inflow of freshwater was minimal. In monsoon, minimum values for both salinity and pH were recorded.

DIN contents of the habitat water were high along the entire study period, which ranged from 50.12 μM (February 2007) to 104.36 μM (September 2006) (Fig. 5.7a). The concentrations of nitrite (1.086–11.263 μM) and ammonia (0.294–4.41 μM) (Fig. 5.7a, b) nitrogen were low in comparison to nitrate (43.66–95.42 μM) nitrogen. Nitrate nitrogen accounted for 85–90 % of DIN (Fig. 5.7a). Dissolved inorganic phosphate

(DIP) content of the habitat water varied from 2.23 to 9.44 μM, showing maximum value in September 2005 (9.44 μM) and minimum in December 2006 (2.23 μM) (Fig. 5.7c). Dissolved silicate (DSi) contents in the habitat waters were comparatively higher – ranging from 42.61 (September 2005) to 90.77 μM (November 2005) (Fig. 5.7d). Seasonally, both DIN and DIP contents of the habitat waters were maximum in monsoon (DIN, 90.22 μM; DIP, 7.45 μM in 2005), intermediate in post-monsoon (DIN, 75.31 μM; DIP, 5.17 μM in 2005) and minimum
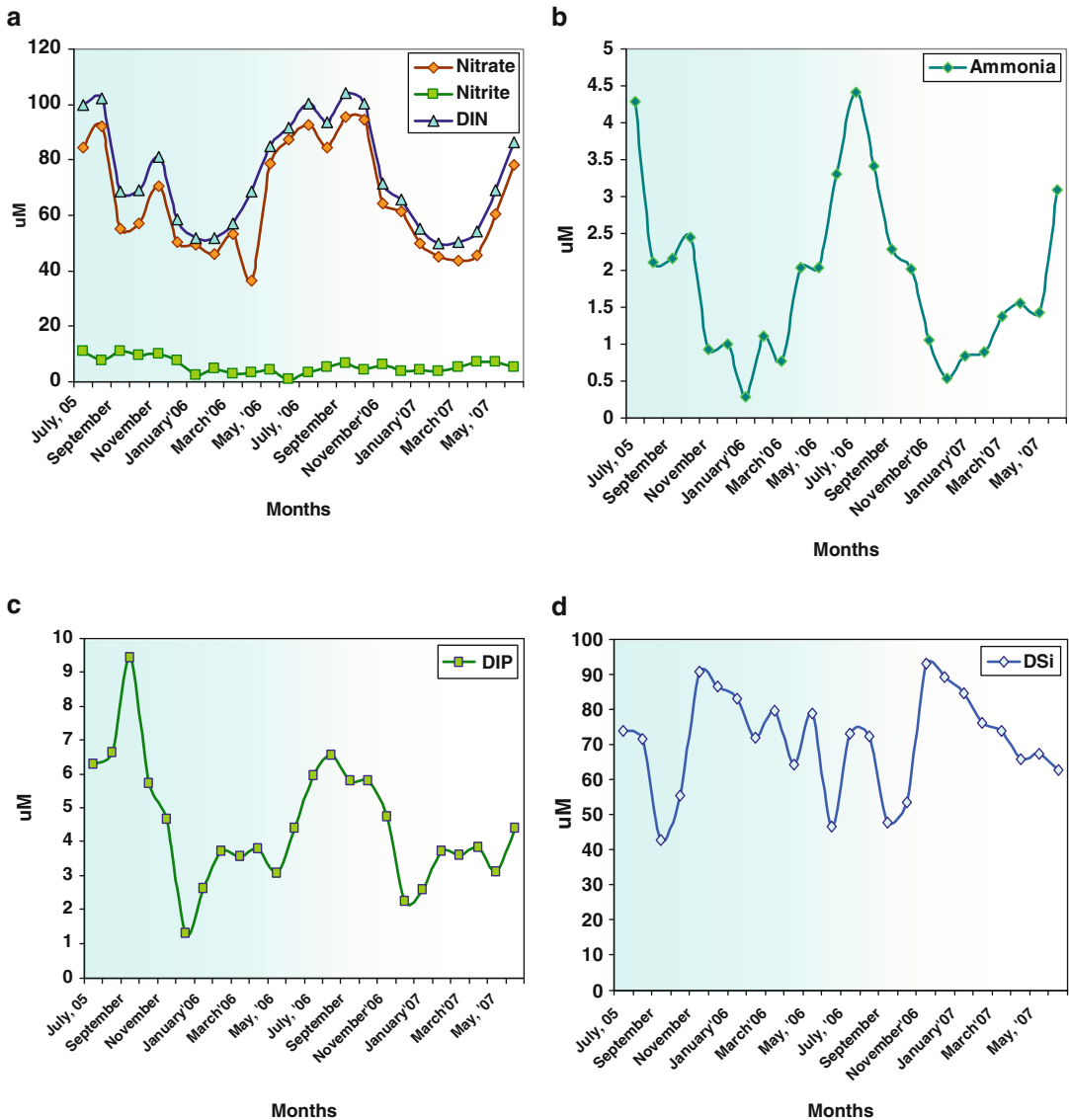
Fig. 5.7 Monthly variations in (**a**) DIN (dissolved inorganic nitrogen), (**b**) ammonia, (**c**) DIP (dissolved inorganic phosphate) and (**d**) DSi (dissolved phosphate) at the freshwater station (Diamond Harbour)

in winter (DIN, 54.24 μM; DIP, 3.21 μM in 2005–2006). This trend persisted for the entire study period with insignificant inter-annual variation. DSi represented an opposite pattern where lower values were recorded in the monsoon months and higher values in winter months.

Significant negative correlation was established between DIN and phytoplankton cell counts ($R^2 = 0.25$, $r = -0.49$ at $p < 0.05$) (Fig. 5.8a). On the other hand, diatom population showed

significant positive correlation with DSi ($R^2 = 0.26$, $r = 0.51$ at $p < 0.05$) (Fig. 5.8b) but negative correlation with seasonal temperature variations ($R^2 = 0.36$, $r = -0.6$ at $p < 0.05$) (Fig. 5.8c).

In the habitat water of the estuarine station (Kakdweep), the pH level ranged from 7 to 7.8 (Fig. 5.9a) and the water temperature from 13.9 °C (January 2007) to 30 °C (June 2007) (Fig. 5.9b). Maximum salinity level was recorded in summer (April and May 2006, April and June
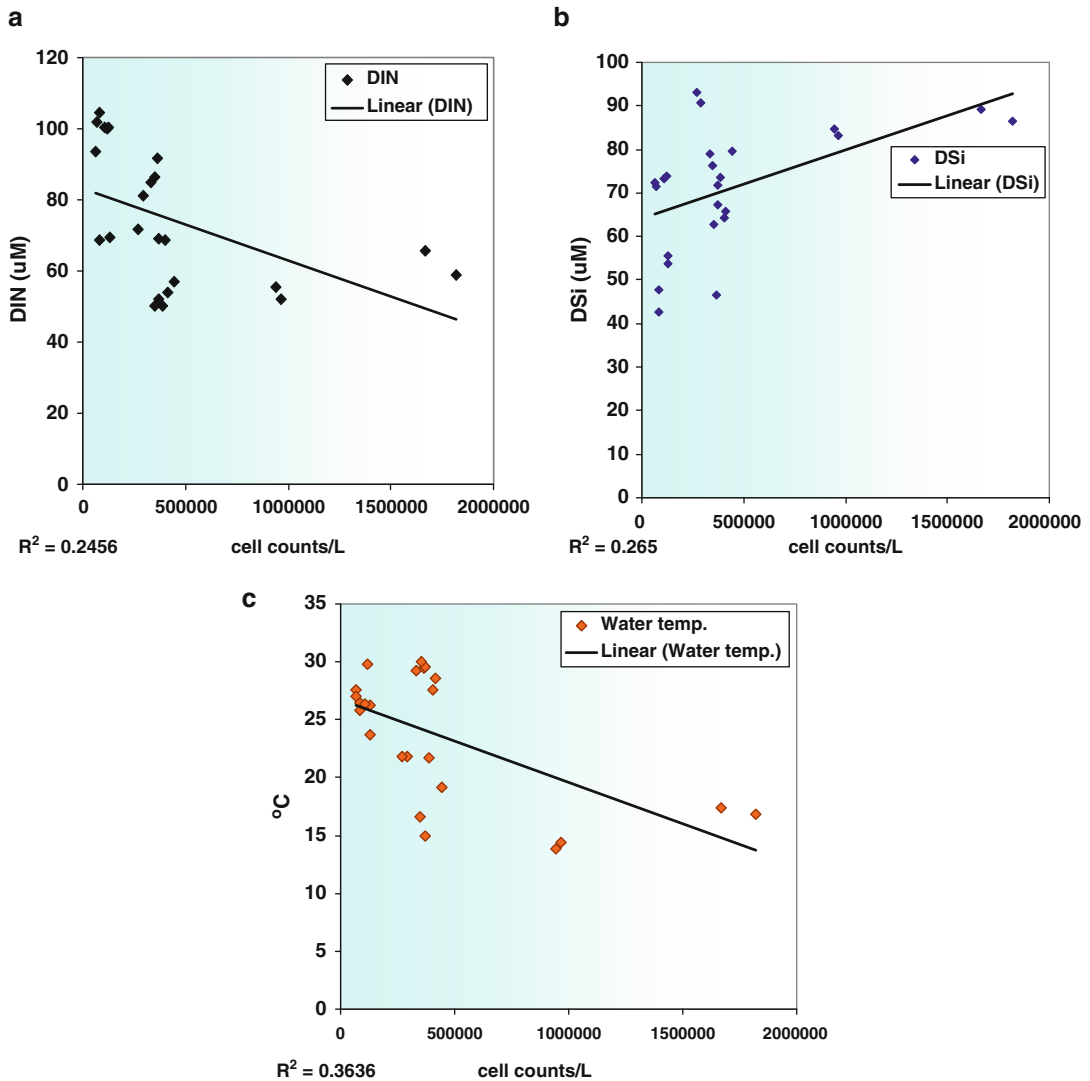
Fig. 5.8 Graphical representation of significant correlation between (**a**) cell count and DIN, (**b**) cell count and DSi and (**c**) cell count and water temperature at the freshwater station (Diamond Harbour)

2007, 17 psu), which dropped in monsoon period (August 2006, 4 psu) (Fig. 5.9c).

DIN (dissolved inorganic nitrogen) contents fluctuated seasonally as well as temporally (Fig. 5.10a). Nitrate content was maximum in August 2006 (87.25 μM) with minimum value in June 2007 (45.32 μM), which suggested that comparatively low levels of nitrate in summer and high amount during monsoon months. Unlike nitrate, ammonia content was significantly lower with the mean concentration being only 0.69 μM

(Fig. 5.10b). Nitrite concentration was intermediate that ranged from 40.22 μM (August 2005) to 14.39 μM (November 2005). Phosphate concentrations did not represent a very regular and recurrent pattern of variation in the data set which ranged from 2.15 to 9.37 μM (Fig. 5.10c). Silicate concentration was quite high in comparison to phosphate levels throughout the year, ranging from 49.93 μM to 129.82 μM with highest value in August 2005 and lowest in December 2006 (Fig. 5.10d). Therefore, in the study area

a

b

c
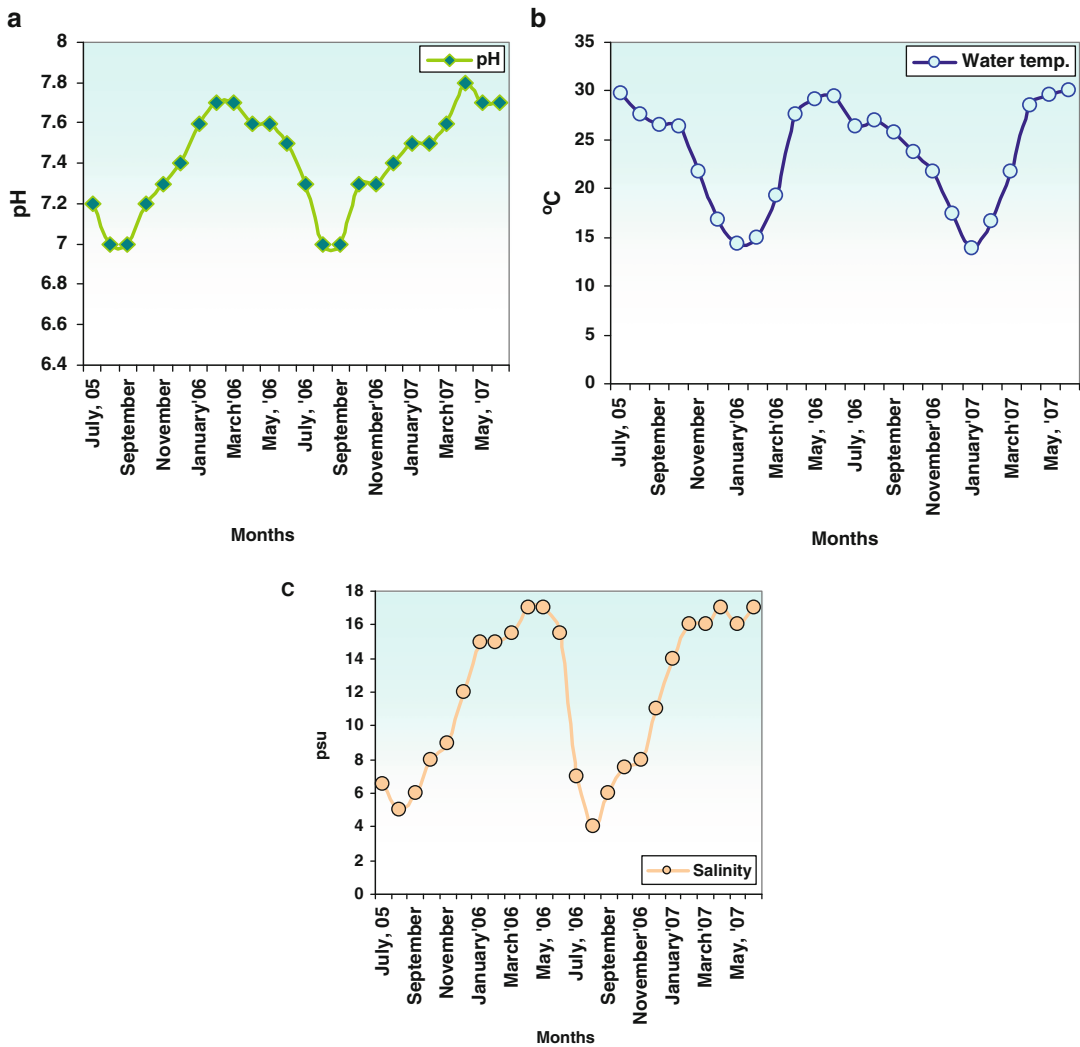
Fig. 5.9 Monthly variations in (**a**) pH, (**b**) water temperature and (**c**) salinity at the estuarine station (Kakdweep)

nutrient concentration was maximum in monsoon period and minimum in the winter and summer months.

Correlation matrix and 2-D scatter plots were performed based on Pearsonian 'r' values which showed that cell count had negative significant correlation with nitrite ($R^2 = 0.27$, $r = -0.52$, $p < 0.05$) (Fig. 5.11a), ammonia ($R^2 = 0.21$, $r = -0.45$, $p < 0.05$) (Fig. 5.11b), DIN ($R^2 = 0.2$, $r = -0.45$, $p < 0.05$) (Fig. 5.12a) and DSi ($R^2 = 0.51$, $r = -0.71$, $p < 0.05$) (Fig. 5.12b) with no significant correlation with nitrate and DIP (Table 5.7). Among the physical parameters significant nega-

tive correlation was established between cell count and temperature only ($R^2 = 0.31$, $r = -0.55$, $p < 0.05$) (Fig. 5.12c).

The marine coastal region showed different physicochemical statuses in comparison to the other two stations. The temperature and pH value of the coastal water of the study area ranged from 15–30 °C to 7–7.6, respectively (Fig. 5.13a, b). Minimum temperature was observed in winter and minimum pH value in monsoon. Maximum salinity level was recorded in winter (36 psu), which dropped in monsoon period (26 psu) (Fig. 5.13c). As evident from Fig. 5.16, DIN con-
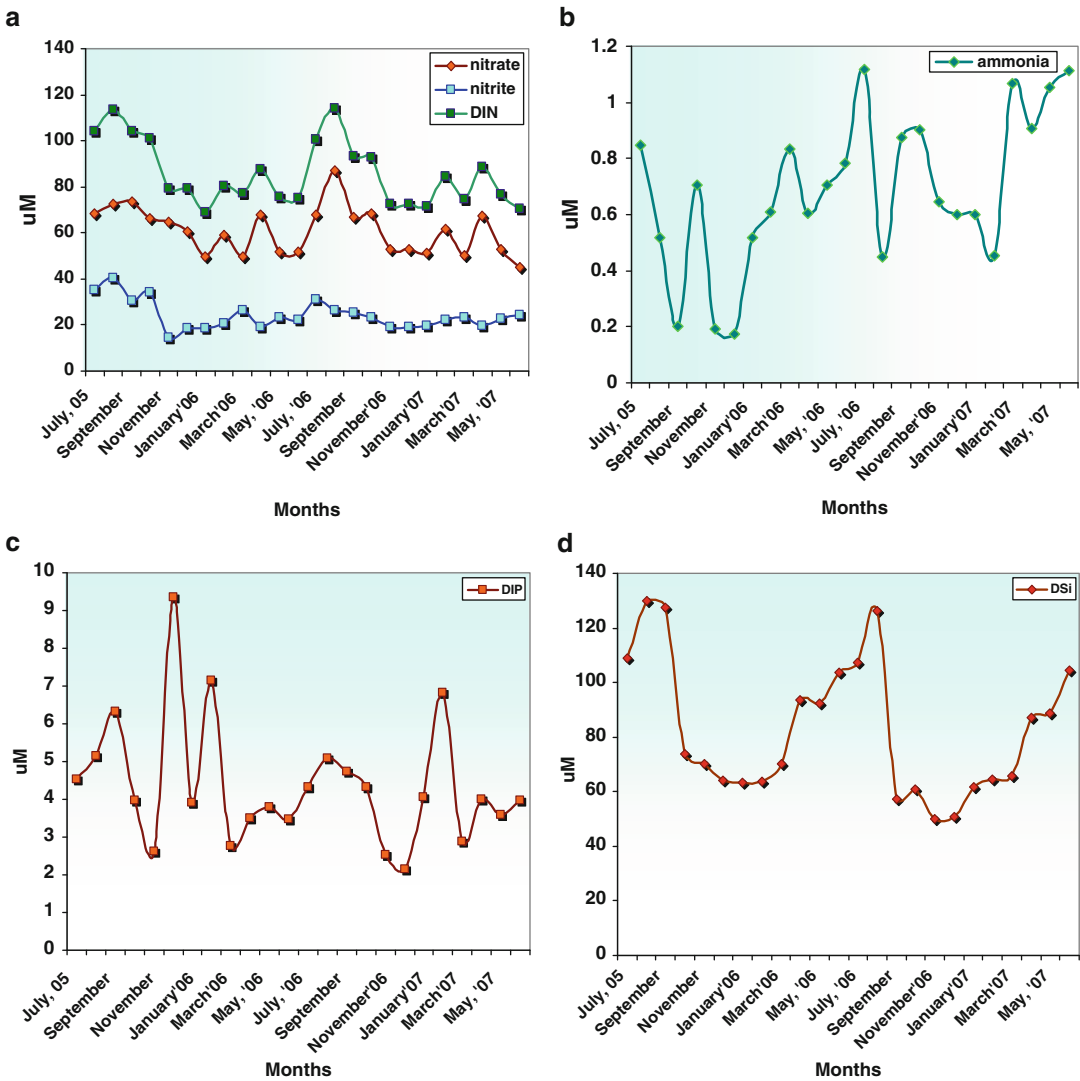
Fig. 5.10 Monthly variations in (**a**) DIN (dissolved inorganic nitrogen), (**b**) ammonia, (**c**) DIP (dissolved inorganic phosphate) and (**d**) DSi (dissolved phosphate) at the estuarine station (Kakdweep)

tent was maximum in October 2006 (28.48 μM) with minimum value in December 2005 (14.32 μM) (Fig. 5.14a). Like the freshwater and estuarine stations, nitrate concentrations were primarily responsible for the variations of DIN contents of the habitat waters. Nitrite concentrations were intermediate which was maximum in September 2005 (3.67 μM) and minimum in March 2007 (1.45 μM). Ammonia concentrations remained low and seldom reached above 1 μM levels in the habitat waters (Fig. 5.14b).

Maximum phosphate concentration was estimated in August 2005 (9.41 μM) and minimum in December 2005 and January 2006 (2.23 μM; Fig. 5.14c). Therefore, in the study area nutrient concentration was maximum in monsoon period. Silicate concentration was quite high in comparison to nitrate and phosphate levels throughout the year, ranging from 19.97 to 127.32 μM with highest value in August 2005 and lowest in January 2006 (Fig. 5.14d) favouring the diatom growth.

a

b
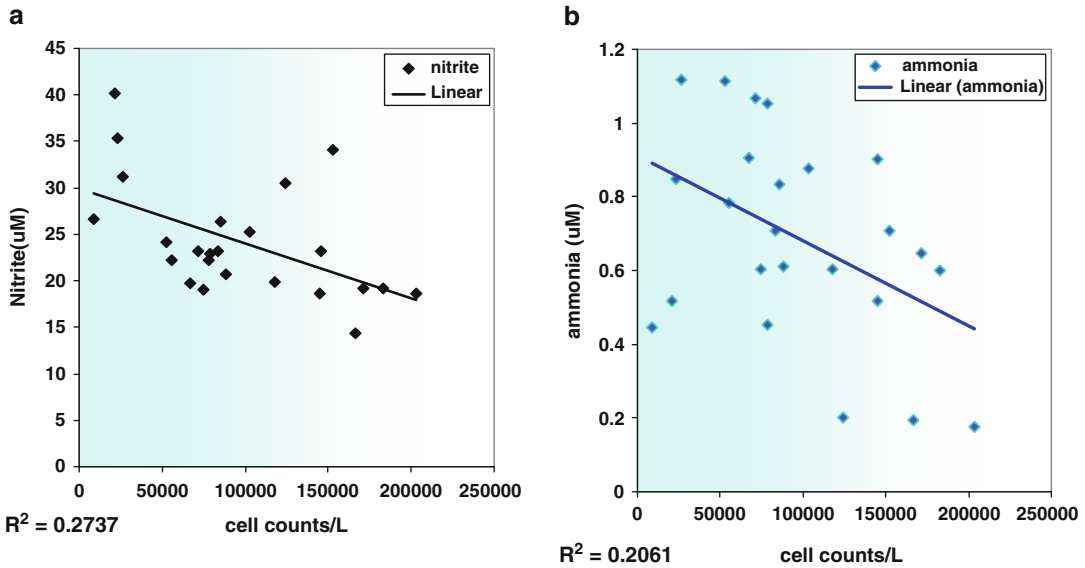
Fig. 5.11 Graphical representation of significant correlation between (**a**) cell count and nitrite and (**b**) cell count and ammonia at the estuarine station (Kakdweep)

Correlation matrix (Table 5.9) and 2-D scatter plots were performed based on Pearsonian r values, which showed that cell count had significant negative correlation with DIN ($R^2 = 0.28$, $r = -0.52$, $p < 0.05$) (Fig. 5.15a) and dissolved silicate ($R^2 = 0.23$, $r = -0.48$, $p < 0.05$) (Fig. 5.15b) and nonsignificant with phosphate and temperature but positive significant correlation with salinity ($R^2 = 0.3$, $r = 0.54$, $p < 0.05$) (Fig. 5.15c) and pH ($R^2 = 0.22$, $r = 0.57$, $p < 0.05$) (Fig. 5.15d) at $n = 24$ (Table 5.8).

5.4.2.3 Phytoplankton Population in Terms of Cell Count and Their Biotic Indices

The findings of our study showed that along coastal West Bengal, a significant variation of phytoplankton population was related to seasonal variations and physicochemical parameters of habitat waters. On an average, among all the sampling stations, the total cell count was maximum at marine coastal zone (mean = 986 cells/mL) and minimum at the estuarine location (mean = 97 cells/mL) while the freshwater zone occupied an intermediate position (mean = 439 cells/mL)

(Fig. 5.16). Seasonal variation with respect to cell count was well evident at all the sampling stations, where winter season was the most productive and monsoon was the least. Gradual decreases in cell count were recorded from the summer to monsoon period whereas gradual increases in cell count from the post-monsoon to the winter period were observed. Cell count of individual species may have played a significant role in determining the diversity of this coastal region. At the freshwater region, total cell counts ranged from 65 cells/mL (August 2006) to 1,820 cells/mL (December 2005). At the estuarine location, it ranged from 9 cells/mL (August 2006) to 203 cells/mL (December 2005). Likewise, cell count ranged from 345 cells/mL (April 2006) to 2,020 cells/mL (January 2006) at the marine coastal region.

Diversity of phytoplankton population at coastal West Bengal showed distinct variations on a monthly as well as on a seasonal basis in terms of different biotic indices. Diversity, measured on the basis of Shannon–Wiener Index (SWI), was maximum at the freshwater station (Mean H′ = 2.67), intermediate at the estuarine station
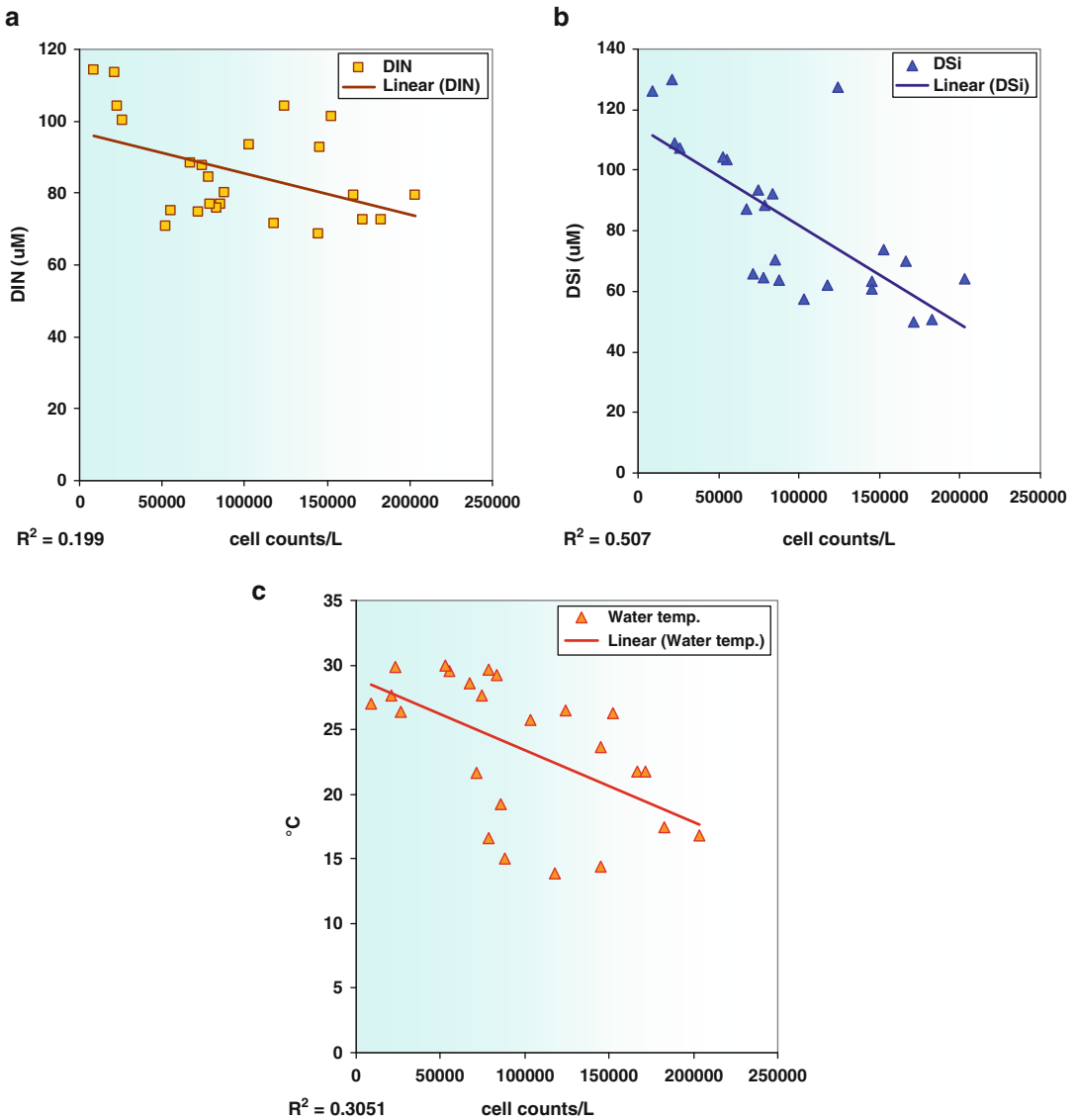
Fig. 5.12 Graphical representation of significant correlation between (**a**) cell count and DIN, (**b**) cell count and DSi and (**c**) cell count and water temperature at the estuarine station (Kakdweep)

(Mean H′ = 2.278) and minimum at the marine region (Mean H′ = 1.90) (Fig. 5.17). Higher values for SWI were recorded in the transition period (March) between winter and summer months at the freshwater station, whereas it was maximum during post-monsoon period at the estuarine and the coastal stations. On the other hand, minimum values for SWI were recorded in winter at marine and estuarine region, whereas it was minimum in monsoon at the freshwater station.

Species evenness is a measure of the contributions of individual taxa to the phytoplankton population. It was found that seasonal variation in species evenness was more pronounced at the marine region as compared to the other stations.

At the freshwater station (Diamond Harbour), SWI varied from 2.13 to 3.23. On a monthly basis, maximum value was recorded in November 2006 (H′ = 3.23) whereas minimum value was in October 2005 (H′ = 2.13) (Fig. 5.18). Maximum
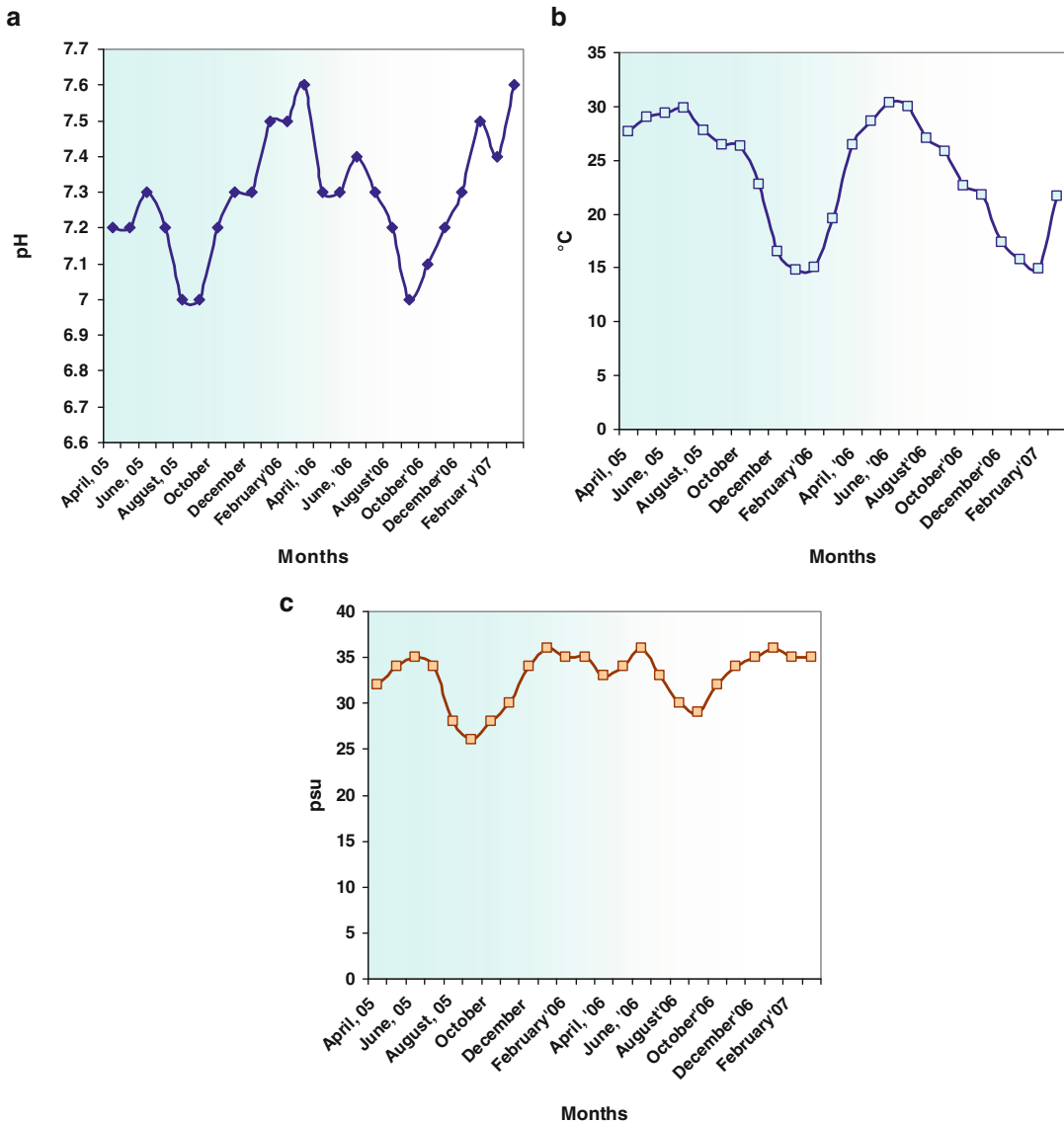
Fig. 5.13 Monthly variations in (**a**) pH, (**b**) water temperature and (**c**) salinity at the coastal marine region (Digha and Junput)

SWI was recorded in the transition period between the summer and winter months (March). The subsequent summer months (April–May–June) also showed a comparatively high SWI values. SWI values were intermediate in the post-monsoon period although there was significant interannual variations. On the contrary, minimum SWI values were obtained in the monsoon months (Fig. 5.19). The mean species evenness (*e*) was relatively high as compared to the other coastal stations (*e*=2.13). Variation in species evenness was not very pronounced in this station although seasonal fluctuations were observed. Seasonally, it was maximum during summer (*e*=2.17) and minimum in winter (*e*=2.09) closely followed by the post-monsoon period (*e*=2.1) (Fig. 5.20).

At the estuarine coastal station (Kakdweep), SWI varied from 1.88 to 2.53. Highest value of SWI was recorded in the post-monsoon period (October–November) whereas lowest value of the same was recorded in winter (December–
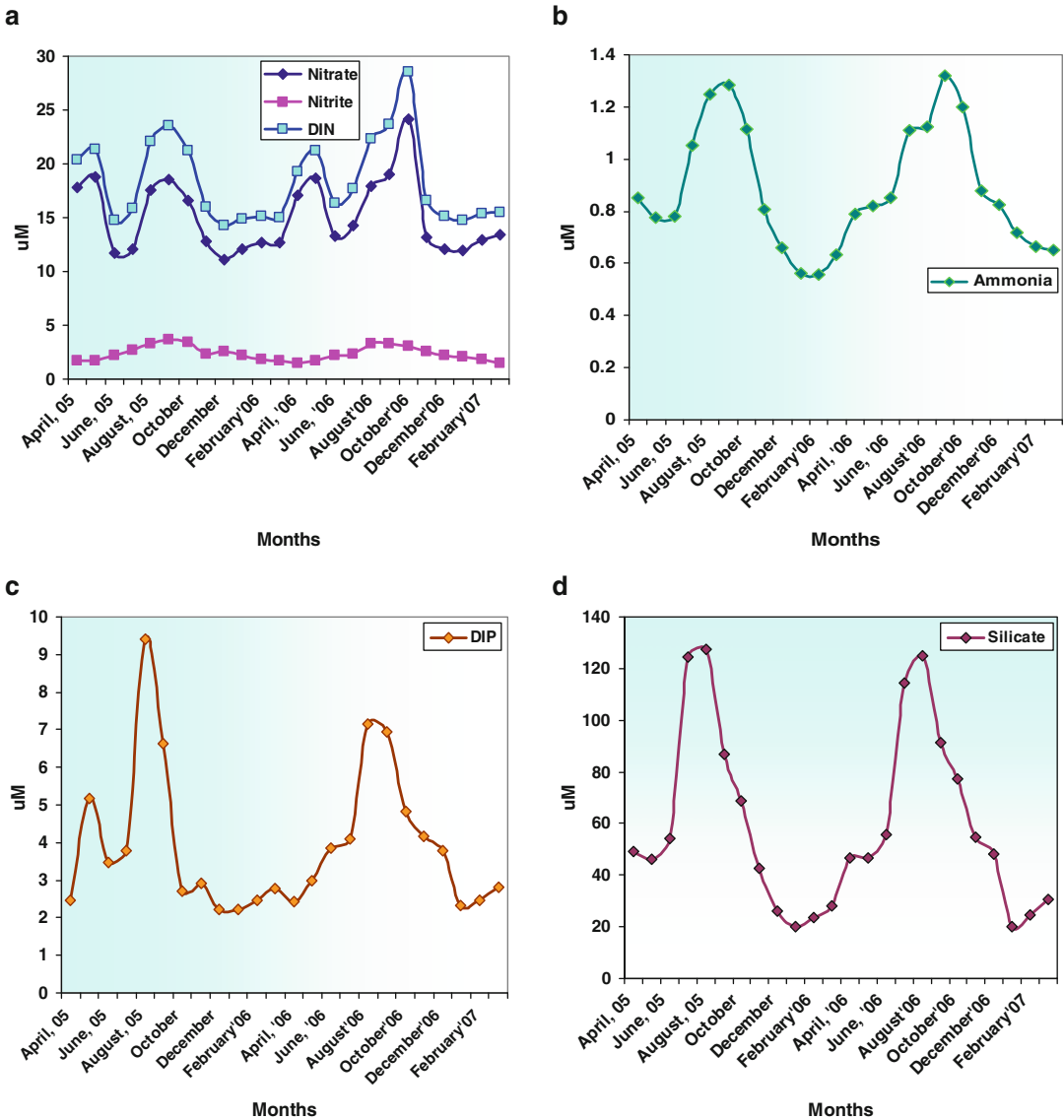
Fig. 5.14 Monthly variations in (**a**) DIN (dissolved inorganic nitrogen), (**b**) ammonia, (**c**) DIP (dissolved inorganic phosphate) and (**d**) DSi (dissolved phosphate) at the coastal marine region (Digha and Junput)

January–February) (Figs. 5.20 and 5.21). The subsequent summer months also showed a comparatively high SWI values which dropped slightly in the monsoon periods. The mean species evenness (*e*) was higher as compared to the freshwater station (*e*=2.17). Variation in species evenness was not very pronounced in this station although seasonal fluctuations were observed. Seasonally, it was maximum during monsoon

(*e*=2.21) followed by the transition period (March) and minimum in post-monsoon (*e*=2.14) closely followed by summer (*e*=2.15) (Fig. 5.21).

At the marine coastal region, SWI varied from 0.33 to 2.76. Highest value of SWI was recorded in the post-monsoon period (October–November), whereas lowest value of the same was recorded in winter (Fig. 5.22). A gradual increase in SWI was

Table 5.9 Correlation matrix plot between cell count, productivity and environmental variables at the freshwater station

	Cell count	DIN	DIP	DSi	Saln	pH	Water temp.	BOD	DO	GPP	NPP	CRR
Cell count		−0.50	−0.75	0.51	0.61	0.21	−0.60	−0.64	0.72	0.89	0.91	0.05
DIN	−0.50		0.58	−0.36	−0.80	−0.42	0.65	0.64	−0.64	−0.60	−0.49	−0.40
DIP	−0.75	0.58		−0.59	−0.78	−0.63	0.52	0.71	−0.73	−0.74	−0.64	−0.35
DSi	0.51	−0.36	−0.59		0.59	0.22	−0.56	−0.21	0.44	0.64	0.55	0.30
Saln	0.61	−0.80	−0.78	0.59		0.46	−0.80	−0.71	0.79	0.76	0.63	0.49
pH	0.21	−0.42	−0.63	0.22	0.46		0.06	−0.49	0.24	0.23	0.06	0.47
Water temp.	−0.60	0.65	0.52	−0.56	−0.80	0.06		0.45	−0.70	−0.71	−0.70	−0.20
BOD	−0.64	0.64	0.71	−0.21	−0.71	−0.49	0.45		−0.80	−0.68	−0.59	−0.33
DO	0.72	−0.64	−0.73	0.44	0.79	0.24	−0.70	−0.80		0.76	0.72	0.19
GPP	0.89	−0.60	−0.74	0.64	0.76	0.23	−0.71	−0.68	0.76		0.96	0.17
NPP	0.91	−0.49	−0.64	0.55	0.63	0.06	−0.70	−0.59	0.72	0.96		−0.09
CRR	0.05	−0.40	−0.35	0.30	0.49	0.47	−0.20	−0.33	0.19	0.17	−0.09	

Correlations (marked correlations are significant at $p < .05000$ $N = 24$)
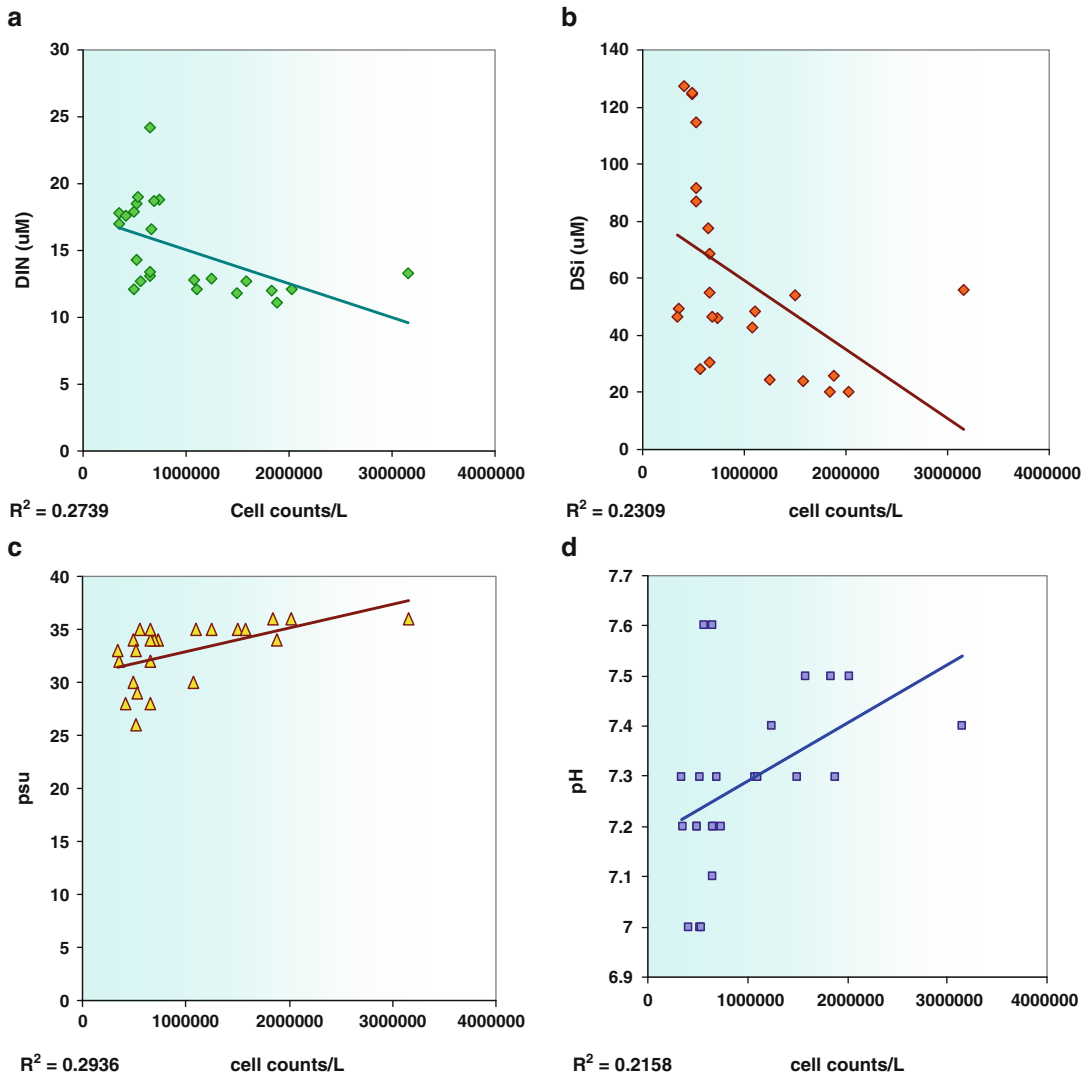
Fig. 5.15 Graphical representation of significant correlation between (**a**) cell count and DIN, (**b**) cell count and DSi and (**c**) cell count and salinity and (**d**) cell count and pH at the coastal marine region (Digha and Junput)

recorded from July onwards reaching maximum in October (2.76) (Fig. 5.22). In winter months, SW Index dropped drastically when single species abundance of *Asterionella japonica* was very high and contributed to more than 90 % of the total phytoplankton population (Fig. 5.23). Similarly, SWI values were relatively low in summer months as well, when *Odontella rhombus* population contributed to >47 % of the total population.

Seasonally, the coastal marine region showed a similar pattern in diversity as was observed in the freshwater and estuarine stations. Highest value of SWI was recorded in the post-monsoon period (October–November) whereas lowest value of the same was recorded in winter (December–January–February) (Fig. 5.24). The subsequent summer months also showed a comparatively low SWI values which gradually increased in the monsoon and post-monsoon
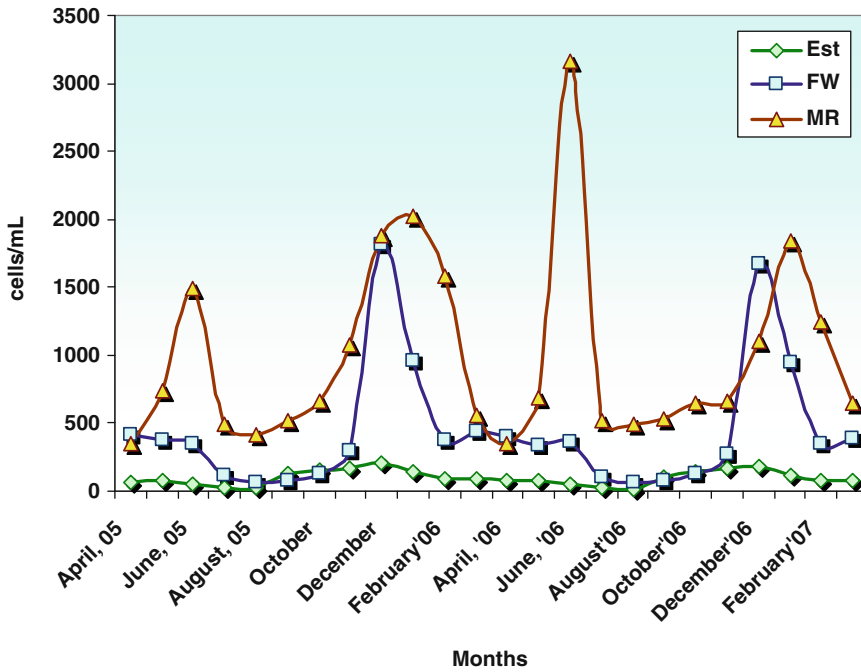
Fig. 5.16 Monthly variations in total cell count (cells/mL) at the three sampling stations (*FW* freshwater station, *Est* estuarine station, and *MR* coastal marine region)
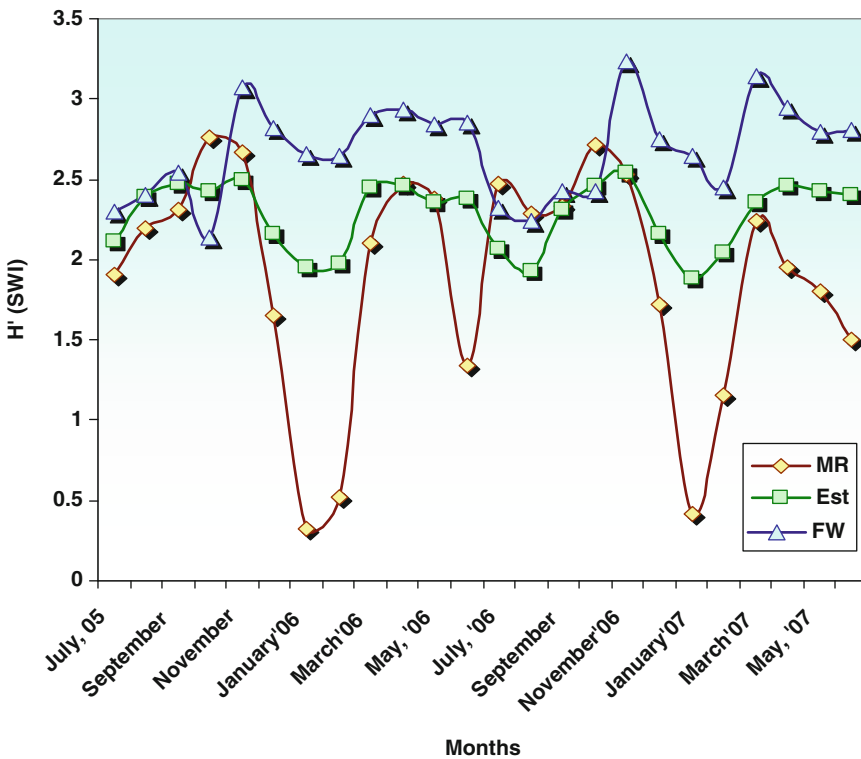

Fig. 5.17 Monthly variations in Shannon–Wiener Index at the three sampling regions (*FW* freshwater station, *Est* estuarine station, and *MR* coastal marine region)
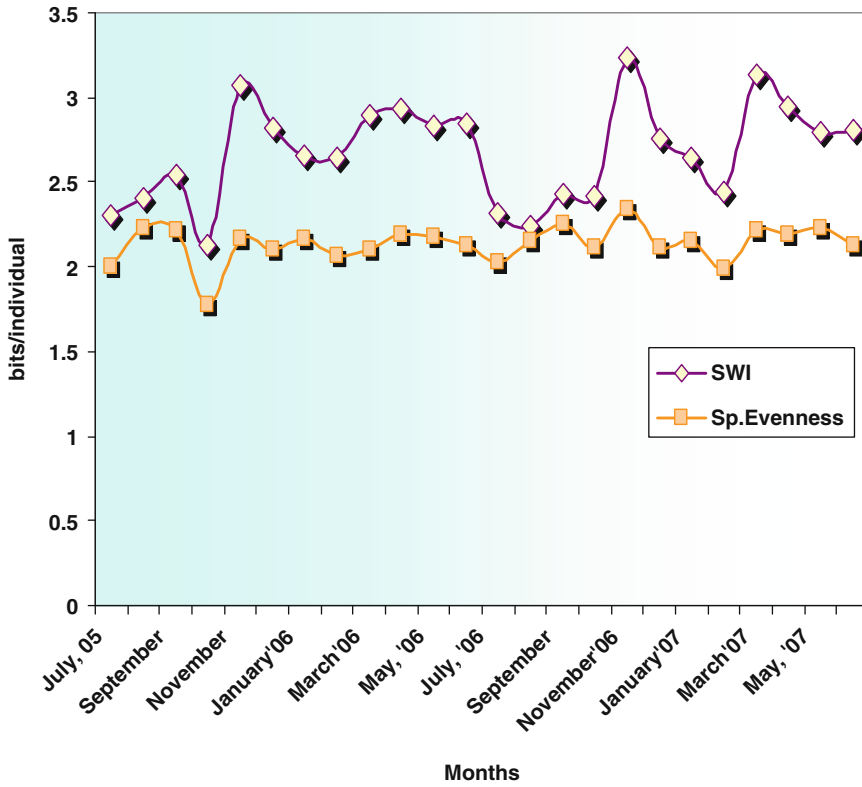
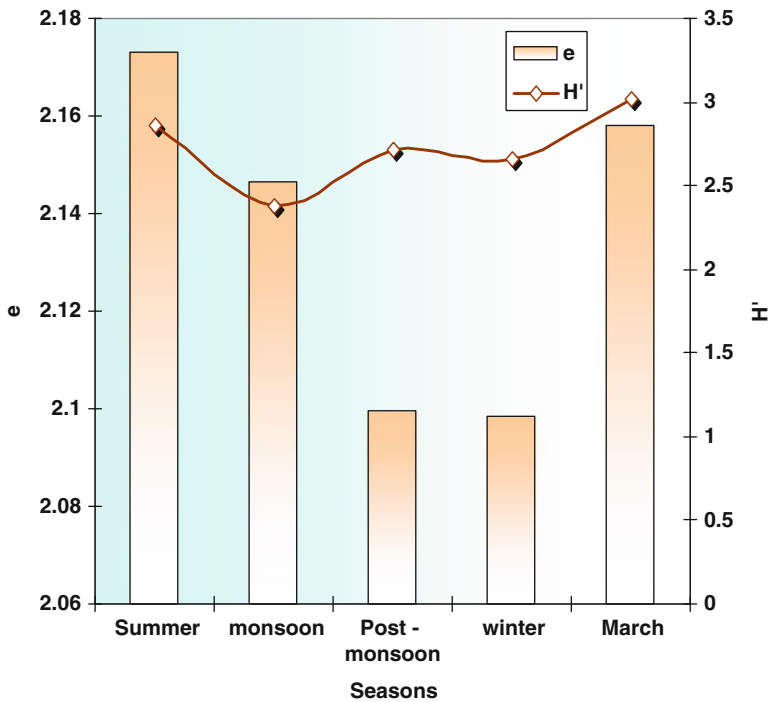**Fig. 5.18** Monthly variations in Shannon–Wiener Index (*SWI*) and species evenness at the freshwater station (Diamond Harbour)

Fig. 5.19 Seasonal variations in Shannon–Wiener Index (*SWI*) and species evenness at the freshwater station (Diamond Harbour)
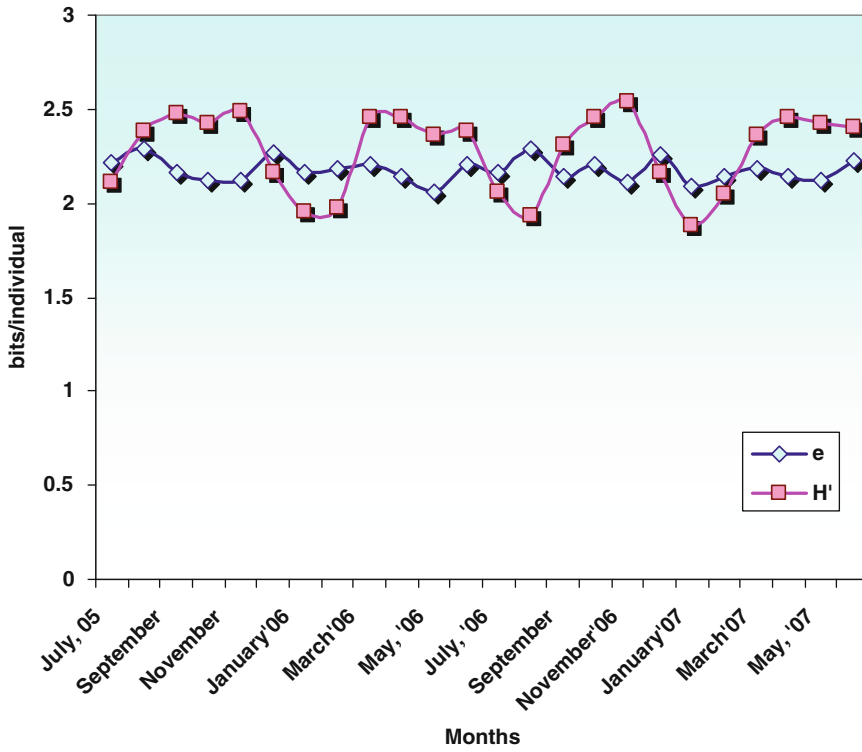
Fig. 5.20 Monthly variations in Shannon–Wiener Index (*SWI*) and species evenness at the estuarine station (Kakdweep)
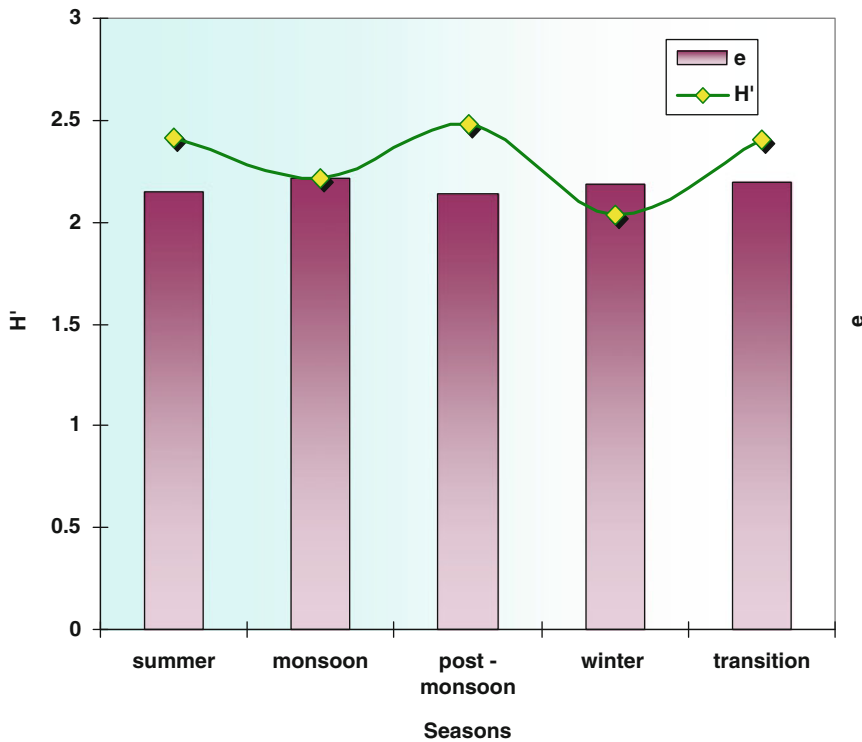

Fig. 5.21 Seasonal variations in Shannon–Wiener Index (*SWI*) and species evenness at the estuarine station (Kakdweep)
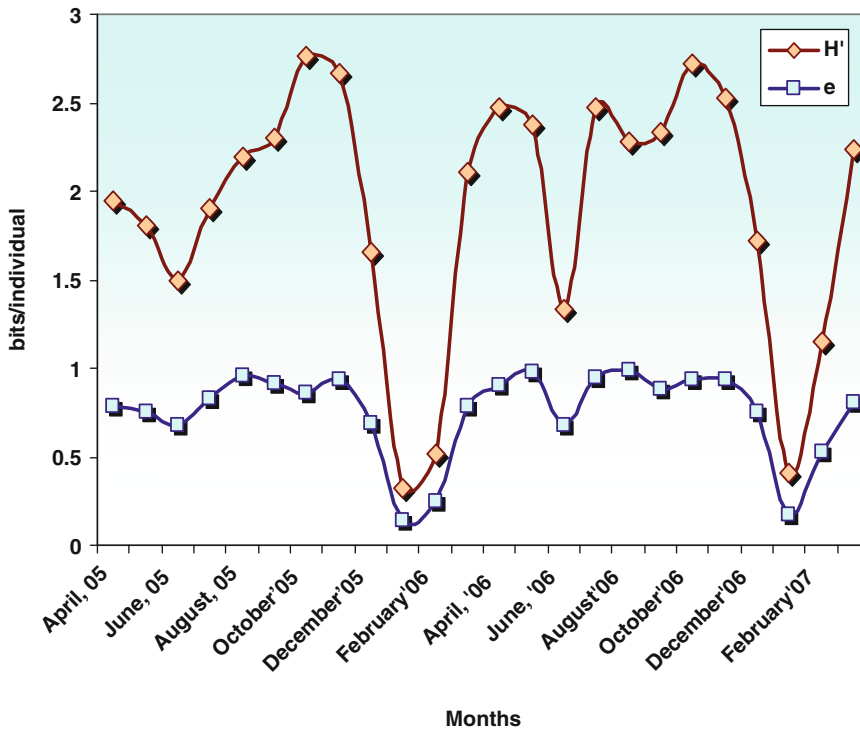
Fig. 5.22 Monthly variations in Shannon–Wiener Index (*SWI*) and species evenness at the coastal marine region (Junput and Digha)

periods. The mean species evenness (*e*) was much lower as compared to the other stations (*e* = 0.75). Variation in species evenness was pronounced in this station both on a monthly as well as on a seasonal basis. Seasonally, it was maximum during monsoon (*e* = 0.92) followed closely by the post-monsoon period (*e* = 0.92) and minimum in winter (*e* = 0.42) (Fig. 5.24). The pattern of variations for both SWI and species evenness was almost similar with significant decrease in winter and summer.

5.4.2.4 Primary Productivity (GPP and NPP) and Oxygen Concentrations

Results show that coastal West Bengal promoted phytoplankton production although there were significant seasonal variations. The study area was highly suitable for the development and diversification of phytoplankton populations especially for diatoms. On an individual site basis, phytoplankton productivity was maximum at the coastal marine region and minimum at the estuarine region with the freshwater station occupying an intermediate position. CRR values also represented a similar pattern as was observed for primary productivity. Seasonally, winter months were most productive and monsoon periods were least productive. DO values being a reflection of the photosynthetic efficiency of phytoplankton population showed a similar seasonal pattern as was observed for primary productivity. In contrast, BOD values were minimum in winter and maximum in monsoon at all the sampling stations.

At the freshwater station, winter months were most productive with respect to carbon equivalents as was evident from GPP values. Typically, monsoon periods were least productive both in respect to phytoplankton productivity (GPP) as
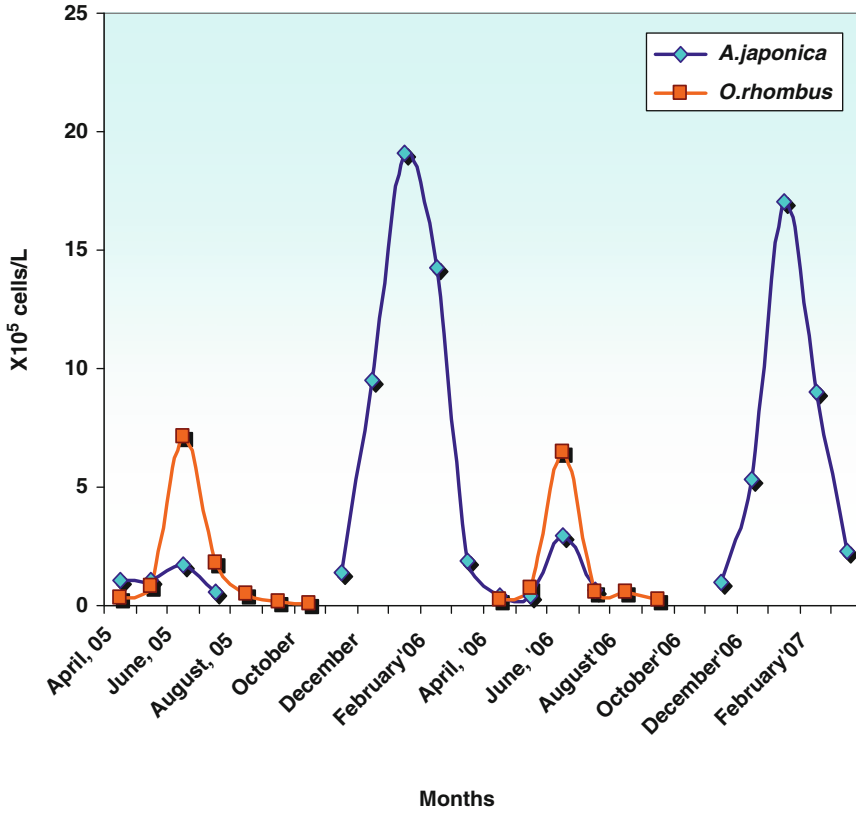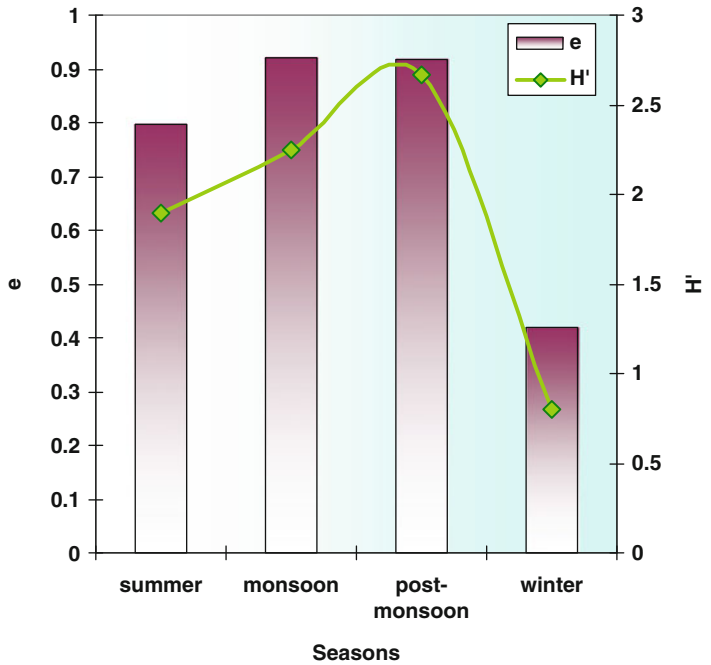
Fig. 5.23 Monthly variations of total cell counts of the two dominant species (*Asterionella japonica* and *Odontella rhombus*) at the coastal marine region

Fig. 5.24 Seasonal variations in SW Index and species evenness at coastal marine region
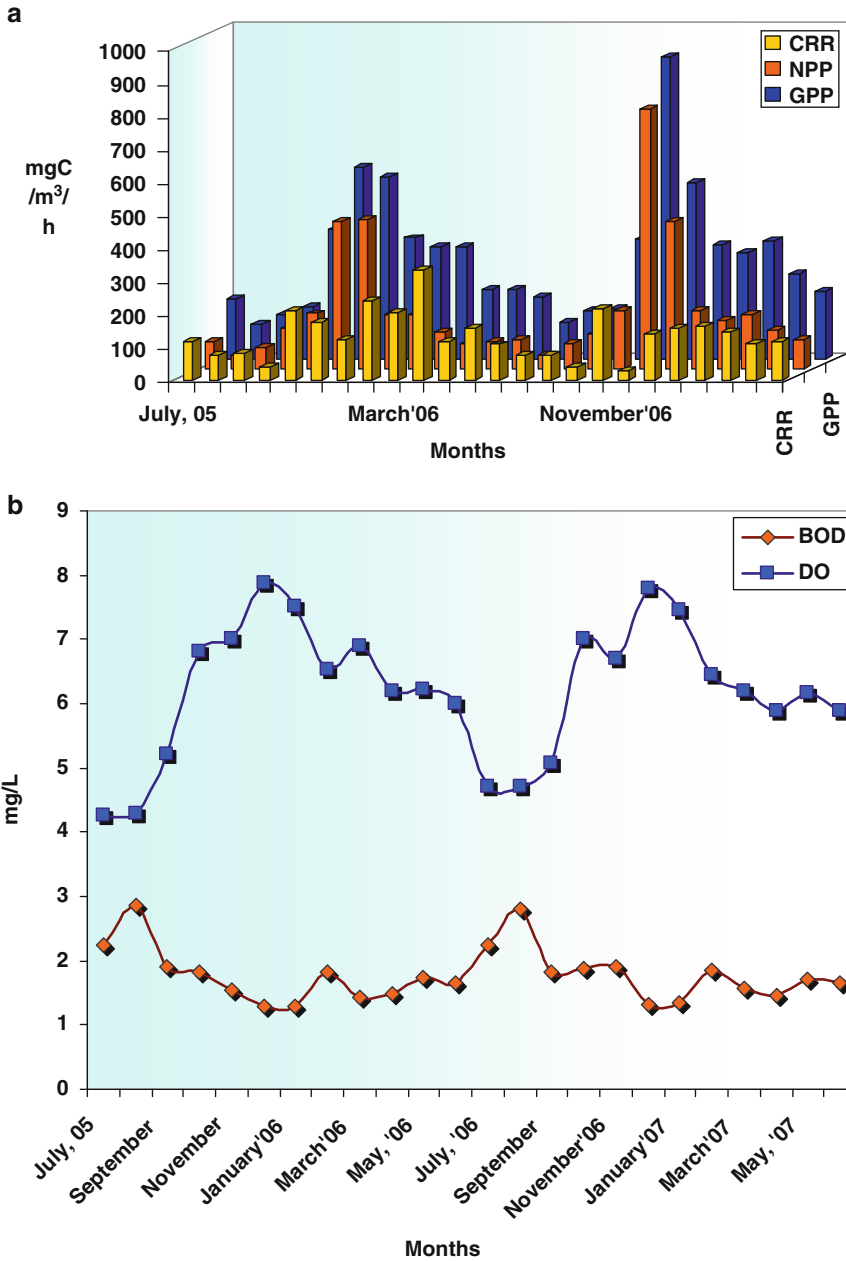
Fig. 5.25 Monthly variation in (**a**) productivity (NPP, GPP and CRR) and (**b**) oxygen concentrations (DO and BOD) at the freshwater station (Diamond Harbour)

well as community productivity (NPP) with insignificant interannual variations. As can be expected, CRR varied significantly as well, where maximum CRR was in winter (178.67 mgC/m^3/h) and minimum in monsoon (86.37 mgC/m^3/h) (Fig. 5.25a). A highly positive significant correla-

tion between GPP and cell count ($R^2 = 0.8$, $r = 0.9$, $p \leq 0.05$) was established (Fig. 5.26a).

Dissolved oxygen (DO) was present in optimal quantity in the habitat waters that ranged from 4.25 mg/L (July 2005) to 7.882 mg/L (December 2005) (Fig. 5.25b). Seasonally, DO
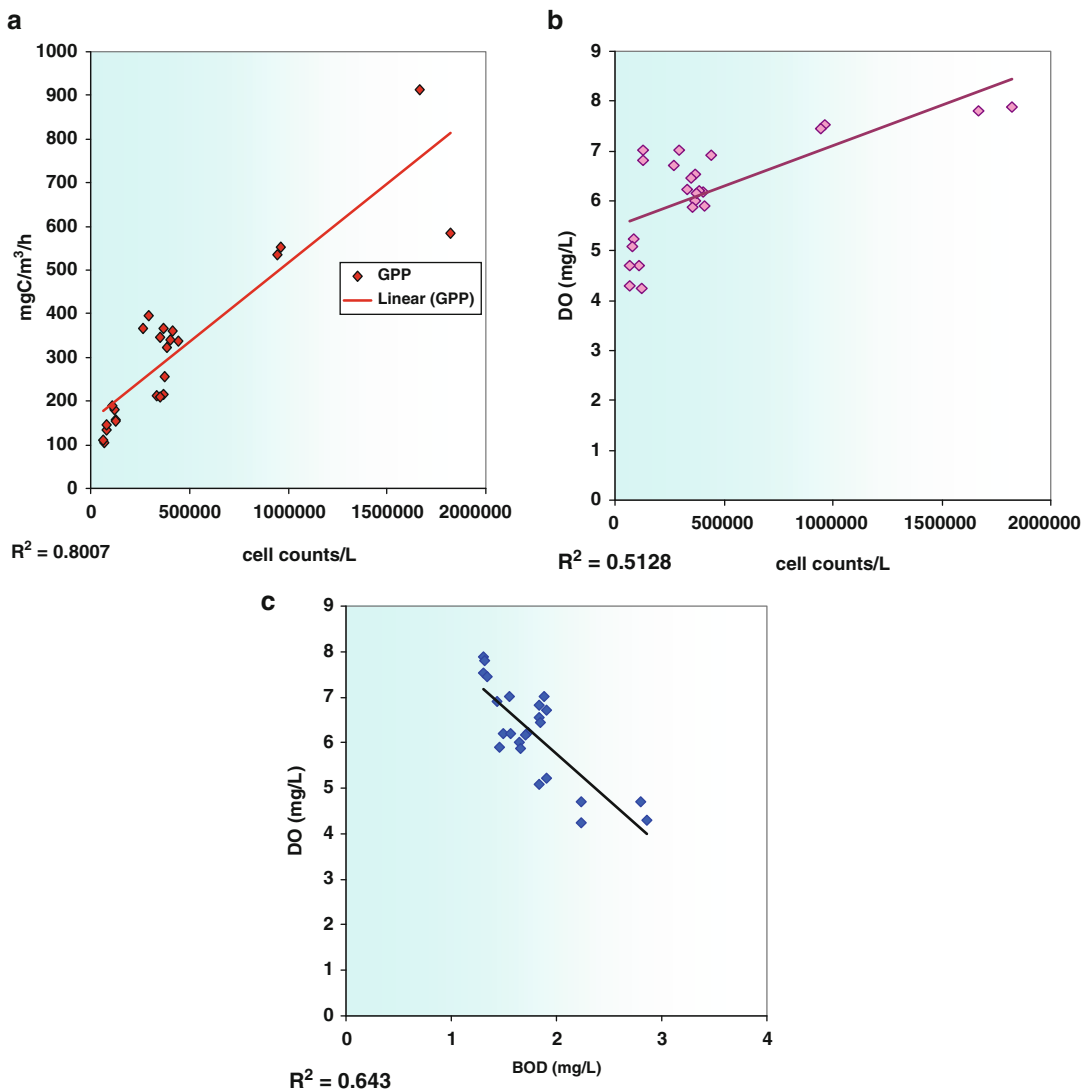
Fig. 5.26 Graphical representation of significant correlation between (**a**) cell count and GPP, (**b**) cell count and DO and (**c**) BOD and DO at the freshwater station

showed a similar trend with that of productivity and cell count that was maximum in winter (7.32 mg/L) and minimum in monsoon (4.59 mg/L). DO contents in the habitat waters had positive significant correlation with cell count ($R^2 = 0.51$, $r = 0.68$, $p \leq 0.05$, $n = 24$) (Fig. 5.26b) whereas BOD, which represented the heterotrophic oxygen requirements, showed an opposite pattern with maximum values in monsoon and minimum values in winter. Thus, a negative correlation was observed between DO

and BOD ($R^2 = 0.64$, $r = 0.8$, $p \leq 0.05$, $n = 24$) (Fig. 5.26c).

Phytoplankton productivity [Gross Primary productivity (GPP)] at the estuarine station was maximum in December 2006 (227.77 mgC/m³/h) when total phytoplankton cell count was maximum as well (203 cells/mL) and minimum in August 2006 (58.95 mgC/m³/h) (Fig. 5.27a). Seasonally, maximum productivity with respect to carbon equivalents was recorded in winter when cell counts showed highest values as well
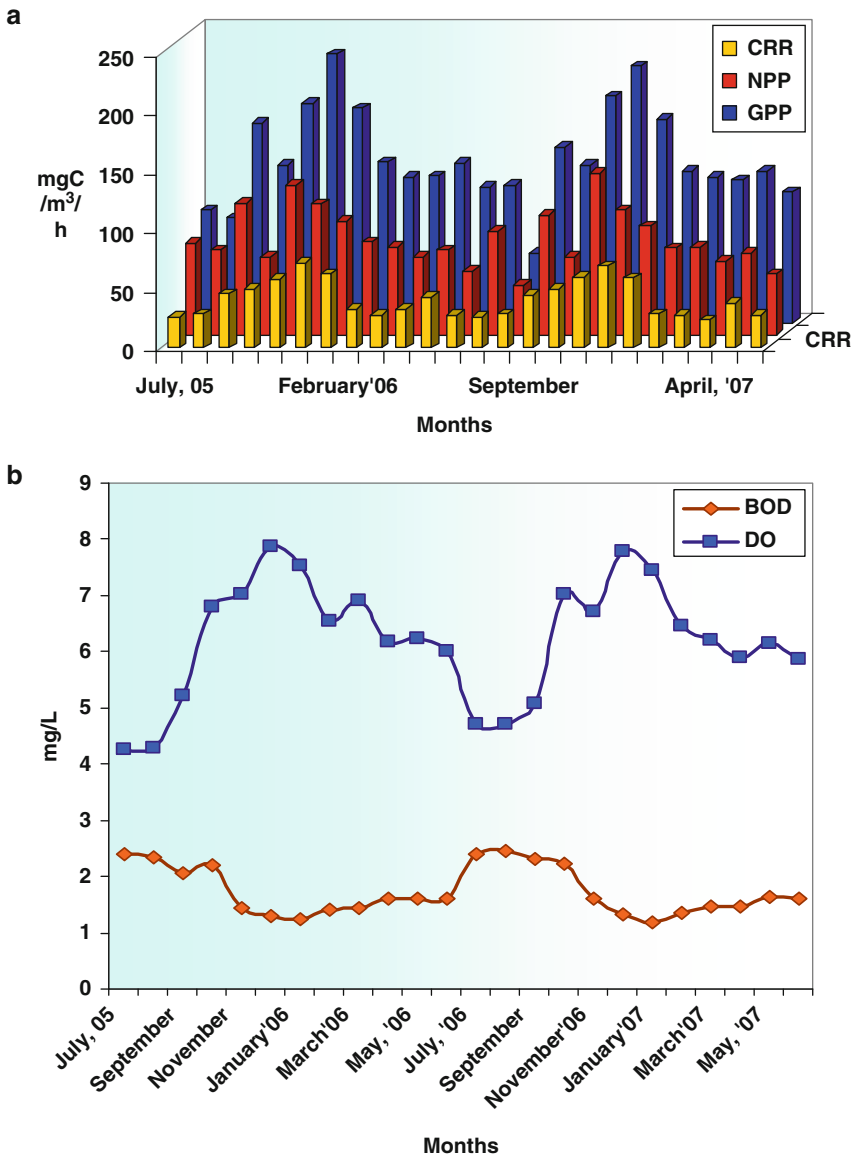
Fig. 5.27 Monthly variation in (**a**) productivity (NPP, GPP and CRR) and (**b**) oxygen concentrations (DO and BOD) at the estuarine station (Kakdweep)

(136 cells/mL). On the contrary, minimum productivity with respect to both carbon equivalents as well as total phytoplankton cell counts was recorded in the monsoon months (cells/mL) (Fig. 5.27a). Results of 2-D scatter plot shows highly significant positive correlation between total phytoplankton cell count and GPP as well ($R^2 = 0.84$, $r = 0.92$, $p < 0.05$, $n = 24$) (Fig. 5.28a). Almost similar patterns were observed for net

primary productivity (NPP), which was maximum in November 2006 (137.78 mgC/m^3/h) and minimum in August 2006 (42.72 mgC/m^3/h). An intermediate significant positive correlation was established between phytoplankton cell count and NPP ($R^2 = 0.48$, $r = 0.7$, $p < 0.05$, $n = 24$) (Fig. 5.28b). Community respiration rate (CRR) being a measure of catabolic loss of carbon equivalents due to respiration was minimum in April 2007
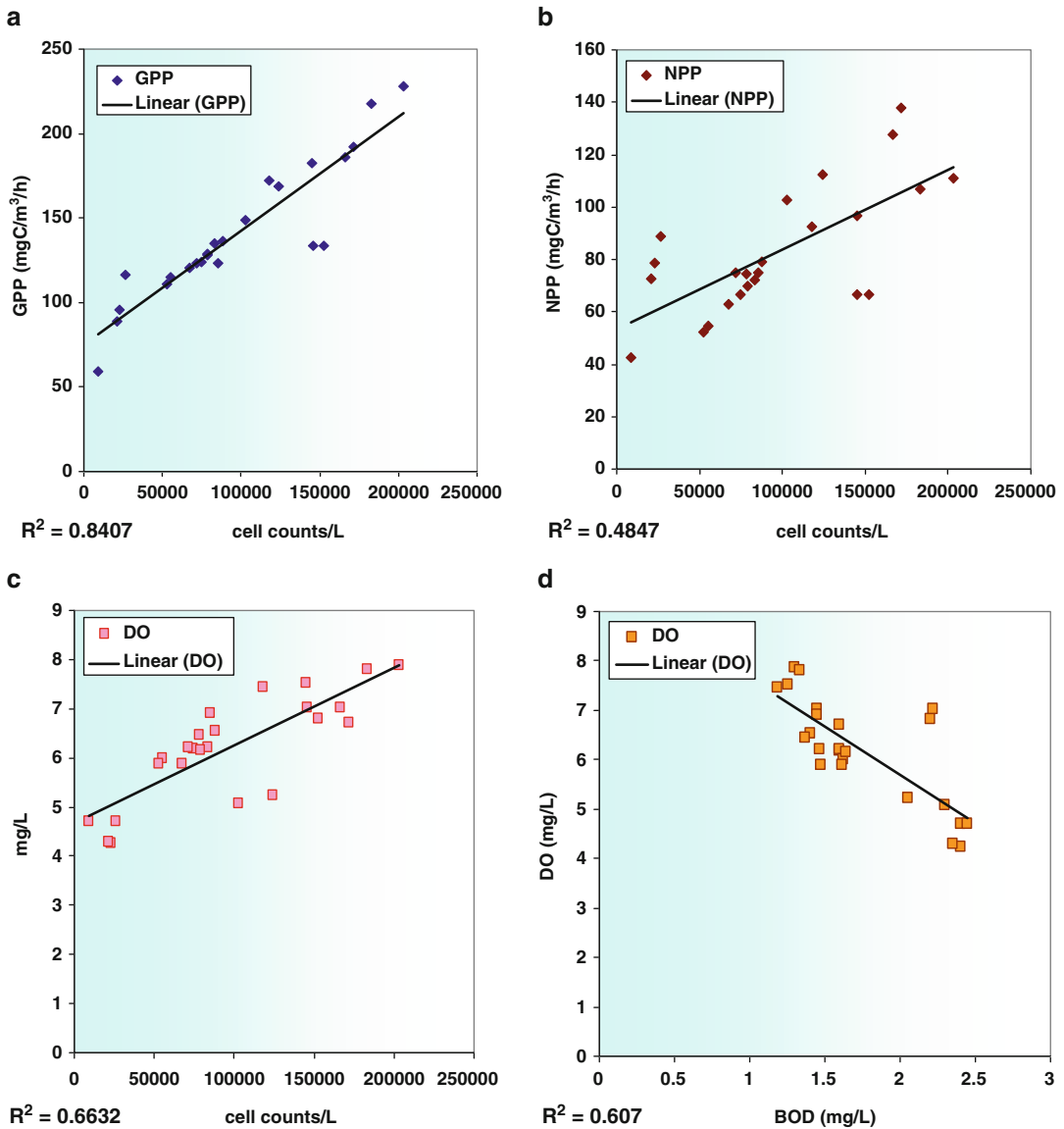
Fig. 5.28 Graphical representation of significant correlation between (**a**) cell count and GPP, (**b**) cell count and NPP, (**c**) cell count and DO and (**d**) BOD and DO at the estuarine station (Kakdweep)

(24. 158 mgC/m³/h) whereas it was maximum in December 2006 (72.2 mgC/m³/h) (Fig. 5.27a).

Dissolved oxygen content is a reflection of the photosynthetic activity of the phytoplankton biomass. Accordingly DO values were higher in those months where plankton count was high, with a maximum of 7.88 mg/L in December 2005 and minimum of 4.25 mg/L in July 2006 (Fig. 5.27b). BOD value ranged from 1.18 to

2.45 mg/L, with highest value in monsoon (August 2006) and lowest in winter (January 2007) when DO content was high (Fig. 5.27b). From the correlation matrix plot, it was observed that there was a positive correlation between cell count and dissolved oxygen content ($R^2 = 0.66$, $r = 0.81$, $p < 0.05$, $n = 24$) (Fig. 5.28c) and negative correlation with BOD ($R^2 = 0.61$, $r = -0.46$, $p < 0.05$, $n = 24$) (Fig. 5.28d).
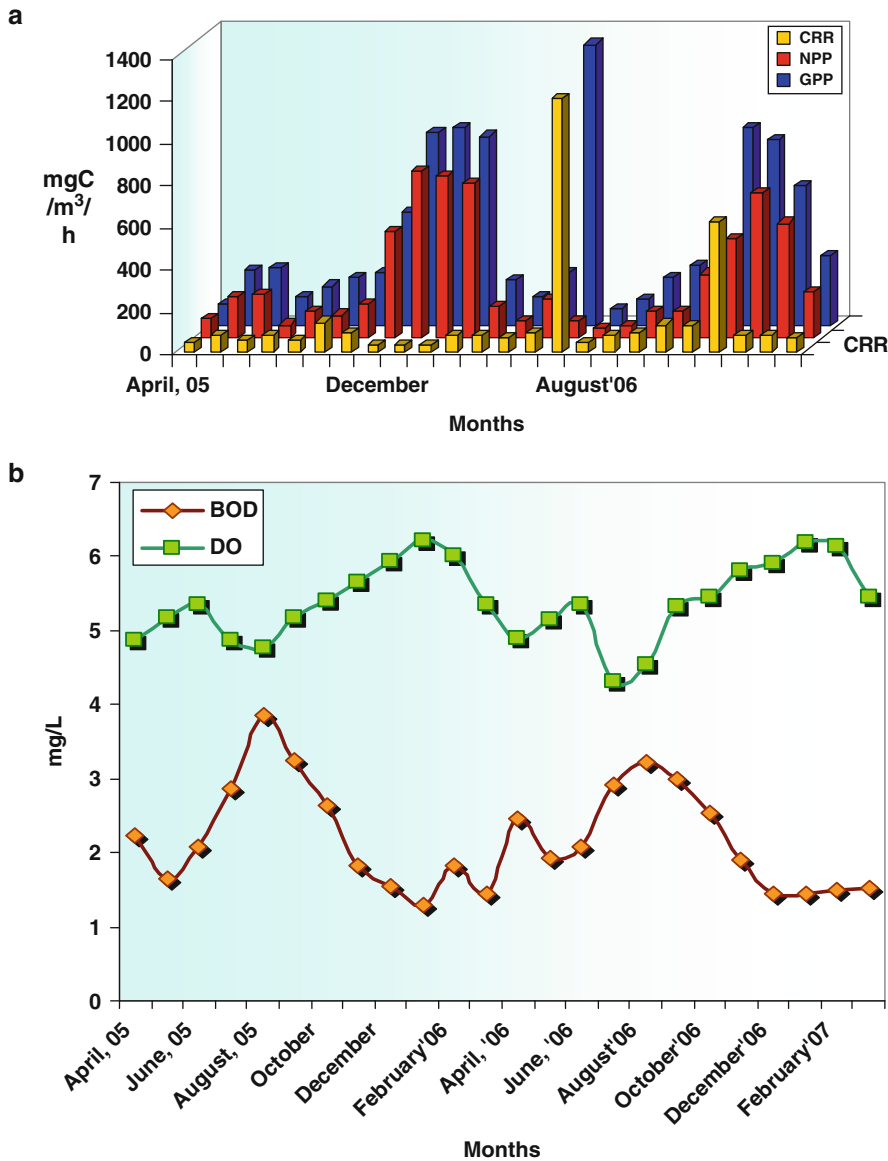
Fig. 5.29 Monthly variation in (**a**) productivity (NPP, GPP and CRR) and (**b**) oxygen concentrations (DO and BOD) at the coastal marine region (Digha and Junput)

At the coastal marine region, maximum productivity [GPP] was recorded in June 2006 (1,330 mgC/m³/h) and minimum productivity was recorded in July 2006 (77.78 mgC/m³/h) (Fig. 5.29a). Highest NPP value was recorded in December 2005 (788.88 mgC/m³/h) when GPP (913.34 mgC/m³/h) also was relatively high whereas it was minimum in July 2006 (44.44 mgC/m3/h). An abruptly maximum CRR value was recorded

in June 2006 (1,191.67 mgC/m³/h) when GPP was high as well although NPP was much low (83.33 mgC/m³/h) (Fig. 5.29a).

On a seasonal basis, highest productivity was recorded in winter, followed by summer with the lowest productivity in monsoon. Regarding productivity, there was interannual variation where productivity in post-monsoon period was higher than summer in 2005, unlike in 2006.

a

b

c
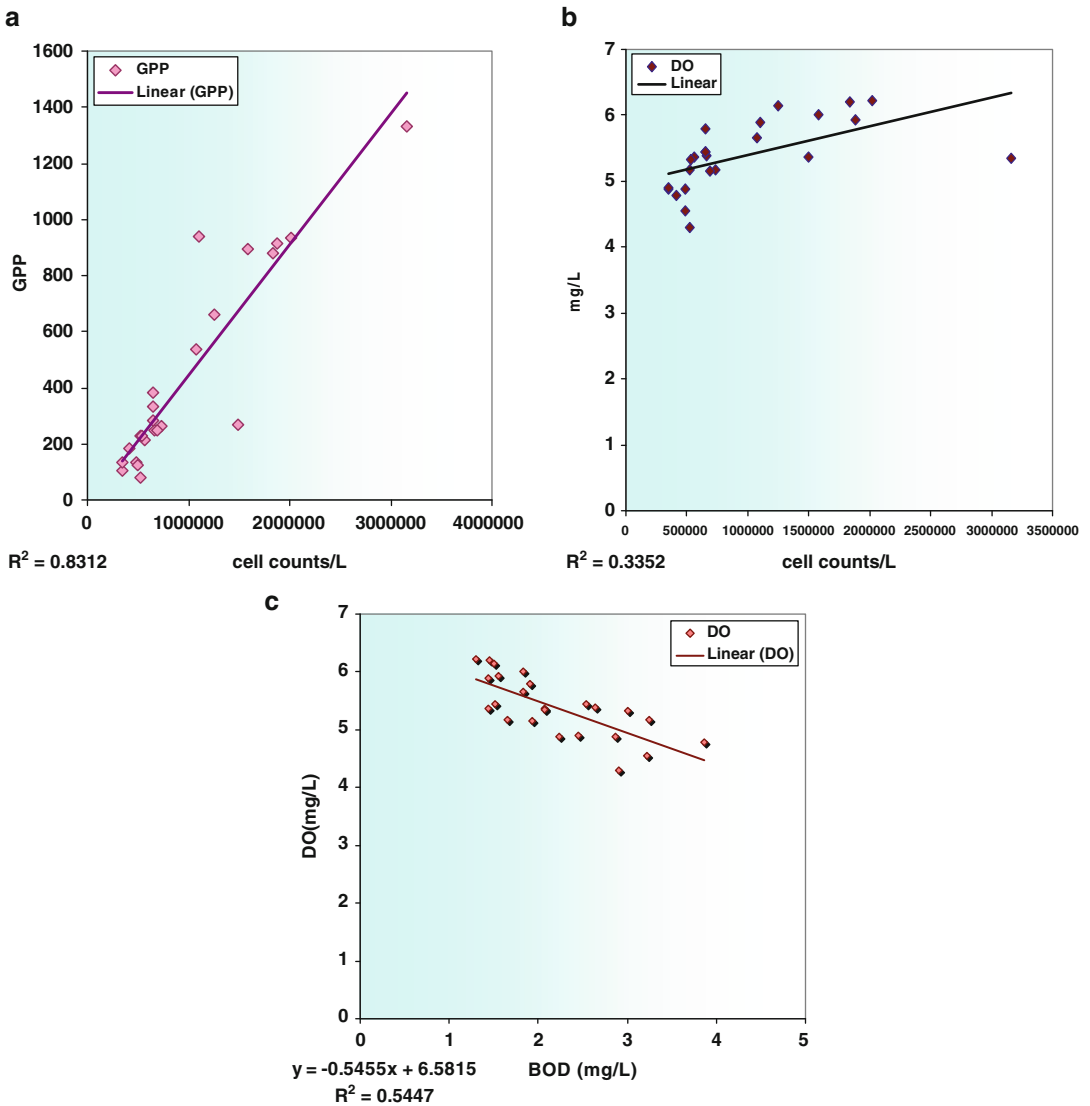
Fig. 5.30 Graphical representation of significant correlation between (**a**) cell count and GPP, (**b**) cell count and DO and (**c**) BOD and DO at the coastal marine region

Gross productivity in 2006–2007 (440.863 mgC/m^3/h) was higher as compared to 2005–2006 (383.361 mgC/m^3/h). Net primary productivity showed similar pattern as was with GPP with highest values in winter, intermediate values in summer and post-monsoon with lowest in monsoon. On the contrary, CRR values were relatively higher in monsoon as compared to the summer and post-monsoon periods

DO values were relatively low, with a maximum of 6.22 mg/L in January 2006 and minimum of 4.3 mg/L in July 2006 (Fig. 5.29b). DO content was maximum in winter and minimum in monsoon. BOD value ranged from 1 to 4 mg/l, with highest value in monsoon (August 2005) and lowest in winter (January 2006) when DO content was high. From the correlation matrix plot, there was a positive correlation between cell count and

Table 5.10 Correlation matrix plot between cell count, productivity and environmental variables at the estuarine station

	Cell count	DIN	DIP	DSi	Saln.	BOD	DO	Water temp.	pH	CRR	NPP	GPP
Cell count		−0.45	0.02	−0.71	−0.01	−0.46	0.81	−0.55	0.00	0.91	0.70	0.92
DIN	−0.45		0.30	0.64	−0.75	0.87	−0.74	0.45	−0.74	−0.36	−0.24	−0.54
DIP	0.02	0.30		0.13	−0.12	0.07	−0.07	−0.23	−0.19	0.03	0.00	0.06
DSi	−0.71	0.64	0.13		−0.28	0.58	−0.78	0.70	−0.33	−0.58	−0.45	−0.65
Saln	−0.01	−0.75	−0.12	−0.28		−0.78	0.45	−0.17	0.94	−0.15	−0.29	0.07
BOD	−0.46	0.87	0.07	0.58	−0.78		−0.78	0.61	−0.75	−0.35	−0.24	−0.57
DO	0.81	−0.74	−0.07	−0.78	0.45	−0.78		−0.70	0.47	0.71	0.34	0.75
Water temp.	−0.55	0.45	−0.23	0.70	−0.17	0.61	−0.70		−0.20	−0.54	−0.45	−0.60
pH	0.00	−0.74	−0.19	−0.33	0.94	−0.75	0.47	−0.20		−0.15	−0.26	0.07
CRR	0.91	−0.36	0.03	−0.58	−0.15	−0.35	0.71	−0.54	−0.15		0.70	0.89
NPP	0.70	−0.24	0.00	−0.45	−0.29	−0.24	0.34	−0.45	−0.26	0.70		0.82
GPP	0.92	−0.54	0.06	−0.65	0.07	−0.57	0.75	−0.60	0.07	0.89	0.82	

Correlations (marked correlations are significant at $p < .05000 N = 24$)

Table 5.11 Correlation matrix plot between cell count, productivity and environmental variables at the coastal marine region

	Cell count	DIN	DIP	DSi	Saln	BOD	DO	Water temp.	pH	GPP	NPP	CRR
Cell count		-0.52	-0.36	-0.48	0.54	-0.49	0.58	-0.34	0.46	0.91	0.56	0.59
DIN	-0.52		0.62	0.54	-0.69	0.66	-0.48	0.47	-0.75	-0.53	-0.58	-0.12
DIP	-0.36	0.62		0.77	-0.65	0.78	-0.50	0.44	-0.73	-0.37	-0.48	0.02
DSi	-0.48	0.54	0.77		-0.61	0.91	-0.77	0.67	-0.71	-0.56	-0.67	-0.03
Saln	0.54	-0.69	-0.65	-0.61		-0.78	0.45	-0.39	0.77	0.52	0.42	0.25
BOD	-0.49	0.66	0.78	0.91	-0.78		-0.74	0.64	-0.77	-0.58	-0.65	-0.10
DO	0.58	-0.48	-0.50	-0.77	0.45	-0.74		-0.85	0.46	0.73	0.86	0.08
Water temp.	-0.34	0.47	0.44	0.67	-0.39	0.64	-0.85		-0.53	-0.58	-0.87	0.14
pH	0.46	-0.75	-0.73	-0.71	0.77	-0.77	0.46	-0.53		0.47	0.48	0.09
GPP	0.91	-0.53	-0.37	-0.56	0.52	-0.58	0.73	-0.58	0.47		0.71	0.60
NPP	0.56	-0.58	-0.48	-0.67	0.42	-0.65	0.86	-0.87	0.48	0.71		-0.12
CRR	0.59	-0.12	0.02	-0.03	0.25	-0.10	0.08	0.14	0.09	0.60	-0.12	

Correlations (marked correlations are significant at $p < .05000$ $N = 24$)
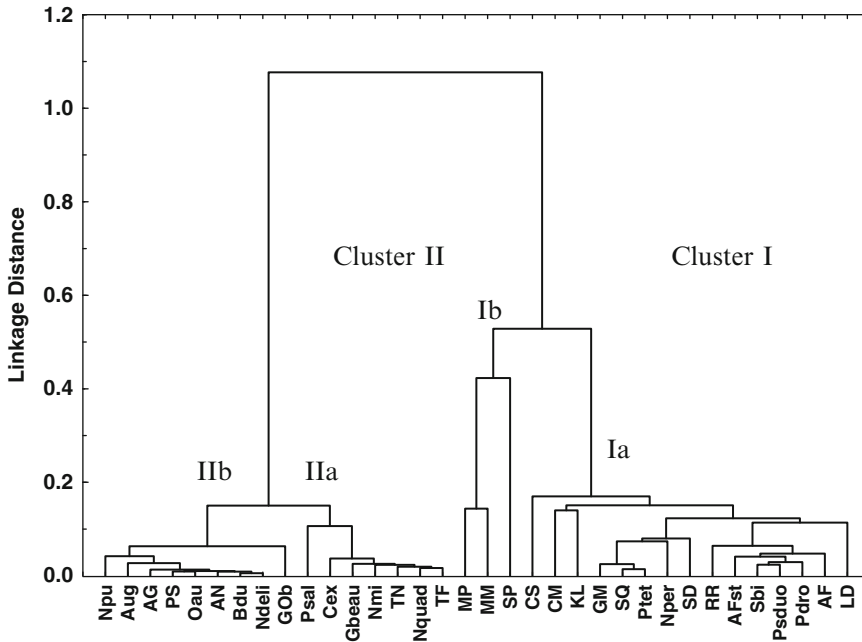
Fig. 5.31 UPGA cluster diagram based on seasonal abundance of different phytoplankton genera recorded from the freshwater station

dissolved oxygen content ($R^2 = 0.34$, $r = 0.58$, $p \leq 0.05$, $n = 24$) (Fig. 5.30b). Similarly, a significant negative correlation was established between DO and BOD ($R^2 = 0.54$, $r = 0.74$, $p \leq 0.05$, $n = 24$) (Fig. 5.30c) (Tables 5.10 and 5.11).

5.4.2.5 Multivariate Procedures

In the present work, cluster analysis (CA) was used to enumerate the diversity patterns in phytoplankton populations along coastal West Bengal. Moreover, we also tried to find out the probable role of the measured environmental variables in analysing the diversity patterns with the application of principal component analysis (PCA).

Figure 5.31 depicts the results obtained by using the 34 most abundant species during the entire study period at the freshwater station (Diamond Harbour). Two distinct groups of phytoplankton association were observed that are designated as I and II. The ultimate outcome of the 34 taxa through cluster analysis reveals the presence of two major clusters among the investigated taxa, one comprising of 16 species and other 18 species. These two major clusters are

mainly separated from each other in accordance to their preferences for different temperature gradients, i.e. Cluster I consists of taxa that had a preference for the warmer periods whereas Cluster II consists of taxa that were mainly abundant in the cooler months.

Cluster I comprised of late spring (transition period), summer and monsoon population. This group primarily represented the populations of the relatively warmer periods when the mean temperature was 28 ± 5 °C. In this group of phytoplankton population, green and blue-green algal members were more abundant in comparison to diatoms. Cluster Ia represented the population of late spring and summer with predominance of green algal genera like *Pediastrum* spp. (*P. tetras*, *P. simplex* var. *duodenarium* and *P. duplex* var. *rotundatum*) and *Ankistrodesmus* spp. (*A. falcatus*, *A. falcatus* var. *stipitatus*) with only two species of diatoms which were *Leptocylindrus danicus* (LD) and *Nitzschia peregrina* (Nper). On a closer observation in respect to linkage distances, the measured distances among members of *Pediastrum* spp. and *Ankistrodesmus* spp.
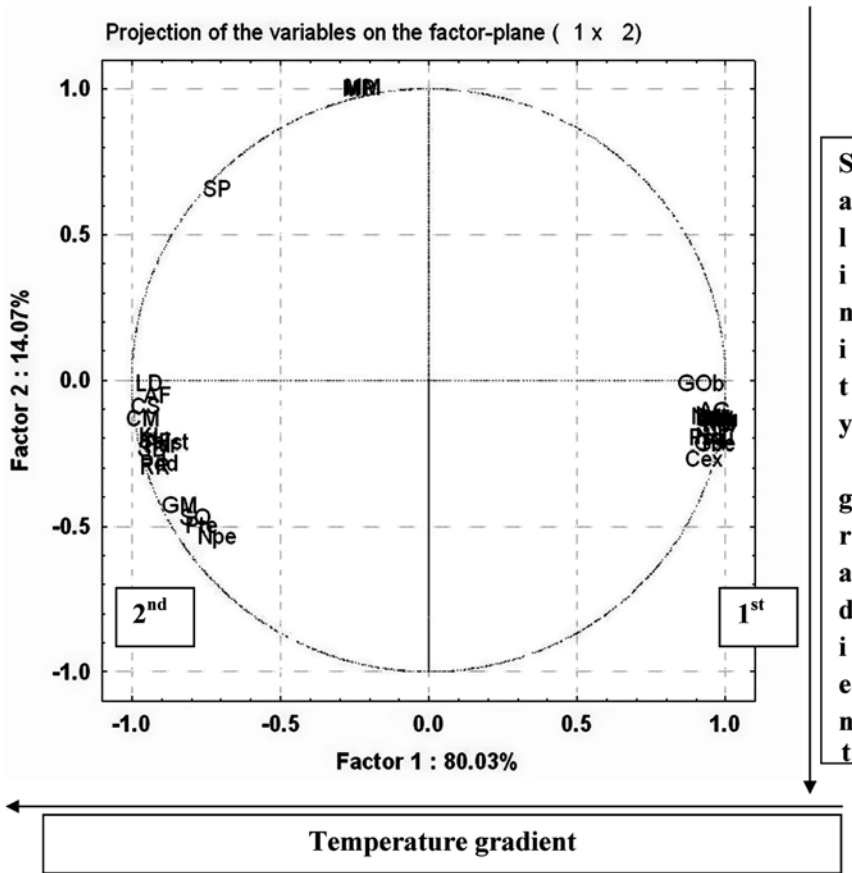
Fig. 5.32 PCA plot of Factor 1 vs. Factor 2 showing the pattern of species orientation based on environmental variables and magnitude of abundance at the freshwater station

ranged from 0.02 to 0.1 which further testifies the very close association among these members in the community. Cluster Ib clustered species that were abundant only during monsoon that included only the cyanobacterial members like *Spirulina platensis* (SP), *Merismopedia minima* (MM) and *Merismopedia punctata* (MP).

Cluster II represented the population of the autumn and winter periods with predominance of diatoms. Cluster IIa accounted for the population of autumn period which was mainly represented by pennate diatom taxa like *Navicula minima* (Nmi), *Nitzschia quadripartita* (Nquad), *Pleurosigma salinarum* (Psal) and Gyrosigma *beaufortianum* (Gbeau). Cluster IIb represented the population of winter months where along with the pennate population of autumn period,

some centric diatoms appeared like *Biddulphia dubia* (Bdu), *Odontella aurita* (Oau), *Aulacoseira granulata* (Aug).

The juxtaposition of taxa was further observed in principal component analysis (PCA) of investigated taxa (Fig. 5.32). The results of PCA confirmed the results of the Cluster diagram. The highly clustered appearance of species scores in the PCA plot can be attributed to the low linkage distances between species in each subgroup of the cluster diagram. The principal component analysis of data matrix (based on correlation coefficient) resulted into extraction of 17 principal components among the taxa. In PCA, principal components exhibiting maximum amount of variations and having eigenvalues above 1.00 are generally considered. In the present investigation,

the first six principal components are represented by eigenvalues greater than 1.0; however only the first two components (PC 1 and PC 2) explain maximum amount of variations As such, the first two components have been taken into consideration for preparation of PCA plot. PC 1 and PC 2 together explain 80.03 % and 14.07 % of the variance, respectively, that cumulatively accounts for 94.1 % of variance among the data.

The two-dimensional diagram showed the distribution of taxa in all the four quadrants (Fig. 5.32). The distribution of taxa in the PCA plot follows the cluster formation of phenogram. PCA also reveals the environmental variables responsible for separation of taxa along the different dimensions.

Based upon factor versus variables scores along each component, PC 1 can be designated as a negative temperature gradient from right to left (Fig. 5.32), whereas PC 2 can be designated as a positive salinity gradient from top to bottom. As evident from the PCA plot, mainly two groups of phytoplankton populations could be observed. The 1st group consists of those species (e.g. *Gyrosigma obtusatum*, *G. beaufortianum*, *Coscinodiscus excentricus*, *Amphiprora gigantea*, *Odontella aurita*, *Actinocyclus normanii*, *Biddulphia dubia*, *Nitzschia delicatissima*, *Pleurosigma salinarum*, etc.) that have a high positive loading along PC 1 with intermediate negative loadings along PC 2. On closer observation, it can be further observed that the differences in loadings among the different members in this group are low, thereby suggesting their similar patterns of occurrence with almost similar affinities to temperature and salinity. On the other hand, the 2nd group consists of those members (e.g. *Leptocylindrus danicus*, *Ankistrodesmus falcatus*, *A. falcatus* var. *stipitatus*, *Cyclotella meneghiniana*, *C. striata*, *Rhizoclonium riparium*, *Nitzschia peregrina*) that have high negative loadings along PC 1 with intermediate negative loadings along PC 2. Within this group variation in loading values of different species suggests greater variations as compared to the members of group 1. This suggests that although the population have similar preferences for temperature and salinity, their abundance and contributions to the entire population may not be similar during the entire period of study when temperature was relatively high. A 3rd group of species was observed which was represented by few species with intermediate negative loadings along PC 1 and very high positive loadings along PC 2. This suggests that genera like *Merismopedia minima* and *M. punctata* mainly flourished under conditions of intermediate temperature and very low salinity, being as low as 0 psu.

From the estuarine station (Kakdweep), similar cluster analysis and principal component analysis were performed with the 25 most abundant taxa recorded. Here again, two distinct groups of phytoplankton population were recorded which were designated as Cluster I and Cluster II, respectively. Cluster I comprised of 8 taxa whereas Cluster II comprised of 17 taxa. As was observed for the freshwater, the grouping of phytoplankton population in the cluster diagram at the estuarine station was also based upon temperature gradients, i.e. Cluster I consists of taxa that had a preference for the warmer periods whereas Cluster II consists of taxa that were mainly abundant in the cooler months (Fig. 5.33).

Cluster I comprised of late spring (transition period), summer and monsoon population. This cluster primarily represented the populations of the relatively warmer periods when the mean temperature was 28±5 °C. This cluster of phytoplankton was composed of green algae and diatoms with greater abundance of diatom genera. Cluster Ia represented the population of late spring and summer with 7 green algal taxa like *Scenedesmus* spp. (*S. dimorphus*, *S. brevicauda*, *S. bijuga* and *S. quadricauda*), *Ankistrodesmus falcatus*, *Kirchneriella lunaris* and *Crucigenia tetrapedia*. On the contrary, Cluster Ib was represented by 10 phytoplankton taxa of which all except *Rhizoclonium riparium* were diatom. This cluster primarily represented the population that dominated the habitat waters during the late monsoon and post-monsoon periods. The more abundant taxa in this cluster were *Cyclotella meneghiniana*, *Thalassiothrix frauenfeldii*, *Gyrosigma obtusatum*, *G. acuminatum*, etc. The comparatively high linkage distances between the different taxa within the same cluster suggest that
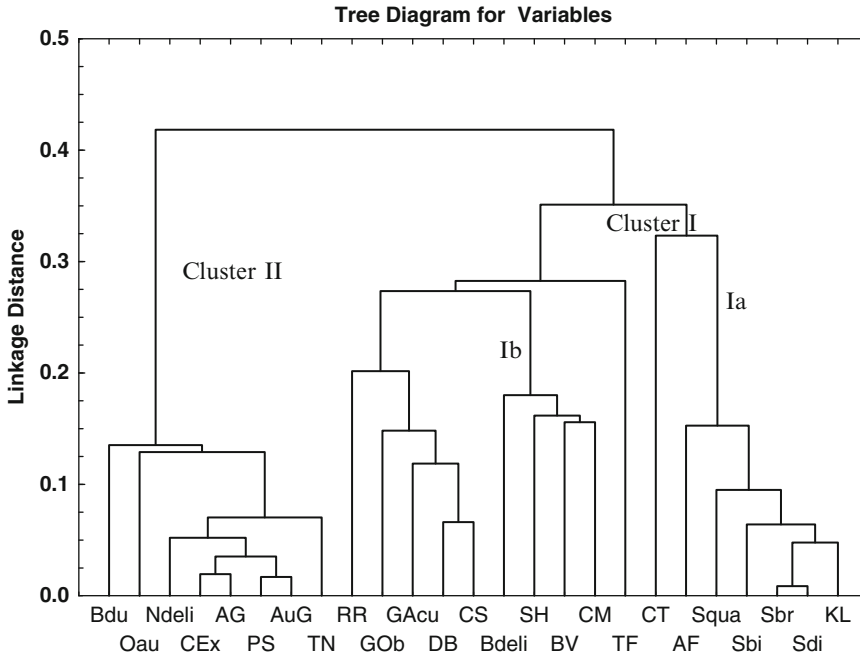
Tree Diagram for Variables

Fig. 5.33 UPGA cluster diagram based on seasonal abundance of different phytoplankton genera recorded from the estuarine station

although their availability were recorded under similar environmental conditions, their cell counts varied significantly during the sampling periods.

Cluster II represented the population of the late post-monsoon and winter periods when diatoms were the only representative taxa with no availability of any green algae. Cluster II was mainly represented by both centric and pennate diatom taxa. The pennate diatom population was represented by taxa like *Nitzschia delicatissima*, *Thalassionema nitzschoides* and *Amphiprora gigantea* whereas the centric diatom population was represented by *Odontella aurita*, *Biddulphia dubia*, *Coscinodiscus excentricus*, *Paralia sulcata* and *Aulacoseira granulata*.

In an attempt to better understand the phytoplankton species composition of the estuarine region as responses to environmental variables, PCA was implemented by taking into account the availability data of the 21 most abundant taxa. Based on eigenvalues, the PCA plot was done taking in consideration PC 1 and PC 2 that together explained 71.35 % of the variance within the data set.

The two-dimensional diagram showed the distribution of taxa in all the four quadrants (Fig. 5.34). The distribution of taxa in the PCA plot follows the cluster formation of phenogram. PCA also reveals the environmental variables responsible for separation of taxa along the different dimensions.

Here again, like our freshwater station, based on the factor loading values of each environmental variable along PC 1 and PC 2, PC 1 could be designated as a negative temperature gradient from right to left (Fig. 5.34) whereas PC 2 can be designated as a positive salinity gradient from top to bottom. As evident from the PCA plot, mainly three groups of phytoplankton populations could be observed. The 1st group consists of those species (e.g. *Biddulphia dubia*, *Odontella aurita*, *Thalassionema nitzschoides*, *Amphiprora gigantea*, *Aulacoseira granulata*) that have a high positive loading along PC 1 with low negative loadings along PC 2. On closer observation, it can be further observed that the differences in loadings among the different members in this group are low, thereby suggesting their similar
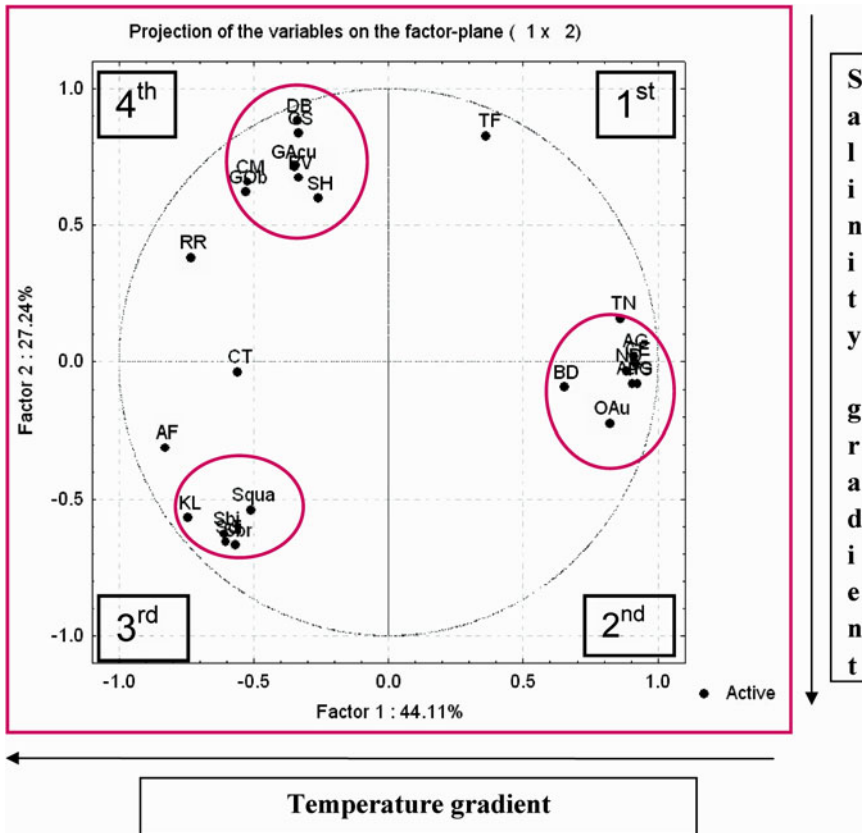
Fig. 5.34 PCA plot of Factor 1 vs. Factor 2 showing the pattern of species orientation based on environmental variables and magnitude of abundance at the estuarine station

patterns of occurrence with almost similar affinities to temperature and salinity. On the other hand, the 2nd group consists of those members (e.g. *S. brevicauda, S. bijuga, S. quadricauda, Ankistrodesmus falcatus*) that have intermediate to high negative loadings along PC 1 with intermediate negative loadings along PC 2. This suggests that the population have similar preferences for temperature and salinity, with almost similar patterns of abundance. A 3rd group of species was observed which was represented by species with intermediate negative loadings along PC 1 and very high positive loadings along PC 2 (*Ditylum brightwellii*, *Cyclotella meneghiniana*, *C. striata*, *Gyrosigma obtusatum*, *G. acuminatum*, *Bacteriastrum varians* and *Stephanodiscus hantzschii*). This shows that these genera mainly flourished under relatively oligohaline conditions when temperature was comparatively low.

As evident in the spatial orientation of the different phytoplankton genera recorded from the estuarine habitat, the plot was more spatially distributed as compared to the PCA from our freshwater station. Accordingly, in an attempt to understand whether if any seasonal succession pattern was operative at this station, multidimensional scaling (MDS) was performed. The applicability of this procedure was that the orientation in MDS plot was done on two dimensional spaces where nonlinear relationships between species scores were taken into consideration as well.

In the MDS plot (Fig. 5.35) of the phytoplankton population at the estuarine station, 3 distinct groups were configured. Starting from an anticlockwise direction (Group 1), members *Scenedesmus* spp. appeared along with *Kirchneriella lunaris* (KL), *Ankistrodesmus falcatus* (AF) and *Crucigenia tetrapedia* that
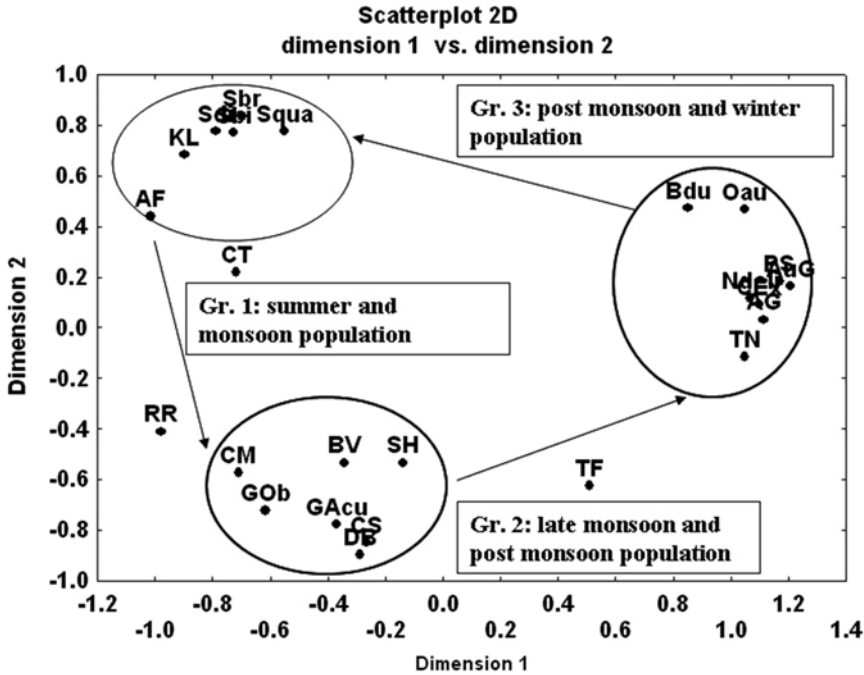
Fig. 5.35 Multidimensional scaling (*MDS*) of different species considering Dimension 1 and Dimension 2 at the estuarine station

represented the population of the summer and early monsoon months. *Rhizoclonium riparium* (RR) began to flourish in late summer months and continued to increase in population to the monsoon period. In the post-monsoon period, as seasonal precipitation receded, there were significant alterations of the available nutrient concentration and accordingly the population fluctuated with the abundance of diatom taxa (Group 2) like *Cyclotella meneghiniana* (CM), *C. striata* (CS), *Gyrosigma obtusatum*, *G. acuminatum*, *Ditylum brightwellii*, *Bacteriastrum varians* and *Stephanodiscus hantzschii* which were available only in the months of October and November with intermittent presence in the late monsoon months. In winter season a different population flourished which was represented by genera like *Biddulphia dubia* (Bdu), *O. aurita* (OAu), *N. delicatissima* (Ndeli), *Thalassionema nitzschoides* (TN), *Amphiprora gigantea* (AG), *Aulacoseira granulata* (AuG), *Pleurosigma salinarum* (PS) and *Coscinodiscus excentricus* (CEx) (Group 3). These genera appeared mostly in the late post-

monsoon period of November and flourished in the winter months and gradually diminished with the approach of the summer months.

Similar cluster analysis and principal component analysis were performed with the 36 most abundant taxa recorded from the coastal marine region. Here, three distinct groups of phytoplankton population were recorded which were designated as Cluster I, Cluster II and Cluster. Cluster I comprised of 15 taxa, Cluster II comprised of 18 taxa and Cluster III was represented only by 3 taxa. Unlike the freshwater and estuarine stations, the linkage distances were comparatively higher which suggest that the within cluster association between species was less specific with respect to the period and magnitude of abundance, as was observed for the other stations. Furthermore, each cluster was further divided into subgroups which represented different associations of phytoplankton species assemblages (Fig. 5.36).

Cluster I was represented by 3 taxa, namely, *Nitzschia sigmoidea* (NS), *Gyrosigma acuminatum* (Gacu) and *Asterionella japonica* (AJ).
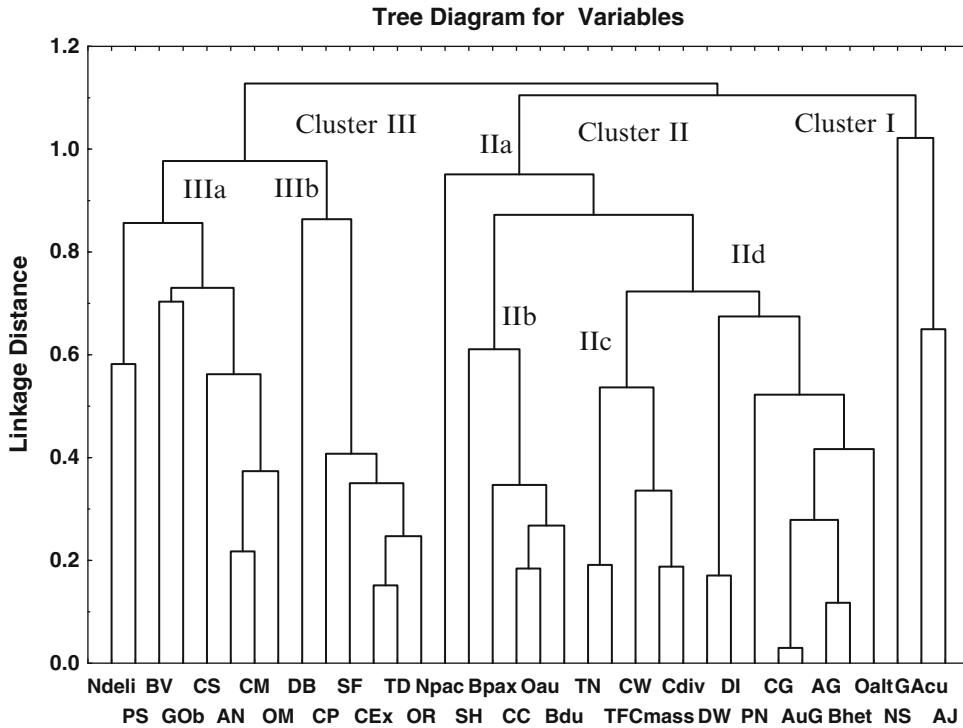
Fig. 5.36 UPGA cluster diagram based on seasonal abundance of different phytoplankton genera recorded from the coastal marine region

All the taxa showed different periods of availability. Among them, A. japonica showed a very high abundance in winter months and contributed maximally to the phytoplankton population of winter.

Cluster II consisted of four subgroups of which IIa was represented by the single species *Nitzschia pacifica* (Npac) that had a very restricted appearance only in the post-monsoon period with low cell counts. Subgroup IIb was composed of five species which were *Stephanodiscus hantzschii* (SH), *Bacillaria paxillifer* (BPax), *Coscinodiscus centralis* (CC), *Odontella aurita* (Oau) and *Biddulphia dubia* (Bdu). These taxa appeared as a component of the phytoplankton population in the late monsoon to post-monsoon periods and continued to flourish till the early summer months (March and April) that accounted for a significant proportion of the phytoplankton population. Subgroups IIc and IId consisted of the taxa appeared mainly in

the late monsoon and post-monsoon periods but did not flourish significantly.

Cluster III comprised of two subgroups that are represented as IIIa and IIIb. Subgroup IIIa consisted of 8 species which are *Nitzschia delicatissima* (Ndeli), *Paralia sulcata* (PS), *Bacteriastrum varians* (BV), *Gyrosigma obtusatum* (GOb), *Cyclotella striata* (CS), *Actinocyclus normanii* (AN), *Cyclotella meneghiniana* (CM) and *Odontella mobiliensis* (OM). These taxa primarily appeared in the early summer period (March and April) and continued to flourish in the early monsoon months (July to September) with relatively low cell counts. Subgroup IIIb was represented by 6 species like *Odontella rhombus* (OR), *Coscinodiscus perforatus* (CP), *Coscinodiscus excentricus* (CEx), *Thalassiosira decipiens* (TD), *Ditylum brightwellii* (DB) and *Surirella fastuosa* (SF). These taxa appeared in the summer months (April–June) and continued to flourish in the monsoon to post-monsoon
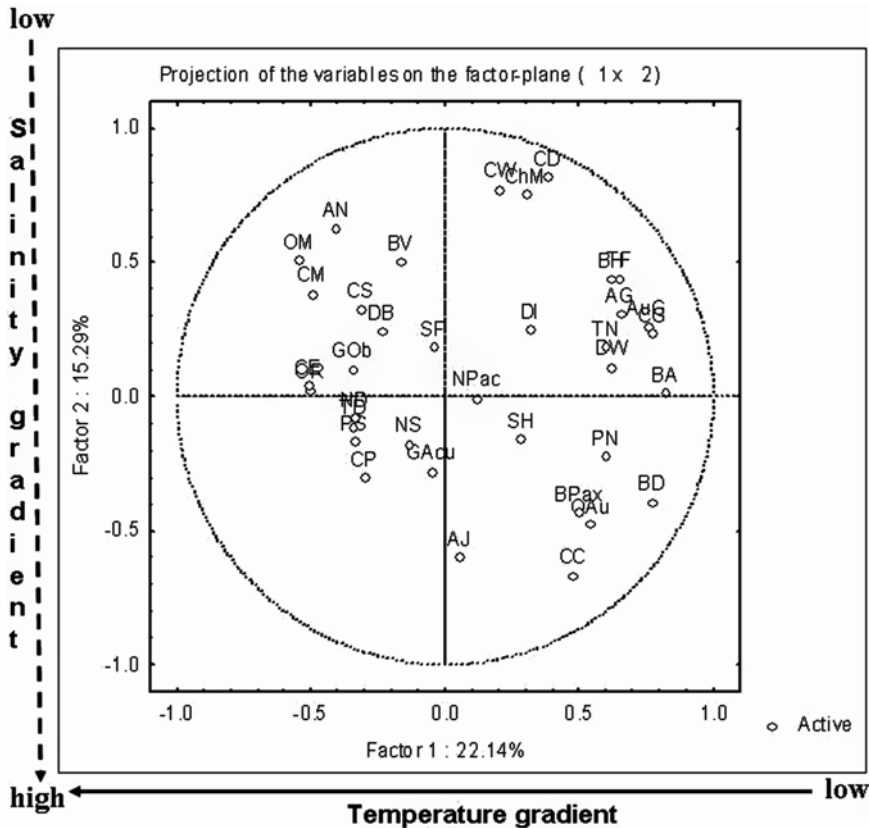
Fig. 5.37 PCA plot of PC1 vs. PC2 showing the pattern of species orientation based on environmental variables and magnitude of abundance at the coastal marine region

periods with comparatively higher cell counts than in the subgroup IIIa.

As evident, the cluster analysis did not show well-demarcated species associations, as was observed for the freshwater station. Accordingly, to further understand the species-specific responses of phytoplankton populations to environmental variables, principal component analysis was carried out as well.

In our principal component analysis (PCA) study of the species composition at the marine coastal region, the factor loading matrix indicates the correlation between each principal component to each of the species. In our study, species that appeared only once in the total sampling period were not considered. Out of 36 species considered, 11 had their strongest correlation with highest factor loading with the first two principal components (PC 1 and PC 2). Accordingly the PCA plot was done

considering PC 1 and PC 2. These two components explained 37.43 % of the variation within the species data. The covariates in the PCA plot were grouped together based on their factor loading values along PC 1/PC 2. Covariability between the species plotted along PC 1 and PC 2 was relatively high because the explained variance by the first two principal components is about 6.5 times higher than it would have been if the time series of the 36 algal species were not correlated at all. Thus, more than one-third of the variation in the 36 algal species during the study period is accounted for by the 1st and 2nd principal components in our plot. On plotting PC 1 against PC 2, the variability in individual species occurrence becomes evident, where the distance between the plotted species points provide a relative measure of the degree of similarity/dissimilarity between species with respect to both their seasonal occurrence and magnitude of abundance.

The temporal pattern of occurrences of each individual species was also accounted by plotting PC 1 vs. PC 2. As evident from our PCA plot, (Fig. 5.37) a negative temperature gradient was established along PC 1. Accordingly, genera with a high positive factor loading along PC 1 flourished in the cooler months with comparatively low water temperature. Thus, genera with positive factor loadings on PC 1 are more abundant in the post-monsoon and winter months when the average temperature is about 12–18 °C. On the contrary, genera with negative factor loading along PC 1 had a preference to flourish in the summer months when the average water temperature is comparatively higher (30–36 °C). PC 2 axis represents the relative degree of variation in temporal occurrence with low to high gradient of species availability during an annual cycle. As evident from the plot PC 2 also represent a salinity gradient from top to bottom in which the species align as per their salinity requirement. Species having a high positive correlation with this vector generally exhibited a specific seasonal occurrence where salinity requirement was low (as the gradient is from low to high).

Accordingly, from the PCA plot (1st quadrant) it was evident that *Biddulphia alternans* (BA) along with other genera like *Thalassionema nitzschoides* (TN), *Diploneis interrupta* (DI) and *Diploneis weissflogii* (DW) are more abundant in the post-monsoon and winter months. Taxa like *C. granii* (CG), *A. gigantea* (AG) and *Aulacoseira granulata* (AuG) have intermediate positive factor loading on PC 1 which are the representative of only the particular post-monsoon period with low or no availability in other seasons. Genera like *Chaetoceros wighami* (CW), *C. messanensis* (ChM) and *C. diversus* (CD) had a very high positive loading along PC 2 with intermediate factor loading along PC 1 which can be clearly explained by the fact that their availability was restricted to the monsoon season (water temperature 28–32 °C) and they never flourished in any other season. Genera with a positive factor loading on PC 1 but negative loading on PC 2 (2nd quadrant) were mostly available in the late post-monsoon to winter months with a high abundance. This is because during this period average

water temperature is low, but with a decrease in both seasonal and riverine precipitation there is a rise in salinity. Accordingly, genera like *Biddulphia dubia* (BD), *Odontella aurita* (OAu) and *Coscinodiscus centralis* (CC) attained their peak growth in this period with high abundance which culminated with a very high cell count of *A. japonica*. Genera in the 3rd quadrant had intermediate negative factor loading for both PC 1 and PC 2. Hence, these genera flourished in the relatively warmer months when salinity was about 32–35 psu but with a low cell count. *Nitzschia sigmoidea* (NS) and *Gyrosigma acuminatum* (GAcu) were available only in the months of March and April. *Nitzschia delicatissima* (ND) and *Paralia sulcata* (PS) were exclusively available only in the months of April to July during the entire study period. Thus, the findings clearly suggested that these genera represented the population of the transitory period from winter to summer months. Finally, the 4th quadrant comprised of those genera which were abundant in the warmer months but were significantly less in the winter months of December and January with a relatively high cell count of individual species. Along with genera like *O. rhombus* (OR) and *C. excentricus* (CE), genera like *Odontella mobiliensis* (OM), *Cyclotella meneghiniana* (CM) and *Actinocyclus normanii* f. *subsala* (AN) had negative loading on PC 1 but intermediate positive loading along PC 2, suggesting their relatively even abundance with high density in the summer and monsoon periods.

For further confirmation of this seasonal pattern of species based upon their abundance data and preference for temperature and salinity, multidimensional scaling (MDS) was performed (Fig. 5.38). The MDS configuration plot of all genera (Dimension 1 vs. Dimension 2) clearly demarcates distinct groups based upon the seasonal preference of the individual species.

In the MDS plot 5 distinct groups were configured. Starting from an anticlockwise direction from summer months (Group 1), the genera *O. rhombus* (OR), *Coscinodiscus excentricus* (CE) and *O. mobiliensis* (OM) appeared together as the dominant genera of the summer months along with *C. meneghiniana* (CM) that was available in
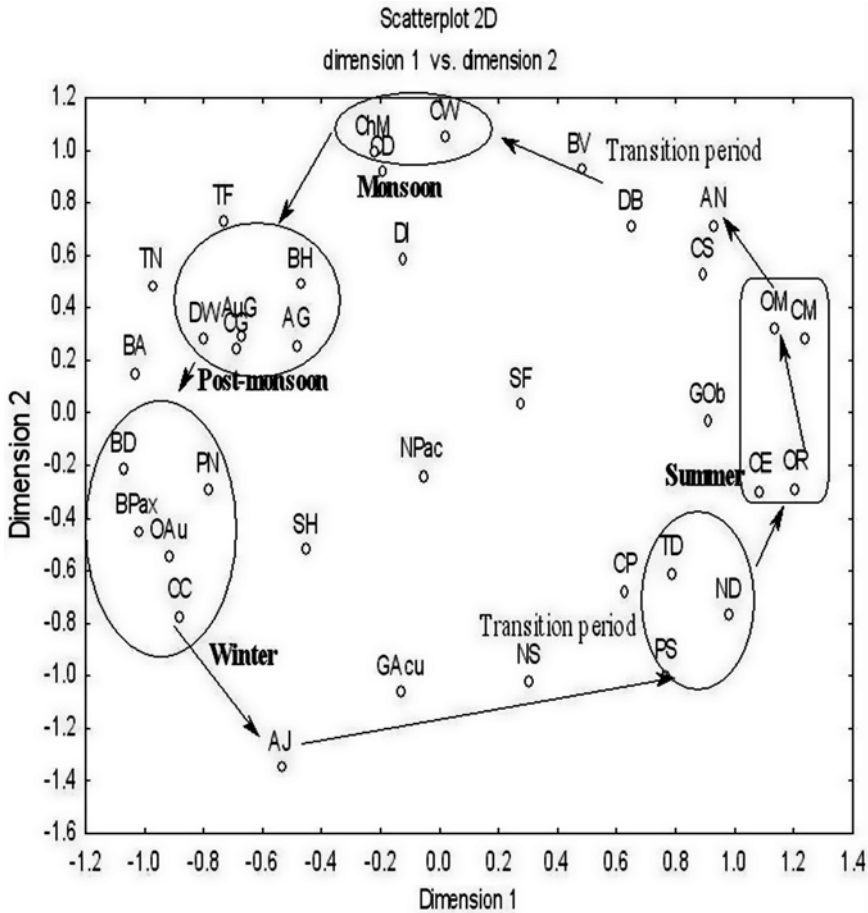
Fig. 5.38 Multidimensional scaling of different species considering Dimension 1 and Dimension 2 at the coastal marine region

other seasons as well but had a preference for the summer months. Genera like *Ditylum bright-wellii* (DB), *Cyclotella striata* (CS) and *A. nor-manii* f. *subsala* (AN) began to flourish in the summer months and continued to increase in population to the monsoon period and accordingly they are representative of the transition from a summer to a monsoon season. With the advent of the monsoon months there is significant alteration of the available nutrient concentration and accordingly the population fluctuates with the abundance of representative genera (Group 2) like *Chaetoceros wighami* (CW), *C. messanensis* (ChM) and *C. diversus* (CD). As monsoon is prolonged there is significant enhancement of nutrient input but reduction in mean salinity. Accordingly, phytoplankton population is highly

specific which is evident from the fact that the different species of *Chaetoceros* do not flourish at any other season of our sampling period except monsoon. In the post-monsoon period phytoplankton population changes with the appearance of representative genera like *B. heteroceros* (BH), *A. granulata* (AuG), *A. gigantea* (AG), *C. granii* (CG) and *D. weissflogii* (DW) (Group 3) which were available only in the months of October and November with intermittent presence in the late monsoon months. In winter season a different population flourished which was represented by genera like *Biddulphia dubia* (BD), *O. aurita* (OAu) *Pleurosigma normanii* (PN), *B. paxillifer* (BPax) and *Coscinodiscus centralis* (CC) (Group 4). These genera appeared mostly in the late post-monsoon period of November and flourished in

the winter months and gradually diminished with the approach of the summer months. This winter population finally culminated with the abrupt rise in *A. japonica* (AJ) population where only a very few individuals of other species developed. Genera like *G. acuminatum* (GAcu) appeared in the late winter months of February and flourished in March till the early summer months of April. Likewise *Nitzschia sigmoidea* (NS) and *N. delicatissima* (ND) (Group 5) appeared in the early summer month of April and accordingly they are considered as representatives of the transitory population between a winter and summer phytoplankton population. *Surirella fustuosa* (SF) and *N. pacifica* (NPac) appeared irregularly with very low cell count. On the contrary, *Stephanodiscus hantzschoides* (SH) appeared all throughout the year and did not show any seasonal preference. Accordingly, these genera appeared in the middle of the MDS configuration in a scattered manner and did not belong to any particular group.

Phytoplankton population of coastal area is controlled by various physical, chemical and biological factors which ultimately regulates the phytoplankton dynamics of particular ecosystem. Results showed that coastal West Bengal represented a diverse phytoplankton population which is primarily composed of members of Cyanophyta, Chlorophyta and Bacillariophyta. Members of Bacillariophyta or diatoms made up the bulk of the population, followed by green and blue-green algae. This was evident from the findings which showed that out of the 75 phytoplankton taxa recorded, 51 were diatoms. In the freshwater and estuarine region, the phytoplankton flora was mainly represented by members of Cyanophyta, Chlorophyta and diatoms. On the other hand, the marine coastal region was represented by diatoms only. The diatom population primarily comprised of the members belonging to the tribes Coscinodisceae, Chaetocerae, Biddulphieae (Centrales) and Naviculeae (Pennales) (Cupp 1943). A high availability of diatoms as a major component of coastal and estuarine plankton population has been reported from other parts of the Indian subcontinent as well. A detailed account of the phytoplankton population along Madras coast was prepared by

Venkataraman (1939) where he reported 98 taxa belonging to 33 genera. In another significant work on Madras coast, 134 species belonging to 64 genera were reported by Subrahmanyan (1946). Later, a total of 57 species of diatoms belonging to 36 genera were reported from the Gulf of Kutch, western coast of India (Gopalakrishnan 1972). In a 1-year study from the Mandovi–Zuari estuary a total of 48 phytoplankton species were identified – of which 37 species were diatoms and only 2 taxa were blue-green algae (Krishna Kumari et al. 2002). In a more recent work from the Zuari estuary, Goa, 66 planktonic diatom species belonging to 29 genera were recorded, of them 36 species were Pennales, whereas 30 species were of Centrales (Redekar and Wagh 2000). The dominance of diatoms as a component from marine coastal regions has been reported from other stations along the Bay of Bengal as well (Madhupratap et al. 2003). Thus, abundance of diatoms has been reported from all the Indian estuaries and coastal waters – where members of Chaetoceraceae, Coscinodiscaceae and Naviculaceae are more abundant (Venkataraman and Wafar 2005). Hence, our findings in the present study along coastal West Bengal were well in agreement with other records from different estuaries of the Indian subcontinent.

From the results it is evident that species composition pattern did not show significant interannual variations. Here, almost the same genera appeared in the same pattern in successive years. Enormous freshwater run-offs from several major rivers may result in strong vertical stratification that inhibits vertical mixing (Gopalakrishnan and Sastry 1985). According to them, lack of intense upwelling of this coast is due to the equator ward flow of the freshwater plume, which resulted in overwhelming of the offshore Ekman transport in the coast of Bay of Bengal. These conditions accounted for the similar seasonal plankton dynamics with minimal interannual variability. This lack of upwelling events can be further attributed to the fact that the Bay of Bengal, especially the northern parts, represents a very narrow shelf (Qasim 1977; SenGupta et al. 1977; Radhakrishna et al. 1978).

Among diatoms on a generic level, *Coscinodiscus*, *Leptocylindrus*, *Chaetoceros*, *Biddulphia*, *Odontella*, *Gyrosigma*, *Ditylum*, *Thalassionema*, *Thalassiothrix*, *Navicul*a and *Nitzschia* have been recorded as dominant taxa from this region. Along with the diatom genera, green algal genera like *Kirchneriella*, *Ankistrodesmus*, *Pediastrum*, *Scenedesmus* and the blue green algal genera like *Merismopedia* and *Microcystis* were available in this region. Abundance of *Chaetoceros* spp. and *Bacteriastrum* spp. were observed only during the monsoon period mainly at the estuarine and marine region along coastal West Bengal. In other reports, dominance of pennate members like *Nitzschia* spp. have been reported from the freshwater regions while genera like *Coscinodiscus* spp. were more abundant in the high-salinity zones of both Zuari River and Mandovi River estuary (Matondkar et al. 2006). Dominance of members of *Chaetoceros* spp. from June to September (monsoon months) has also been reported from the neritic zone of the Urdaibai estuary at northern Spain (Trigueros and Orive 2001).

From our study along coastal West Bengal, it was established that each station had different dominant representative taxa such as *Leptocylindrus danicus* at freshwater station, *Thalassiothrix frauenfeldii* at estuarine station and *Asterionella japonica* at marine region. A similar high abundance of *Asterionella japonica* in winter months has been reported from the adjacent Orissa coast where it made up almost 99 % of the total population (Sasamal et al. 2005). In the estuarine and marine region, abundance of euryhaline taxa like *Skeletonema costatum*, *Thalassiosira decipiens*, *Thalassionema nitzschoides* was recorded. High abundance of chain forming diatom genera like *Leptocylindrus danicus*, *Thalassiosira decipiens* and *Skeletonema costatum* have been reported from the Alboràn Sea, a continuation of southwest Mediterranean Sea (Mercado et al. 2005). These taxa are common in other estuaries around the world as well which are subjected to large salinity variations due to precipitation and riverine discharge, including Apalachee Bay (Curl 1959), Perdido

Bay, (Livingston 2001), Indian River Lagoon (Badylak and Phlips 2004), Florida and in many estuaries of North Carolina (Mallin 1994). The rise in larger-sized pennate diatoms along with colonial forms like *Asterionella japonica*, *Thalassionema nitzschoides, Thalassiothrix frauenfeldii*, *Gyrosigma beaufor-tianum*, *Pleurosigma salinarum*, *Bacillaria paxillifer*, *Nitzschia sigmoidea*, etc. during the cooler post-monsoon and winter months can be attributed to the strong northeastern winds (De Jonge and van Beusekom 1995). The availability of these taxa at highly diverse habitats at different parts of the world further suggests that these euryhaline phytoplankton genera are cosmopoli-tan in distribution and can develop under diverse physicochemical conditions.

Diversity indices are calculated on the basis of total biomass data obtained from cell count method and the number of individuals, which indicate the community pattern of the particular ecosystem. Results showed that diversity was highest at freshwater station and minimum at the estuarine station, with marine coastal region occupying an intermediate position. This was in agreement with earlier reports from Santa Catalina basin, off the coast of California and Norwegian Sea, where low diversity has been reported due to physical variability in the estua-rine and the sandy coast (Jumars 1976). Our study showed that, in the month of July or in monsoon season, nutrient concentration was high with well mixing due to seasonal precipitation and riverine influx of nutrient rich water. This resulted in the development of a suitable condi-tion for phytoplankton diversification that accounted for maximum SW Index in the post-monsoon period with stabilized nutrient pool. Thus, in the present study, post-monsoon period (October–November) appeared to be most conducive for phytoplankton diversity showing maximum diversity index throughout the study area, although total phytoplankton cell counts were maximum in winter. Observation of maxi-mum diversity in post-monsoon period agrees well with the earlier reports for Hugli estuary, north east coast of India (De et al. 1994) and Vellar estuary (Hangovan 1987).

High species evenness with negligible variations at the freshwater and estuarine stations signifies that the percentage contributions of individual taxon to the total phytoplankton population were almost similar during the entire sampling period. This was in contrast to the marine region where it was maximum in monsoon months and minimum in winter. Decreasing tendency of SW Index and species evenness indicate shifting of phytoplankton community from high species richness to bloom formation, as reported by many authors in eutrophic and hypertrophic lakes and reservoirs (Jacobsen and Simonsen 1993; Padisak 1993). Thus, the drop in biotic indices in winter at the marine station was primarily due to very high abundance of *Asterionella japonica* population that accounted for more than 90 % of the phytoplankton population. A similar finding was recorded for the summer months at the coastal marine station as well with the development of a different population (*Odontella rhombus*). In the monsoon period, the water column was highly disturbed due to seasonal precipitation, riverine inflows and alternating air currents due to cyclonic weather. As a result, phytoplankton count was low with intermediate value for species evenness in the monsoon period.

Results of cluster analysis and multidimensional scaling further testified the specific seasonal patterns of phytoplankton availability. Cluster analysis maximizes between group associations and minimizes within group association (Ramette 2007). Thus, the very narrow distances between the subgroups within each cluster suggest the close association between the different algal taxa. On the other hand, the high linkage distances between each cluster further suggest that each population is highly demarcated from each other. MDS plots help in orienting variables in a two-dimensional space where nonlinear relationships are also taken into consideration. Thus, while understanding the seasonal patterns among phytoplankton population from both these multivariate procedures, it is clearly evident that seasonal succession at the freshwater station was not very pronounced. On the other hand, seasonal patterns were more evident at the estuarine station. At the coastal marine region, seasonal

succession was clearly evident where each season was clearly represented by distinct species assemblages.

Results showed that both productivity and cell counts were maximum at the coastal marine region and minimum at the estuarine region. Highly significant correlations between phytoplankton cell counts and GPP clearly established that GPP was actually the total photosynthetically fixed carbon by the phytoplankton population. Seasonally, as can be expected from cell count data, productivity was maximum in winter and minimum during the monsoon period along West Bengal coast. Planktonic photosynthetic productivity is one of the major contributors to the overall productivity of open aquatic ecosystems. The efficiency of energy transfer from phytoplankton to consumers and ultimate production at upper trophic levels vary with algal species composition. It is well known that diatom-dominated marine upwelling systems sustain more fish biomass per unit of phytoplankton biomass than cyanobacteria-dominated lakes, which was also evident in coastal West Bengal. Unlike, the coastal marine and freshwater regions, the low productivity at the estuarine station can be attributed to the excessive fishing activity and transportation of vessels from Kakdweep. Such commercial exploitation could have resulted in highly disturbed water column that may have accounted for an unstable stratification, resulting in decrease in productivity. NPP is a measure of available photosynthetically fixed carbon after eliminating the catabolic loss of organic matter due to respiration (CRR). Accordingly, a drop in NPP and rise in CRR clearly shows that carbon utilization was comparatively high in comparison to carbon assimilation. Such an observation can be attributed to the fact that a rise in nutrient-rich freshwater influx in the habitat waters under warm conditions led to an increase in the heterotrophic population which accounted for the enhanced carbon utilizations. A similar result was also obtained from the Mandovi River estuary (Verlencar and Qasim 1985) having highest productivity in the post-monsoon season with intermediate values in the pre-monsoon period and the lowest productivity in monsoon. A drop

in primary productivity in the monsoon months and a rise of the same in the post-monsoon period was also reported from Lake Tana in Ethiopia (Wondie et al. 2007).

Variations in DO contents showed a similar pattern of variation as was observed for cell counts and productivity in both freshwater and estuarine stations. Thus, DO levels at the freshwater station were comparatively higher than at the estuarine station. Although the freshwater and estuarine stations represented optimum DO levels, DO levels at the marine coastal region represented an undersaturated condition although cell counts were maximum among all the three stations. During the monsoon months, heavy seasonal precipitation promotes an enhanced freshwater inflow with high suspended matter content, resulting in a very turbid water column at the marine region. This turbid nature of the water column may result in a decrease in the photic zone. Thus, although the incident irradiance was high, the average irradiance in the water column was relatively low which may have accounted for the drop in DO levels in the habitat waters at the marine coastal region with low photosynthetic activity. Another significant observation was the rise in BOD levels in the monsoon months and a drop in the same during the winter periods. The significant negative correlations between DO and BOD levels at all the sampling stations indicate the high heterotrophic growth during the monsoon months which resulted in the decreased DO levels.

It is evident from the findings that physicochemical properties of habitats play a determining role in the development and proliferation of phytoplankton populations at coastal West Bengal. In this tropical coastal area, optimal light and nutrient availability in association with other physical parameters like pH, temperature and salinity allowed diverse populations to develop with high cell counts.

Temperature in association with salinity played a significant role in determining the phytoplankton species composition. The restrictive appearance of cyanobacterial taxa in the freshwater region during summer and early monsoon period is a testimonial of the fact that cyanobacteria had a distinct preference for hypo-saline conditions with high temperature. Studies on cyanobacterial populations from other parts of the world further established this correlation between temperature and blue-green algal abundance as was observed at the Great Barrier Reef in Australia (Ayukai 1992), the Mediterranean (Caroppo 2000) and Indiana River Lagoon in Florida (Badylak and Phlips 2004). Chlorophycean members were mainly restricted from the freshwater to estuarine stations which suggest that green algal population developed well under oligohaline to mesohaline conditions when temperature was relatively high. In contrast to green and blue-green algal taxa, diatoms flourished mainly under mesohaline to hyper-saline conditions with low temperature. Thus, diatoms were available from freshwater to marine region although there was a shift in the population with increase in centric diatom population as the river approached the sea.

Results of PCA further underline the role of temperature and salinity in determining the species composition at each coastal station. In PCA, new synthetic ordinates are developed, based upon the linear relationships between variables. Accordingly, PCA plots of species abundance in relation to environmental variables clearly suggest that temperature and salinity are the most important factors that determine the species composition at all the stations along coastal West Bengal. An increase in Bacillariophycean members under conditions of low temperature in winter (fall) and spring has also been observed from Nakdong River, South Korea (Ha et al. 1998), where almost similar conditions of temperature and salinity were observed as was along coastal West Bengal.

The pH level varied from 7 to 8.3 at the entire sampling area which indicates the neutral to alkaline nature of the habitat waters. Several reports from different coastal regions of the world represent similar neutral to alkaline pH gradients (Skirrow 1975; Pegler and Kempe 1988; Brussaard et al. 1996; Hinga 2002). Salinity seems to play a significant role in pH changes as it influences the various equilibrium constants of temperature and alkalinity.

Phytoplankton development and succession is dependent not only on physical parameters but

also on chemical factors like dissolved oxygen and nutrient availability (Reynolds 1984). Nitrogen and phosphorus are the most essential components for development of biological populations with no exception for phytoplankton as well. In an aquatic environment nitrogen, sources are mainly available as nitrate and nitrite, whereas phosphorus source is available in the form of phosphate. It has long been proposed that marine and estuarine phytoplankton abundance is N limited, whereas freshwater phytoplankton is P limited. Relatively high levels of DIN and DIP were maintained during the entire study period at all the stations which suggest that nutrient levels were well above the optimum levels and did not act as limiting factors. Cultural eutrophication was also an important factor for the relatively high DIN and DIP levels in this region. At the freshwater station DIN and DIP contents were comparatively higher than DSi. On the other hand, DIN and DSi contents were higher in the estuarine station and in the marine coastal region. Moreover, during the monsoon months, as seasonal precipitation increased, it resulted in a rise in inflow of nutrient-rich freshwater from perennial sources and from other tributaries. This accounted for an increase in nutrients especially DIN and dilution of phytoplankton population. Thus, the DIN-rich habitat waters allowed the development of cyanobacterial taxa like *Gloeocapsa* sp., *Gleothece* sp., *Merismopedia* spp., *Microcystis aeruginosa*, *Spirulina* spp., which are efficient nitrogen fixers. Diatoms accounted for a major proportion of the phytoplankton population especially during the post-monsoon and winter months. Diatom production can be limited by the availability of dissolved silicate (DSi) and DSi depletion relative to other major nutrients (Kilham 1971; Schelske and Stoermer 1971; Malone et al. 1980). DSi levels were maintained in optimum conditions throughout the study area. The comparatively low DSi concentrations in winter months were primarily due to excessive growth of planktonic diatom population which can be inferred from correlation studies as well. Thus, although salinity and temperature were the primary regulatory factors in the

species composition and succession patterns at coastal West Bengal, nutrient availability also played an important role in phytoplankton dynamics.

This region represented a highly diverse phytoplankton population where seasonal succession was relatively pronounced. Temperature and salinity gradients were the principle determining factors for the seasonal variability in species composition, although nutrient concentrations also played an important role. The freshwater station was more affected due to anthropogenic nutrient loadings, whereas the marine coastal region was least. The estuarine station was a disturbed ecosystem that resulted in less diversification of phytoplankton population. The marine region was comparatively more stable from an ecological point of view where different aspects of population dynamics were more evident as compared to the other stations along coastal West Bengal.

5.4.2.6 Taxonomic Account of Common Phytoplankton Taxa Recorded from Indian Coast

Division – Cyanophyta
Class – Cyanophyceae
Order – Chroococcales
Family – Chroococcaceae

1. *Gloeocapsa punctata* Naegeli (Plate 5.5, Fig. A)

[Desikachary, 1959, p. 115, pl. 23, Fig. 2]

Plant mass blue green, floating, consisting of small aggregated of 8–16 individuals which are spherical and inclosed by thick sheaths; cells 2 μ in diameter; contents blue–green, homogenous

2. *Microcystis aeruginosa* Kuetz. emend. Elekin (Plate 5.5, Fig. B)

[Desikachary, 1959, p. 93, pl. 17, Figs. 1, 2 & 6, pl. 18, Fig. 10]

An irregularly lobed, saccate and clathrate colony of numerous spherical cells which are much crowded within a gelatinous matrix (several colonies invested by a common tegument), colonial mucilage hyaline and homogenous; cell contents blue green, highly granular; cells 3.5 μ in diameter
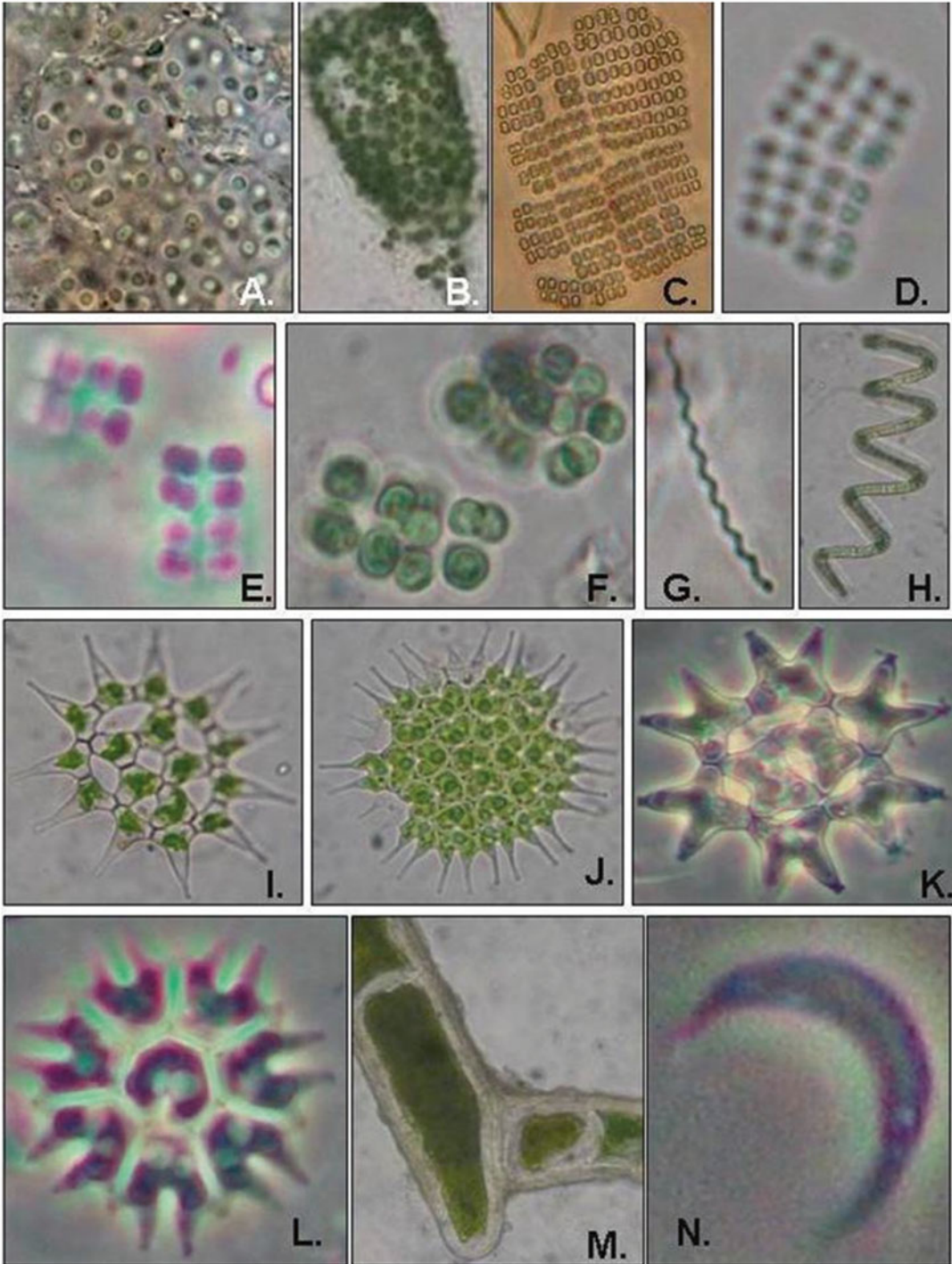
Plate 5.5 (**A**) *Gloeocapsa punctata* Naegeli, (**B**) *Microcystis aeruginosa* Kuetz. *emend.* Elekin, (**C**) *Merismopedia glauca* (Ehrenb.) Naegeli, (**D**) *Merismopedia minima* Beck, (**E**) *Merismopedia punctata* Meyen, (**F**) *Gloeothece rupestris* (Lyngb.) Bornet *in* Wittrock & Nordstedt, (**G**) *Spirulina meneghiniana* Zanard. *ex* Gomont, (**H**) *Spirulina platensis* (Nordst.) Geitler, (**I**) *Pediastrum simplex* (Meyen) Lemmermann, (**J**) *Pediastrum simplex* var. *duodenarium* (Bailey) Rabenhorst, (**K**) *Pediastrum duplex* var. *rotundatum* Lucks, (**L**) *Pediastrum tetras* (Ehrenb.) Ralfs, (**M**) *Rhizoclonium riparium*(Roth) Harvey, (**N**) *Ankistrodesmus falcatus* (Corda) Ralfs

3. *Merismopedia glauca* (Ehrenb.) Naegeli (Plate 5.5, Fig. C)

[Desikachary, 1959, p. 155, pl. 29, Fig. 5]

Colony of 16–64 ovate cells, very regularly arranged to form quadrangular colonies; 5 μ in diameter; 30-celled colony 30 μ wide; cell contents bright blue green, homogenous

4. *Merismopedia minima* Beck (Plate 5.5, Fig. D)

[Desikachary, 1959, p. 154, Pl. 29, Fig 11]

Cells four to many in small colonies, 0.498–0.664 μ broad

5. *Merismopedia punctata* Meyen (Plate 5.5, Fig. E)

[Desikachary, 1959, p. 155, pl. 23, Fig. 5 & pl. 29, Fig. 6]

A rectangular plate of 32–128 ovate cells, usually loosely arranged, sometimes in compact groups of 4–8 individuals, the groups widely separated within a broad, gelatinous envelope; cells 3 μ in diameter; cells contents homogenous, blue green

6. *Gloeothece rupestris* (Lyngb.) Bornet in Wittrock and Nordstedt (Plate 5.5, Fig. F)

[Prescott, 1982, p. 462, Pl. 103, Figs. 2, 3]

Cells ovate, irregularly arranged throughout a copious colourless or brownish gelatinous matrix, in 2′s and 4′s in small families surrounded by a definite sheath; plant mass free floating, cells 4–6–(9) μ in diameter, 15 μ long

Order – Oscillatoriales

Family – Oscillatoriaceae

7. *Spirulina platensis* (Nordst.) Geitler (Plate 5.5, Fig. H)

Thallus blue green; 6 μ broad, not attenuated at the ends, more or less regularly spirally coiled; spirals 30 μ broad, distances between the spirals 45 μ; cells nearly as long as broad, 6 μ long, cross-walls granulated; end cells broadly rounded

8. *Spirulina meneghiniana* Zanard. ex Gomont (Plate 5.5, Fig. G)

[Desikachary, 1959, p. 195, Pl. 36, Fig 8]

Trichome 1.99 μ broad, flexible, irregularly spirally coiled, forming a thick blue-green thallus, spiral 4.684 μ broad

Family – Hydrodictyaceae

9. *Pediastrum duplex* var. *rotundatum* Lucks (Plate 5.5, Fig. K)

[Prescott, 1982, p. 224, Pl. 48, Fig. 8]

Marginal cells with stout lobes which have convex rather than parallel margins; apices of lobes closer together than in the typical plant

10. *Pediastrum simplex* (Meyen) Lemmermann (Plate 5.5, Fig. I)

[Prescott, 1982, p. 227, Pl. 50, Fig. 2]

Colony entire, composed of 16–32–64 smooth-walled cells, inner cells 5- or 6-sided; peripheral cells with the outer free wall extended to form a single tapering, horn-like process with concave margins; cells 12–18 μ in diameter

11. *Pediastrum simplex* var. *duodenarium* (Bailey) Rabenhorst (Plate 5.5, Fig. J)

[Prescott, 1982, p. 227, Pl. 50, Figs. 4, 5]

Colony perforate, composed of 36 cells with their inner margins concave, the outer margins of inner cells forming a long process, peripheral cells forming a stout process; cells 12 μ in diameter, 27 μ long; 36-celled colony 135 μ in diameter

12. *Pediastrum tetras* (Ehrenb.) Ralfs (Plate 5.5, Fig. L)

[Ralfs, 1844, p. 469]

Colony entire; inner cells (frequently none) with 4–6 straight sides but with one margin deeply incised; peripheral cells crenate with a deep incision in the outer margin, their lateral margins adjoined along $\frac{2}{3}$ of their length; cells 8–12–(16) μ in diameter

Family – Oocystaceae

13. *Ankistrodesmus falcatus* (Corda) Ralfs (Plate 5.5, Fig. N)

[Prescott, 1982, p. 253, Pl. 56, Figs. 5, 6]

Cells somewhat spindle shaped, solitary, not enclosed in a colonial sheath; chloroplast one, a parietal plate without pyrenoids; cells 4 μ in diameter; 65 μ long, sometimes longer

14. *A. falcatus* var. *stipitatus* (Chod) Lemmermann (Plate 5.6, Fig. Q)

[Prescott, 1982, p. 254, Pl. 56, Figs. 14, 15]

Cells lunate (rarely almost straight) attached at one pole to filamentous algae or other submerged aquatics; usually gregarious, forming clusters of 2–8; cells 3 μ in diameter; 20 μ long
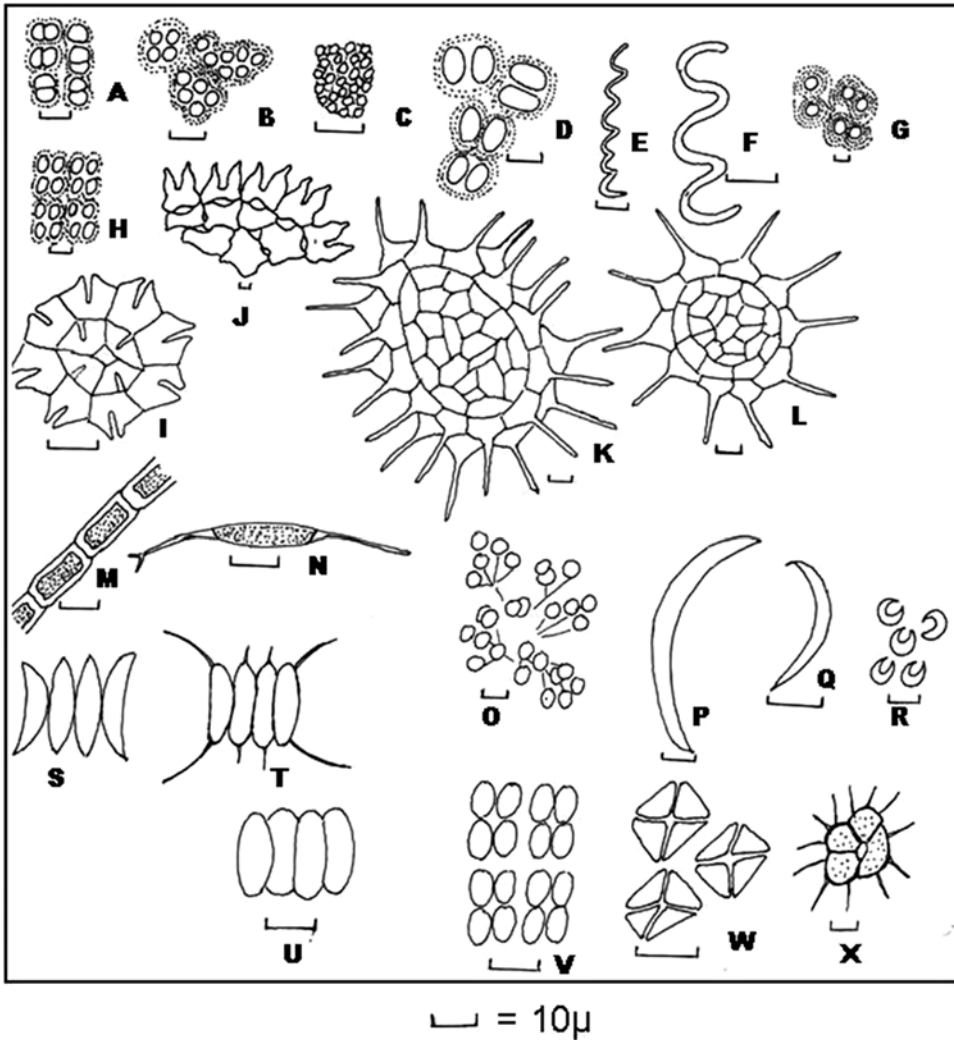
⌐_⌐ = 10μ

Plate 5.6 Explanation of plates (*Camera lucida* drawings of phytoplankton genera recorded) (**A**) *Gloeocapsa punctata* Naegeli, (**B**) *Merismopedia glauca* (Ehrenb.) Naegeli, (**C**) *Microcystis aeruginosa* Kuetz. *emend.* Elekin, (**D**) *Merismopedia minima* Beck, (**E**) *Spirulina meneghiniana* Zanard. *ex* Gomont, (**F**) *Spirulina platensis* (Nordst.) Geitler, (**G**) *Gloeothece rupestris* (Lyngb.) Bornet *in* Wittrock & Nordstedt, (**H**) *Merismopedia punctata* Meyen, (**I**) *Pediastrum tetras* (Ehrenb.) Ralfs, (**J**) *Pediastrum duplex* var. *rotundatum* Lucks, (**K**) *Pediastrum simplex* var. *duodenarium (*Bailey) Rabenhorst, (**L**) *Pediastrum simplex* (Meyen) Lemmermann, (**M**) *Rhizoclonium riparium* (Roth) Harvey, (**N**) *Schroederia judayi* G. M. Smith, (**O**) *Dictyosphaerium pulchellum* Wood, (**P**) *Ankistrodesmus falcatus* (Corda) Ralfs, (**Q**) *Ankistrodesmus falcatus* var. *stipitatus* (Chod) Lemmermann, (**R**) *Kirchneriella lunaris* (Kirch.) Moebius, (**S**) *Scenedesmus dimorphus* (Turp.) Kuetzing, (**T**) *Scenedesmus quadricauda* (Turp.) de Brébisson *in* de Brébisson & Godey, (**U**) *Scenedesmus bijuga* (Turp.) Langerheim, (**V**) *Crucigenia rectangularis* (A. Braun) Gay, (**W**) *Crucigenia tetrapedia* (Kirch.) West & West, (**X**) *Tetrastrum staurogeniaeforme* (Schröder) Lemmermann

15. *Dictyosphaerium pulchellum* Wood (Plate 5.6, Fig. O)

[Prescott, 1982, p. 238, Pl. 51, Figs. 5–7]

Colony spherical composed of as many as 32 spherical cells arranged in series of four dichotomously branched threads, inclosed in mucilage; cells 3–10 μ in diameter

16. *Schroederia judayi* Smith (Plate 5.6, Fig. N)

[Prescott, 1982, p. 256, Pl. 57, Figs. 5, 6]

Cells fusiform, straight, the poles narrowed and extended into long setae, one of which terminates into short bifurcations; one chloroplast with single pyrenoid; cells 4 μ in diameter, 55 μ long including the setae which are 13 μ long

17. *Kirchneriella lunaris* (Kirch.) Moebius (Plate 5.6, Fig. R)

[Prescott, 1982, p. 258, Pl. 58, Fig. 2]

Colony composed of numerous cells arranged in groups of 4–16 within a closed, gelatinous envelope; cells flat, strongly curved crescents with rather obtuse points; chloroplast covering the convex wall; cells 5 μ in diameter, 10 μ long; colonies 100–250 μ in diameter

Family – Scenedesmaceae

18. *Scenedesmus bijuga* (Turp.) Langerheim (Plate 5.6, Fig. U)

[Prescott, 1982, p. 276, Pl. 63, Figs. 2, 7]

Colony composed of 2–8 cells in a single (rarely alternate) flat series; cells ovate, without teeth or spines; cells 6 μ in diameter, 12 μ long

19. *Scenedesmus dimorphus* (Turp.) Kuetzing (Plate 5.6, Fig. S)

[Prescott, 1982, p. 277, Pl. 63, Figs. 8, 9]

Colony composed of 4 or 8 fusiform cells arranged in a single series; the inner walls with straight, sharp apices; the outer cells lunate, strongly curved with acute apices; cells 4 μ in diameter; 19 μ long

20. *Scenedesmus quadricauda* (Turp.) de Brébisson in de Brébisson and Godey (Plate 5.6, Fig. T)

[Prescott, 1982, p. 277, Pl. 63, Figs. 8, 9]

Colony consisting of 2-4-8 oblong, cylindrical cells usually in one series (sometimes in two alternate series); outer cells with a long curved spine at each pole; inner cells without spines or with mere papillae at the apices; cells variable in size, 12 μ in diameter, 20 μ long

21. *Crucigenia rectangularis* (A. Braun) Gay (Plate 5.6, Fig. V)

[Prescott, 1982, p. 285, Pl. 65, Figs. 7, 8]

Colony free floating consisting of ovate cells, very regularly arranged about a rectangular central space in two pairs, with the apices adjoining; cells 5.5 μ in diameter, 8 μ long

22. *Crucigenia tetrapedia* (Kirch.) West & West (Plate 5.6, Fig. W)

[Prescott, 1982, p. 285, Pl. 65, Fig. 9; Pl. 66, Fig. 1]

Colony free floating consisting of four triangular cells cruciately arranged about a minute central space; outer free wall and lateral walls straight, the angles acutely rounded; cells 6 μ in diameter; frequently forming a rectangular plate of 16 cells (four quartets)

23. *Tetrastrum staurogeniaeforme* (Schröder) Lemmermann (Plate 5.6, Fig. X)

[Pl. 66, Fig 3, Pg 286, Prescott]

A colony of 4 triangular cells, cruciately arranged about a small rectangular space; lateral margins of the cell straight, the outer free walls convex and furnished with hairlike setae; cells 3.81–4.15 μ in diameter, colony 10.74 μ width, setae 4.15–4.98 μ long

Order – Cladophorales

Family – Cladophoraceae

24. *Rhizoclonium riparium* (Roth) Harvey (Plate 5.6, Fig. M)

[Krishnamurthy, 2000, pl. 5, fig. 2]

It forms a membranaceous layer; the algae is soft and woolly to touch and intricately woven into loosely lying dense mats. The colour of the algae is bright grass green. The diameter of the filament is 60.35 μ. The length of the cell varies from 89.81 to 97.96 μ.

Division – Bacillariophyceae

Section – Centricae

Subfamily – Discoidae

Tribe – Coscinodisceae

Subtribe – Melosirinae

25. *Aulacoseira granulata* var. *angustissima* (Plate 5.7, Fig. Z)

[*Melosira granulata* (Ehr.) Ralfs var. *angustissima* Müll, Hustedt, 1930a, Bd VII, Teil 1, pp. 250, Fig. 104 d; Venkataraman, 1939, p. 297, Fig. 2]

Filaments long with narrow and long cells, the height of the cells being several times the diameter, diameter 5 μ, height of half cell 12 μ; number of punctae in the lower cell is 10 in 10 μ

Subtribe – Skeletoneminae

26. *Skeletonema costatum* (Greville) Cleve (Plate 5.7, Fig. X)

$$\sqsubset\!\sqsupset = 10\mu$$
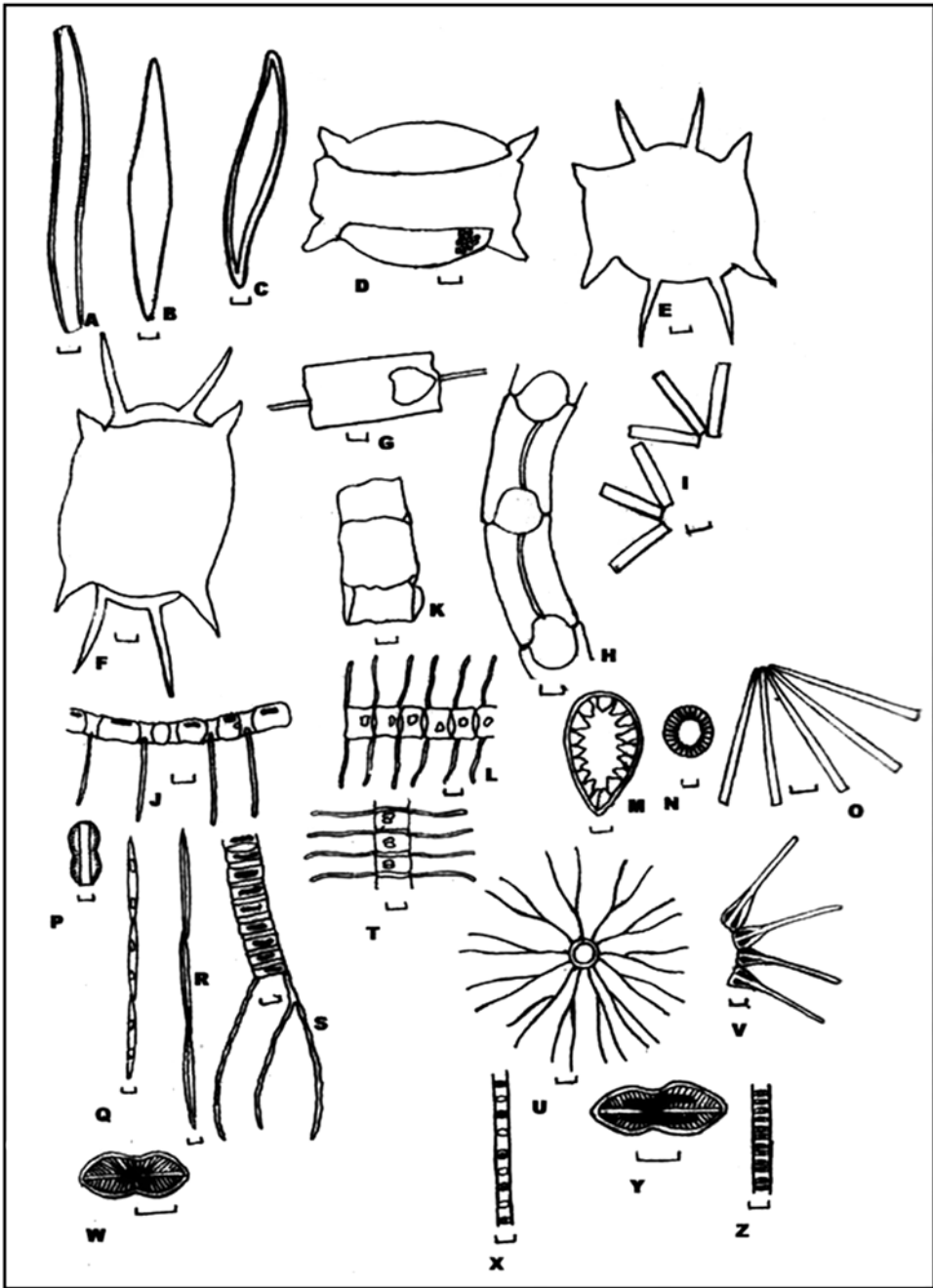
Plate 5.7 (**A**) *Nitzschia sigmoidea* Ehrenberg, (**B**) *Pleurosigma normanii* Ralfs, (**C**) *Gyrosigma obtusatum* (Sull. & Wormley) Boyer, (**D**) *Odontella rhombus* (Ehrenb.) Kützing, (**E**) *Odontella mobiliensis* (J. W. Bailey) Grunow, (**F**) *Biddulphia heteroceros* Grunow, (**G**) *Ditylum brightwellii* (West) Grunow, (**H**) *Eucapmia zoodiacus* Ehrenberg, (**I**) *Thalassionema nitzschoides* Grunow, (**J**) *Chaetoceros curvisetus* Cleve, (**K**) *Biddulphia alternans* (Bailey) van Heurck, (**L**) *Chaetoceros messanensis* Castracane, (**M**) *Surirella fastuosa* var. *recedens* (A. Schmidt) Cleve, (**N**) *Cyclotella meneghiniana* Kutzing, (**O**) *Thalassiothrix frauenfeldii* Grunow, (**P**) *Nitzschia bilobata* var. *minor* Grunow, (**Q**) *Nitzschia pacifica* n. sp., (**R**) *Nitzschia delicatissima* Cleve, (**S**) *Chaetoceros diversus* Cleve, (**T**) *Chaetoceros wighami* Brightwell, (**U**) *Bacteriastrum varians* Lauder, (**V**) *Asterionella japonica* Cleve, (**W**) *Diploneis weissflogii* (A. Schmidt) Cleve, (**X**) *Skeletonema costatum* (Greville) Cleve, (**Y**) *Diploneis interrupta* (Kutzing) Cleve, (**Z**) *Aulacoseira granulata* var. *angustissima*

[Hustedt, Bd. VII, Teil 1, p. 311, Fig. 149; Subrahmanyan, 1946, p. 89, Fig. 7, 8 and 9]

Frustules weakly silcified, lens shaped with rounded ends forming long slender straight chains with the aid of marginal spines which run parallel to the axis of the chain, space between the cells longer than the cells, chromatophores two plates which at times dissected, no visible structures on the valve, diameter of cells 10 μ

27. Thalassiosira decipiens (Grunow) Jørgensen (Plate 5.8, Fig. C)

[Subrahmanyan, 1946, p. 89, Fig. 19]

Cells disc shaped, valves flat with minute spines along the border, valve aerolated, areolae in three or more systems, their size becoming smaller towards the border, in the centre, about 12 in 10 μ and towards border 15 in 10 μ; diameter 60 μ

Subtribe – Coscinodiscinae

28. *Cyclotella meneghiniana* Kutzing (Plate 5.7, Fig. N)

[Venkataraman, 1939, pp. 299, Figs. 11 and 14; Subrahmanyan, 1946, p. 92, Figs. 25, 26 and 27]

Frustules discoid in valve view, margin well defined, coarsely striated and the striae wedge shaped, striae 8 in 10 μ, diameter 15 μ

29. *Cyclotella striata* (Kutzing) Grunow (Plate 5.8, Fig. F)

[Subrahmanyan, 1946, p. 92, Fig. 31]

Cells disc shaped, 20 μ in diameter, valves with more or less broad evenly striated border, striae 10–12 in 10 μ. Central portion with plexes and coarsely punctuate

30. *Coscinodiscus granii* Gough (Plate 5.8, Fig. B)

[Hustedt, 1930b, Bd. VII, Teil 1, pp. 436, Fig. 237; Venkataraman, 1939, pp. 300, Figs. 16 and 17; Cupp, 1943, pp. 56, Fig. 21; Subrahmanyan, 1946, p. 96, Figs. 33, 35 and 39]

Cells with excentric arched valves, central areolae in definite rosette. Eight aerolae in 10 μ near centre, 10 midway to margin and 11 near margin; on edge of valve mantle 13 in 10 μ, chamber openings small, dot-like, diameter 105 μ.

31. *Coscinodiscus excentricus* Ehrenberg (Plate 5.8, Fig. A)

[Hustedt 1930b, Bd. VII, Teil 1, pp. 388, Fig. 201; Cupp, 1943, pp. 52, Fig. 14; Subrahmanyan, 1946, p. 93, Figs. 29 and 30]

Cells disc shaped., valves almost flat, narrow margin, areolae hexagonal, arranged in slightly curved, nearly parallel rows, based on arrangement of seven divisions, central areola with seven areolae grouped around it, areolae 7 in 10 μ at centre, 9 midway and 10 near margin, chromatophores small, numerous, diameter 65 μ

32. *Coscinodiscus excentricus* Ehrenberg var. *fasciculata* Hustedt (Plate 5.8, Fig. E)

[Hustedt, 1930b, Bd. VII, Teil 1, p. 390, Fig. 202; Subrahmanyan, 1946, p. 93, Figs. 32 and 38]

Cells disc shaped, valve aerolated, areolae in several tangential series and because of this appearing as though in radial bundles, number of aerolae in the centre 9 in 10 μ and at the border 12 in 10 μ, diameter 65 μ

33. *Actinocyclus normanii* f. *subsala* (Juhl.-Dannf.) Hustedt (www.itis.gov) (Plate 5.8, Fig. D)

[*Coscinodiscus radiatus* Ehrenberg Cupp, 1943, pp. 56, Fig. 20]

Cells flat, coin-shaped discs, valves flat, valve surface with coarse areolae, without rosette or central area, areolae nearly same size on whole valve, 4 in 10 μ, except at margin where they are smaller, 6 in 10 μ, inner chamber openings rather indistinct, outer membrane of the areolae apparently homogeneous, diameter 50 μ

Suborder – Solenoideae

Family – Solenieae

Subfamily – Lauderiineae

34. *Leptocylindrus danicus* Cleve (Plate 5.8, Fig. G)

[Subrahmanyan, 1946, p. 113, Figs. 109, 110]

Cells cylindrical, 10 μ in diameter and 50–80 μ in length, forming long chains. No structure visible on the valve. Chromatophores numerous and disc shaped.

Subfamily – Biddulphioideae

Tribe – Chaetocereae

35. *Bacteriastrum delicatulum* Cleve (Plate 5.8, Fig. H)

[Hustedt, 1930b, Bd. VII, Teil 1, p. 612, Fig. 353; Subrahmanyan, 1946, p. 125, Figs. 161–163]

Cells longer than broad. Setae eight, perpendicular to chain axis, basal part long. Apertures
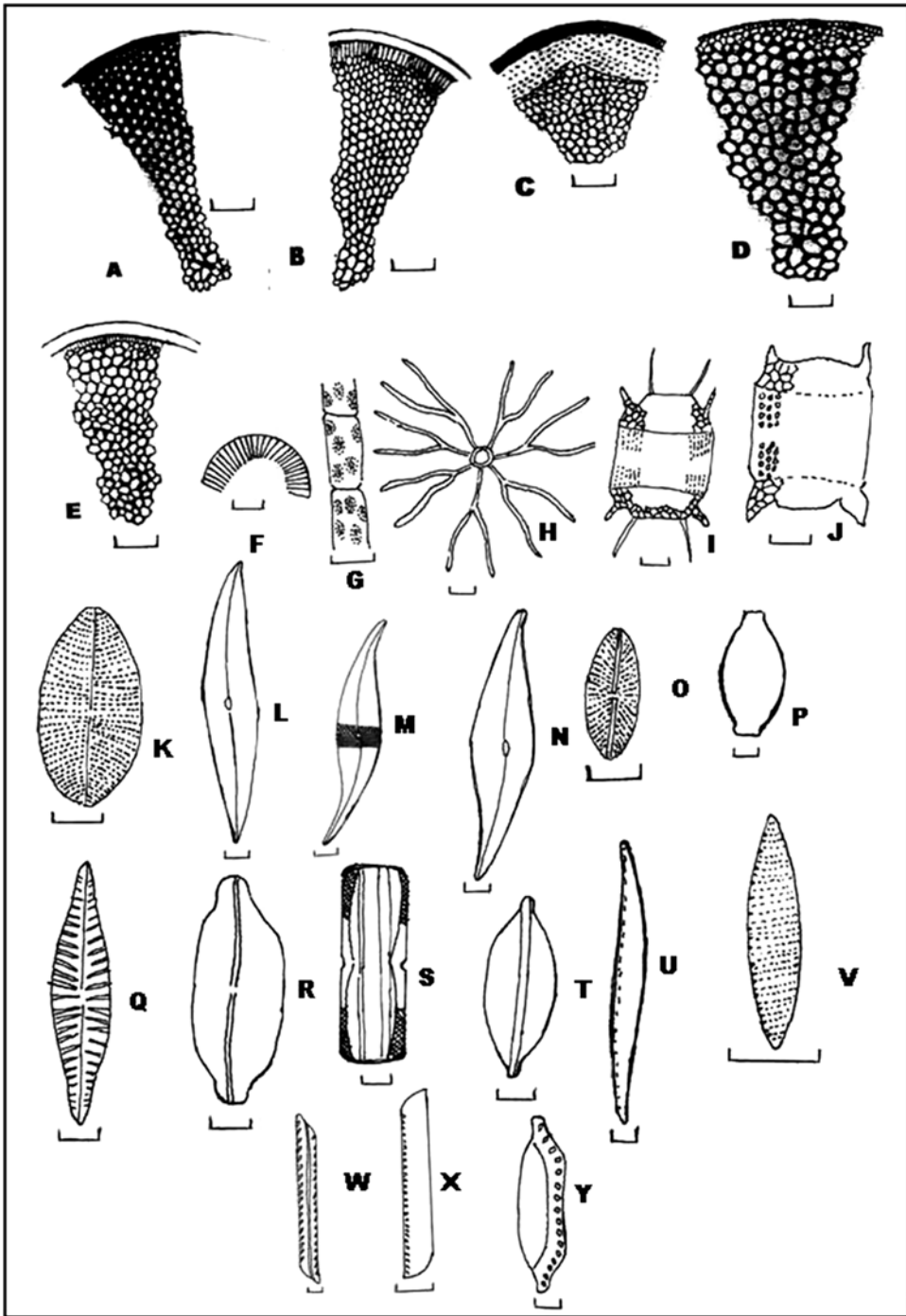
Plate 5.8 (**A**) *Coscinodiscus excentricus* Ehrenberg, (**B**) *Coscinodiscus granii* Gough, (**C**) *Thalassiosira decipiens* (Grunow) Jørgensen, (**D**) *Actinocyclus normanii* f. *subsala* (Juhl.-Dannf.) Hustedt, (**E**) *Coscinodiscus excentricus* Ehrenberg var. *fasciculata* Hustedt, (**F**) *Cyclotella striata* (Kutzing) Grunow, (**G**) *Leptocylindrus danicus* Cleve, (**H**) *Bacteriastrum delicatulum* Cleve, (**I**) *Odontella aurita*(Lyngb.) C. Agardh, (**J**) *Biddulphia dubia* (Brightwell) Cleve, (**K**) *Cocconeis dirupta* Greg., (**L**) *Gyrosigma beau-fortianum* Hust., (**M**) *Gyrosigma acuminatum* (Kütz.) Rabenh., (**N**) *Pleurosigma salinarum* Grunow, (**O**) *Navicula minima*Grunow, (**P**) *Navicula mutica* Kutz. fo. *cohni* (Hilse.) Grunow, (**Q**) *Navicula peregrina* (Ehrenberg) Kutzing, (**R**) *Navicula quadripartita* Hustedt, (**S**) *Amphiprora gigantea* Grunow, (**T**) *Cymbella naviculiformis* Allerswald, (**U**) *Bacillaria paxillifer* (O. F. Müller) Hendy, (**V**) *Nitzschia amphibia* Grunow, (**W**) *Nitzschia ignorata* Kresske, (**X**) *Nitzschia obtusa* Smith, (**Y**) *Nitzschia punctata* W. Smith

large. Terminal setae bent over the chain. Diameter of cell 11 μ

36. *Bacteriastrum varians* Lauder (Plate 5.7, Fig. U)

[Subrahmanyan, 1946, p. 127, Figs. 170–172 and 175]

Cells cylindrical, setae 19, bifurcated at about middle and extended up to the tip, at right angles to the chain axis, terminal setae with fine spines arranged in spiral rows, 12 μ in diameter

37. *Chaetoceros curvisetus* Cleve (Plate 5.7, Fig. J)

[Hustedt, 1930b, Bd. VII, Teil 1, pp. 737, Fig. 426; Cupp, 1943, pp. 137, Fig. 93 (pp. 138); Subrahmanyan, 1946, p. 143, Figs. 238, 244–246]

Chains spirally curved. No distinct end cell. Apical axis of cell measuring 12 μ. Cells in broad girdle view oblong, setae starting from the corners. Aperture somewhat broadly elliptical. Setae all directed towards one side of the chain. Chromatophores a single plate with pyrenoid

38. *Chaetoceros diversus* Cleve (Plate 5.7, Fig. S)

[Hustedt, 1930b, Bd. VII, Teil 1, pp. 716, Fig. 409; Subrahmanyan, 1946, p. 142, Figs. 235, 241–243]

Cells with apical axis measuring 5 μ in length, forming straight chains which are usually short, apertures very small, setae, some hairlike; others thicker, tubular and spinous

39. *Chaetoceros messanensis* Castracane (Plate 5.7, Fig. L)

[Hustedt, 1930b, Bd. VII, Teil 1, pp. 718, Fig. 410; Subrahmanyan, 1946, p. 142, Figs. 236, 237 and 240]

Cells forming long straight chains, apical axis 12.5 μ in length, the corners of adjacent cells touching each other, apertures elliptical, bristles thin, chromatophore a single plate

40. *Chaetoceros wighami* Brightwell (Plate 5.7, Fig. T)

[Hustedt, 1930b, Bd. VII, Teil 1, pp. 724, Fig. 414; Cupp, 1943, pp. 136, Fig. 91; Subrahmanyan, 1946, p. 142, Fig. 247]

Cells somewhat tender forming chains, apical axis measuring 10 μ, cells in broad girdle view oblong with sharp corners, the corners of neighbouring cells touching each other and enclosing a narrow slitlike aperture, setae thin and fragile, inner ones perpendicular to the chain axis; end setae more or less parallel to the chain axis, chromatophore platelike

Tribe – Biddulphieae

Subtribe – Eucampiinae

41. *Eucampia zoodiacus* Ehrenberg (Plate 5.7, Fig. H)

[Cupp, 1943, pp. 145, Fig. 103; Subrahmanyan 1946, p. 145, Figs. 248, 250–253]

Cells flattened, elliptical–linear in valve view, united in chains by two blunt processes, length of cell along apical axis 25 μ, chains spirally curved, with relatively narrow lanceolate or elliptical apertures, apertures variable in size and shape, valves distinctly sculptured, chromatophores small, numerous

Subtribe – Triceratiinae

42. *Ditylum brightwellii* (West) Grunow (Plate 5.7, Fig. G)

[Cupp, 1943, pp. 148, Fig. 107A, 107B; Subrahmanyan, 1946, p. 147, Figs. 263 and 264]

Cells prism shaped with strongly rounded angles to nearly cylindrical, usually 3–5 times as long as broad, valves triangular to circular with a central hollow spine, valve rim strengthened by small parallel ribs, girdle zone very long, chromatophores small, numerous, nucleus central, diameter 74 μ

Subtribe – Biddulphiinae

43. *Biddulphia alternans* (Bailey) van Heurck. (Plate 5.7, Fig. K)

[Cupp, 1943, p. 166, Fig. 115; Subrahmanyan, 1946, pp. 153, Figs. 277 and 282 (*Triceratium alternans*)]

Valves quadrangular, with straight or somewhat unevenly concave sides. Corners slightly elevated, rounded, separated from the central part by costae or ribs. Only a slight constriction between valve and girdle zones. Irregular ribs on both valve and girdle. Fine areolae (slime pores) on corners, 17 in 10 μ. Areolae 9 in 10 μ in centre of valve. Length along side of valve 30 μ

44. *Odontella aurita* (Lyngb.) C. Agardh (Plate 5.8, Fig. I)

[*Biddulphia aurita* (Lyngbye) Brébisson and Godey, Cupp, 1943, p. 161, Fig. 112-A (1), 112-A (2), 112-A (3)]

Valves elliptical–lanceolate, with obtuse processes inflated at the base. Centre part of valve

convex, more or less flattened at the top from which long spines project. Girdle zone sharply differentiated from the valve zone by a clear depression. Cell wall strongly siliceous, areolated punctuated. Areolae 8–10 in 10 μ, on the valve in radial rows. On the girdle band in pervalvar rows, 7–10 rows in 10 μ, with 8–14 punctae

45.   *Biddulphia dubia* (Brightwell) Cleve (Plate 5.8, Fig. J)

[Cupp, 1943, p. 164, Fig. 114; *Triceratium dubium* Brightwell, Subrahmanyan, 1946, p. 151, Figs. 274–276 and 278]

Valves rhombic–lanceolate. Processes obtuse. Centre part of valve convex. Valve with numerous small spines and a larger one near base of each process. Valve zone and girdle zone divided by a deep groove. Valves distinctly punctate, 9 puncta in 10 μ. Length of apical axis 54 μ

46.   *Biddulphia heteroceros* Grunow (Plate 5.7, Fig. F)

[Subrahmanyan, 1946, p. 155, Figs. 288, 298 and 303]

Cells box-shaped without a sharp constriction between valve and girdle in girdle view. Horns from each pole of apical axis well developed, directed slightly away from pervalvar axis. Two strong spines on each valve a short distance from the horns. Valve between spines slightly higher that between spines and horns somewhat flat. Areolation almost the same size on valve and girdle, in regular rows, 9 in 10 μ

47. *Odontella mobiliensis* (J. W. Bailey) Grunow [www.itis.gov] (Plate 5.7, Fig. E)

[*Biddulphia mobiliensis* Bailey, Hustedt, 1930b, Bd. VII, Teil 1, p. 840, Fig. 495; Subrahmanyan, 1946, p. 155, Figs. 286, 287, 291–296 and 299, Pl. II, Figs. 1 and 2]

Cells single, length of apical axis 60 μ, valves elliptical–lanceolate, convex, with a flat or nearly flat central part, valve processes slender, directed diagonally outward, two long spines placed far apart but about equally far from the processes, directed obliquely outward, straight, cells relatively thin walled, without a sharp constriction between valve and girdle zone, sculpturing fine, reticulate, 15 areolae in 10 μ on valve and valve mantle.

48. *Odontella rhombus* (Ehrenb.) Kützing [www.itis.gov] (Plate 5.7, Fig. D)

[*Biddulphia rhombus* Ehrenberg, Hustedt, 1930b, Bd. VII, Teil 1, p. 842, Fig. 496, 497; Cupp, 1943, p. 163, Fig. 113]

Valves rhombic–elliptical, cells thick walled, strongly sculptured, processes small, short and obtuse, length of apical axis 35 μ, surface of valve convex, beset with small spines over entire surface, valve zone and girdle zone divided by deep groove, areolae on valve 9 in 10 μ, irregular at centre, then more or less regular radiating, girdle band more delicately sculptured 12 areolae in 10 μ in regular prevalvar rows

Section – Pennatae
Subsection – Araphideae
Subfamily – Fragilariodeae
Tribe – Fragilarieae
Subtribe – Fragilariinae

49.   *Thalassionema nitzschoides* Grunow (Plate 5.7, Fig. I)

[Cupp, 1943, pp. 182, Fig. 133; Subrahmanyan, 1946, pp. 167, figs. 344–346]

Frustules united into zigzag chains. Cells in girdle view linear–rectangular, in valve view linear–lanceolate, poles alike, 50 μ long, 3 μ broad

50.   *Thalassiothrix frauenfeldii* Grunow (Plate 5.7, Fig. O)

[Cupp, 1943, pp. 184, Fig. 135; Subrahmanyan, 1946, pp. 169, figs. 349, 351, 354–357 and 360]

Cells united into star-shaped colonies. In girdle view linear. Valves very narrow, linear, ends distinct, one-end blunt rounded, near the other end usually widened then decreased to form a wedge-shaped point. Valves 53 μ long, 7 μ wide. Valves structure less

51. *Asterionella japonica* Cleve (Plate 5.7, Fig. V)

[Venkataraman, 1939, pp. 309, Fig. 34; Cupp, 1943, pp. 188, Fig. 138; Subrahmanyan, 1946, pp. 170, figs. 361 and 371]

Cells united into starlike spiral colonies. In girdle view, very narrow linear with parallel sides, with greatly enlarged three-cornered region at the base. Cells united at the corners of enlarged region. Valves very narrow, then with a widened knob-like region at the base. Length of valve 85 μ; length of enlarged

region 15 μ, width of enlarged part 6 μ. Chromatophores ½ small plates, in basal enlarged part only

Suborder – Monoraphidineae

Family – Achnanthaceae

Subfamily – Cocconeoideae

52. *Cocconeis dirupta* Greg. (Plate 5.8, Fig. K)

[Gregory, 1857, pp. 491, pl. 9, fig. 25]

Cells broadly elliptic, about 40 μ long and 30 μ broad, striae 21 in 10 μ. Raphe sigmoid. Axial area narrow, dilating into a very small central area

Subsection – Biraphideae

Subfamily – Naviculoideae

Tribe – Naviculeae

53. *Gyrosigma beaufortianum* Hust. (Plate 5.8, Fig. L)

[Foged, 1978, p. 73, 21: 8]

Valves slightly sigmoid with acute ends. Raphe central, sigmoid, central area small, rhombic, length 55.025 μ and breadth 6 μ

54. *Gyrosigma acuminatum* (Kütz.) Rabenh. (Plate 5.8, Fig. M)

[*Gyrosigma spencerii* (Quekett) Cleve, Cupp, 1943, p. 194, Fig. 144]

Valves sigmoid, lanceolate, with obtuse ends. Raphe central. Central nodule elliptical. Transverse striae 18 in 10 μ; longitudinal striae 25 in 10 μ. Length of valves 185 μ

55. *Gyrosigma obtusatum* (Sull. & Wormley) Boyer (Plate 5.7, Fig. C)

[*Gyrosigma scalproides* (Rabh.) Hustedt, 1930b, Heft 10, pp. 226, Fig. 339; Venkataraman, 1939, pp. 319, fig. 76]

Valves linear with parallel sides and obliquely rounded ends. Raphe straight, nearly central, slightly sigmoid at the ends. Longitudinal striae very faint. Length of valve along apical axis 76 μ and breadth 8 μ

56. *Pleurosigma normanii* Ralfs (Plate 5.7, Fig. B)

[Cupp, 1943, pp. 196, Fig. 148; Subrahmanyan, 1946, pp. 175, figs. 378, 379, 385 and 387]

Valves broadly lanceolate, slightly sigmoid, with subacute ends. Raphe nearly central, sigmoid. Length of valve 115 μ

57. *Pleurosigma salinarum* Grunow (Plate 5.8, Fig. N)

[Hustedt, 1930b, Heft 10, p. 228, Fig. 344; Venkataraman, 1939, p. 320, fig. 78]

Valves linear lanceolate, slightly sigmoid. Raphe central. Central nodule elongated. Length 120 μ, breadth 17 μ

58. *Diploneis weissflogii* (A. Schmidt) Cleve (Plate 5.7, Fig. W)

[Subrahmanyan, 1946, pp. 177, fig. 397]

Valves strongly constricted, with sub-elliptical ends, 28 μ long and 12.5 μ broad, at the constriction 8 μ broad. Central nodule with approximate horns.

59. *Diploneis interrupta* (Kutzing) Cleve (Plate 5.7, Fig. Y)

[Hustedt, 1930b, Heft 10, pp. 252, Fig. 400; Venkataraman, 1939, pp. 323, fig. 82]

Valves deeply constricted, the segments elliptical, rounded at the ends. Central nodule elongated, quadrate with parallel horns. Furrow linear, narrow. Costae strong usually interrupted in the middle of the valve. Length of the valve 35 μ, breadth in the middle 10 μ

60. *Navicula minima* Grunow (Plate 5.8, Fig. O)

[Hustedt 1930b, pp. 272, fig. 441]

Valves are lanceolate in shape, with tapering ends. Striations are very fine. Length 13.96 μ, breadth 3.49 μ

61. *Navicula mutica* Kutz. fo. cohni (Hilse.) Grunow (Plate 5.8, Fig. P)

[Foged 1978, pp. 93, pl. XXVIII, fig. 10]

Valves are elliptic lanceolate in shape, with rounded ends. Striations fine and delicate. Length 13.96 μ, breadth 6.98 μ

62. *Navicula peregrina* (Ehrenberg) Kutzing (Plate 5.8, Fig. Q)

[Hustedt, 1930b, Heft 10, p. 300; Venkataraman, 1939, p. 326, fig. 85]

Valves lanceolate with obtuse ends. Axial area distinct, narrow, central area broadened, elliptical, length 62.12 μ and breadth 14.9 μ

63. *Navicula quadripartita* Hustedt (Plate 5.8, Fig. R)

[Foged, 1979, pl. XXIX, Fig. 18]

Valves elliptical with broadly rounded ends. Central area widened, striations radial; the number of striae in 10 μ is 14, length 17.92 μ, breadth 5.31 μ

Subfamily – Amphiproroideae

64. *Amphiprora gigantea* Grunow (Plate 5.8, Fig. S)

[Subranmanyan, 1946, p. 184, Figs. 410 and 413]

Cells strongly constricted. Keel with hyaline margin. Junction line curved like a bow. Cells 75 μ long. Keel punctae forming obliquely decussating rows, 15 rows in 10 μ. Connecting zone with numerous longitudinal divisions

Subfamily – Gomphocymbelloideae

65. *Cymbella naviculiformis* Allerswald (Plate 5.8, Fig. T)

[Hustedt, 1930b, Heft 10, p. 356, Fig. 653; Venkataraman, 1939, p. 346, Fig. 119]

Valve elliptic lanceolate with capitate ends. Axial area narrow, linear, suddenly dialated in middle. Striations radial. Length 30.04 μ, breadth 10.12 μ, number of striations 13 in 10 μ

Subfamily – Nitzschioideae

Tribe – Nitzschieae

66. *Bacillaria paxillifer* (O. F. Müller) Hendy (Plate 5.8, Fig. U)

[*Bacillaria paradoxa* Gmelin, Subrahmanyan, 1946, p. 187, Figs. 417, 421 and 427]

Cells in girdle view linear and rectangular, united by their valves to form a mat-like colony, individual cells of which exhibit gliding movement in the living condition. Valves linear, spindle shaped in outline, 150 μ long, 8 μ broad. Keel punctae 7 in 10 μ. Transapical striae fine, 21 in 10 μ

67. *Nitzschia amphibia* Grunow (Plate 5.8, Fig. V)

[Hustedt, 1930b, Heft 10, p. 414, Fig. 793; Venkataraman, 1939, p. 353, Fig. 149]

Valves linear to linear lanceolate with the ends slightly produced and sometimes rounded. Striations coarse. Length 17.45 μ, breadth 3.49 μ, striae 15 in 10 μ

68. *Nitzschia bilobata* var. *minor* Grunow (Plate 5.7, Fig. P)

[Cupp, 1943, p. 200, Fig. 152]

Valves linear lanceolate, constricted in the middle, apiculate at the ends. Keel puncta 12 in 10 μ. Striae 25 in 10 μ. Cells broad, oblong, truncate, constricted in the middle. Length of the valve 55 μ, width of widest point 6 μ

69. *Nitzschia ignorata* Kresske (Plate 5.8, Fig. W)

[Foged, 1979, p. 215, Pl. XLII, Fig. 6]

Frustules broad, linear with ends obliquely truncate. Striations punctate, punctae very fine and linear, number of striations 10 in 10 μ. Length 44 μ, breadth 4.5 μ

70. *Nitzschia obtusa* Smith (Plate 5.8, Fig. X)

[Hustedt, 1930b, Heft 10, p. 422, Fig. 817; Venkataraman, 1939, p. 354, Fig. 147]

Frustules broad, linear with ends obliquely truncate. Striations punctate, punctae fine and linear. Length 98 μ and breadth 10 μ

71. *Nitzschia punctata* W. Smith (Plate 5.8, Fig. Y)

[Foged 1979, p. 209, pl. XL, Fig. 16]

Valves linear with slightly concave margins. Ends wedge shaped and rounded. Striae clear, 10 in 10 μ. Length 22.908 μ, breadth 5.312 μ

72. *Nitzschia sigmoidea* Ehrenberg (Plate 5.7, Fig. A)

[Hustedt, 1952, p. 147]

Cells solitary. Frustules isopolar, straight in valve view but sigmoid in girdle view; bilaterally symmetrical valves linear lanceolate, straight. The sigmoid shape of the frustule is entirely due to the form of the valve margin and girdle. Two chloroplasts per cell. Length of valve 172.5 μ

73. *Nitzschia delicatissima* Cleve (Plate 5.7, Fig. R)

[Cupp, 1943, p. 204, Fig. 158 (p. 206)]

Valve narrow, linear, acute. Cells united into stiff hairlike chains by the overlapping tips of the cells. Chains usually short, motile. Length of valve 80 μ; width 3 μ. Keel puncta 20 in 10 μ. No striae visible. Chromatophores two per cell

74. *Nitzschia pacifica* n. sp. (Plate 5.8, Fig. Q)

[Cupp, 1943, p. 204, Fig. 157]

Cells spindle shaped with more or less pointed ends. United into stiff chains by the overlapping points of the cells. Chains motile as a whole. Length of valve 94 μ, width 6 μ. Keel puncta distinct, 14 in 10 μ. Chromatophores two per cell

Subfamily – Surirelloideae

Tribe – Surirelleae

75. *Surirella fastuosa* var. *recedens* (A. Schmidt) Cleve (Plate 5.7, Fig. M)

[Cupp, 1943, p. 208, Fig. 160]

Cells wedge shaped, rounded at the angles. Valves ovate. Costae or ribs about 2.5 in 10 μ, robust, dialated at the margin. Central space lanceolate. Marginal striae distinct, 18 in 10 μ. Striae in central field 17 in 10 μ. Length of valve 60 μ, width 35 μ (Plate 5.13, Fig. N)
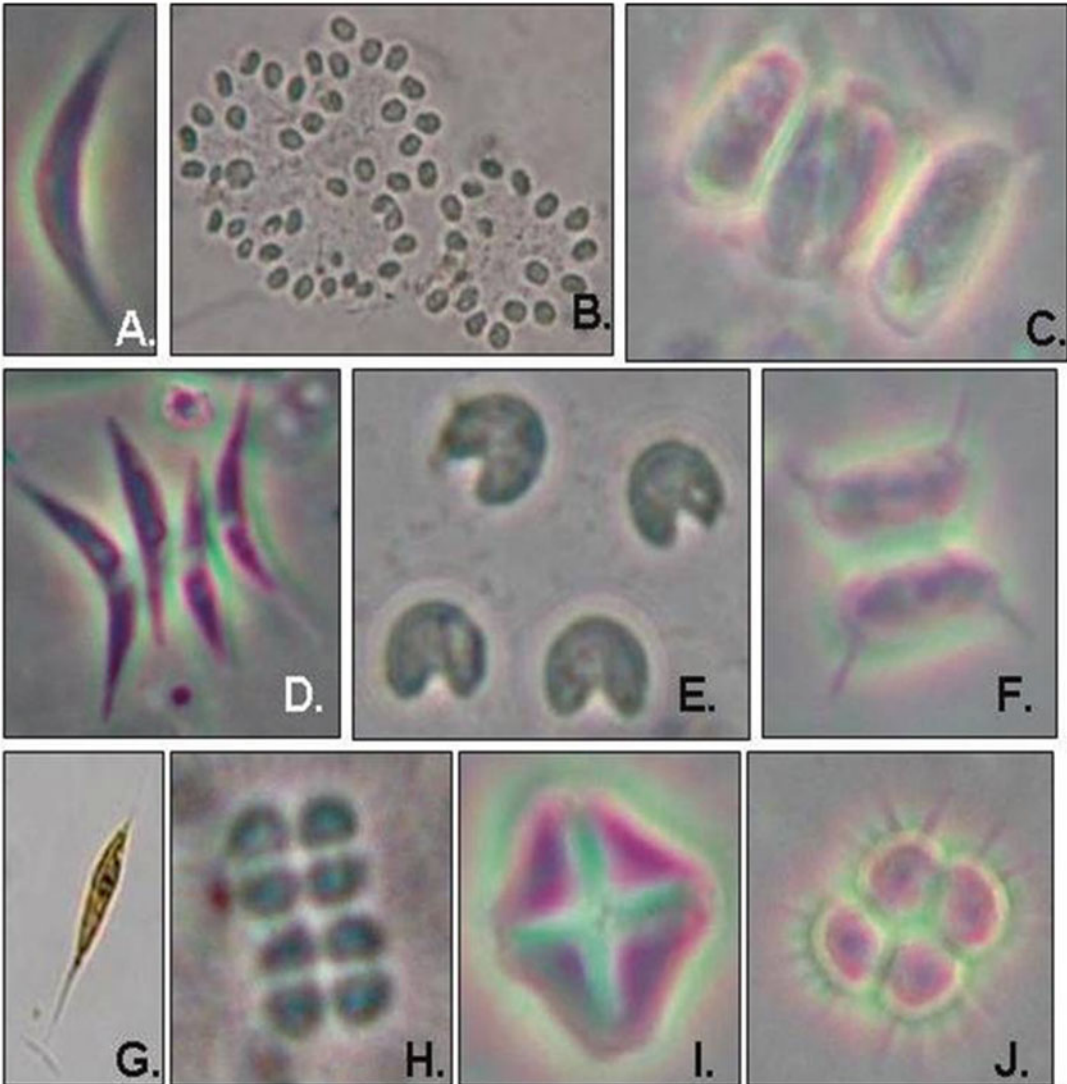

Plate 5.9 (**A**) *Ankistrodesmus falcatus* var. *stipitatus* (Chod) Lemmermann, (**B**) *Dictyosphaerium pulchellum* Wood, (**C**) *Scenedesmus bijuga* (Turp.) Langerheim, (**D**) *Scenedesmus dimorphus* (Turp.) Kuetzing, (**E**) *Kirchneriella lunaris* (Kirch.) Moebius, (**F**) *Scenedesmus quadricauda* (Turp.) de Brébisson *in* de Brébisson & Godey, (**G**) *Schroederia judayi* G. M. Smith, (**H**) *Crucigenia tetrapedia* (Kirch.) West &West, (**I**) *Crucigenia rectangularis* (A. Braun) Gay, (**J**) *Tetrastrum staurogeniaeforme* (Schröder) Lemmermann
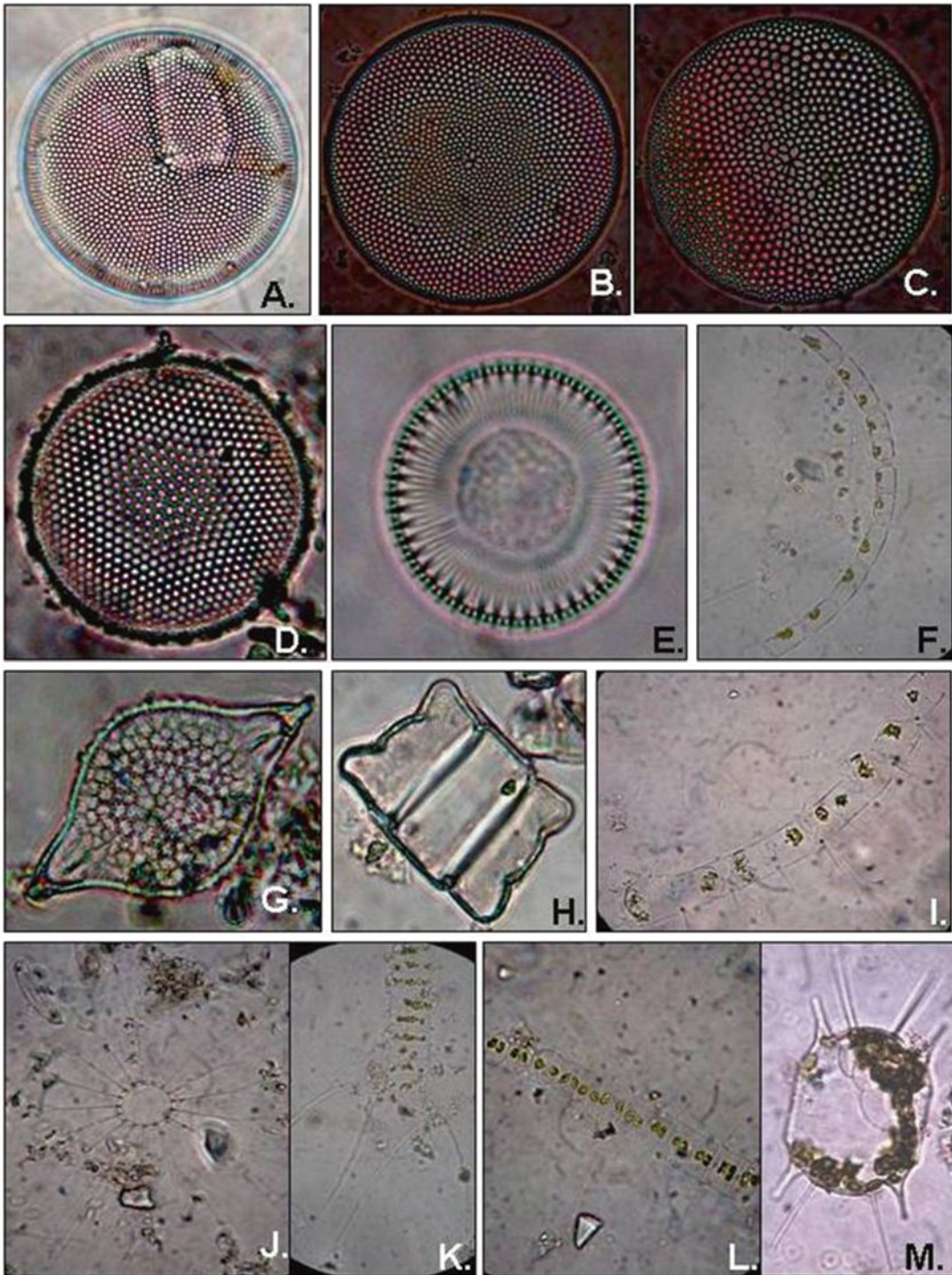
Plate 5.10 (**A**) *Coscinodiscus granii* Gough, (**B**) *Coscinodiscus excentricus* Ehrenberg, (**C**) *Actinocyclus normanii* f. *subsala* (Juhl.-Dannf.) Hustedt, (**D**) *Thalassiosira decipiens* (Grunow) Jørgensen, (**E**) *Cyclotella meneghiniana* Kutzing, (**F**) *Chaetoceros curvisetus* Cleve, (**G**) *Odontella rhombus* (Ehrenb.) Kützing, (**H**) *Biddulphia alternans* (Bailey) van Heurck, (**I**) *Chaetoceros massenensis* Castracane, (**J**) *Bacteriastrum varians* Lauder, (**K**) *Chaetoceros diversus* Cleve, (**L**) *Chaetoceros wighamii* Brightwell, (**M**) *Odontella mobiliensis* (J. W. Bailey) Grunow
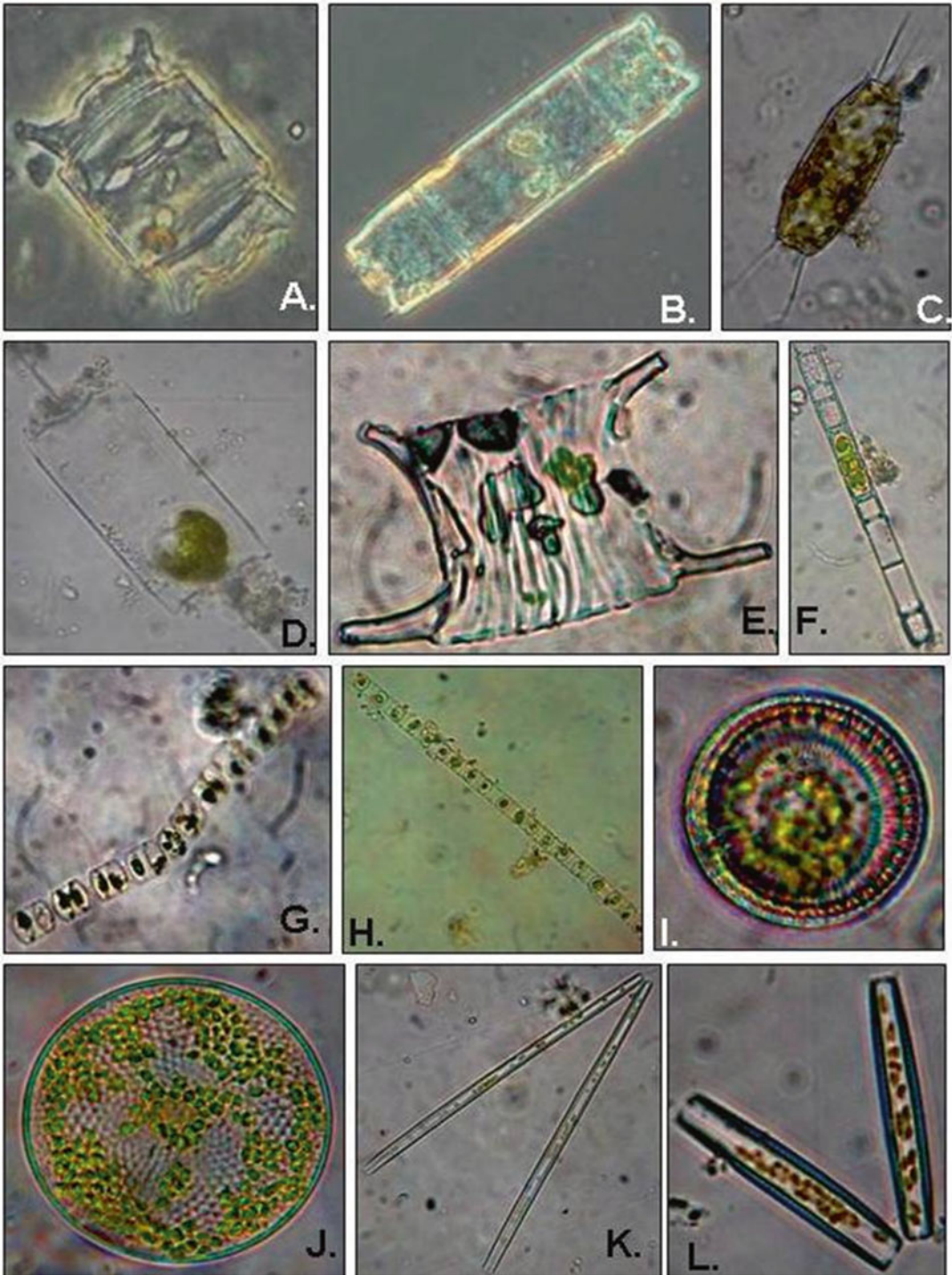
Plate 5.11 (**A**) *Odontella aurita* (Lyngbye) Brébisson and Godey, (**B**) *Biddulphia dubia* (Brightwell) Cleve, (**C**) *Biddulphia heteroceros* Grunow, (**D**) *Ditylum brightwelli* (West) Grunow, (**E**) *Eucapmia zoodiacus* Ehrenberg, (**F**) *Leptocylindrus danicus* Cleve, (**G**) *Skeletonema costa-* *tum* (Greville) Cleve, (**H**) *Aulacoseira granulata* (Ehr.) Ralfs var. *Angustissima*, (**I**) *Cyclotella striata* (Kutzing) Grunow, (**J**) *Coscinodiscus excentricus* Ehrenberg var. *fasciculata* Hustedt, (**K**) *Thalassiothrix frauenfeldii* Grunow, (**L**) *Thalassionema nitzschoides* Grunow
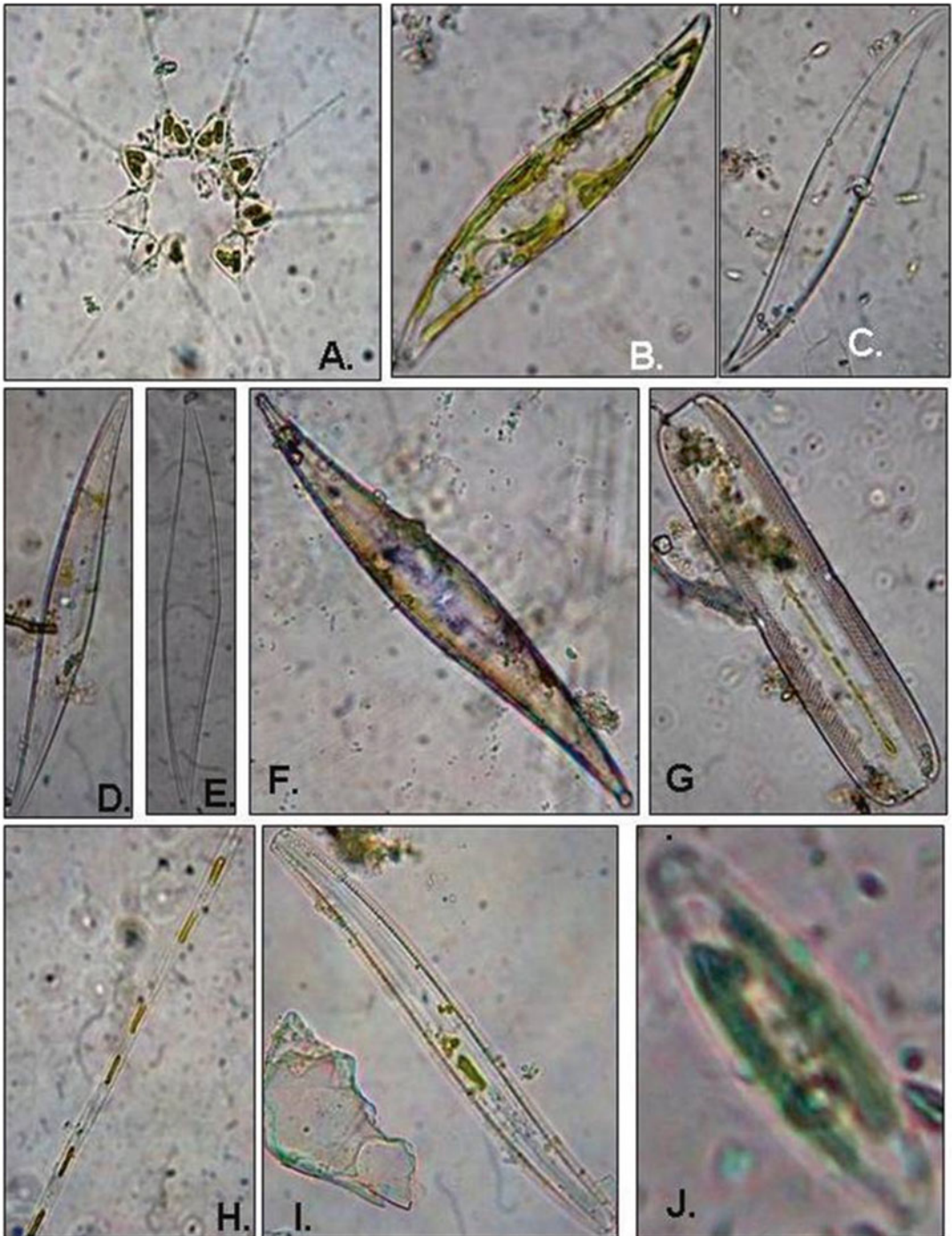
Plate 5.12 (**A**) *Asterionella japonica* Cleve, (**B**) *Gyrosigma obtusatum* (Sull. & Wormley) Boyer, (**C**) *Gyrosigma acuminatum* (Kütz.) Rabenh., (**D**) *Pleurosigma salinarum* Grunow, (**E**) *Pleurosigma normanii* Ralfs, (**F**) *Gyrosigma beautifortianum* Hust., (**G**) *Amphiprora gigantea* Grunow, (**H**) *Nitzschia delicatissima* Cleve, (**I**) *Nitzschia sigmoidea* Ehrenberg, (**J**) *Navicula peregrina* (Ehrenberg) Kutzing
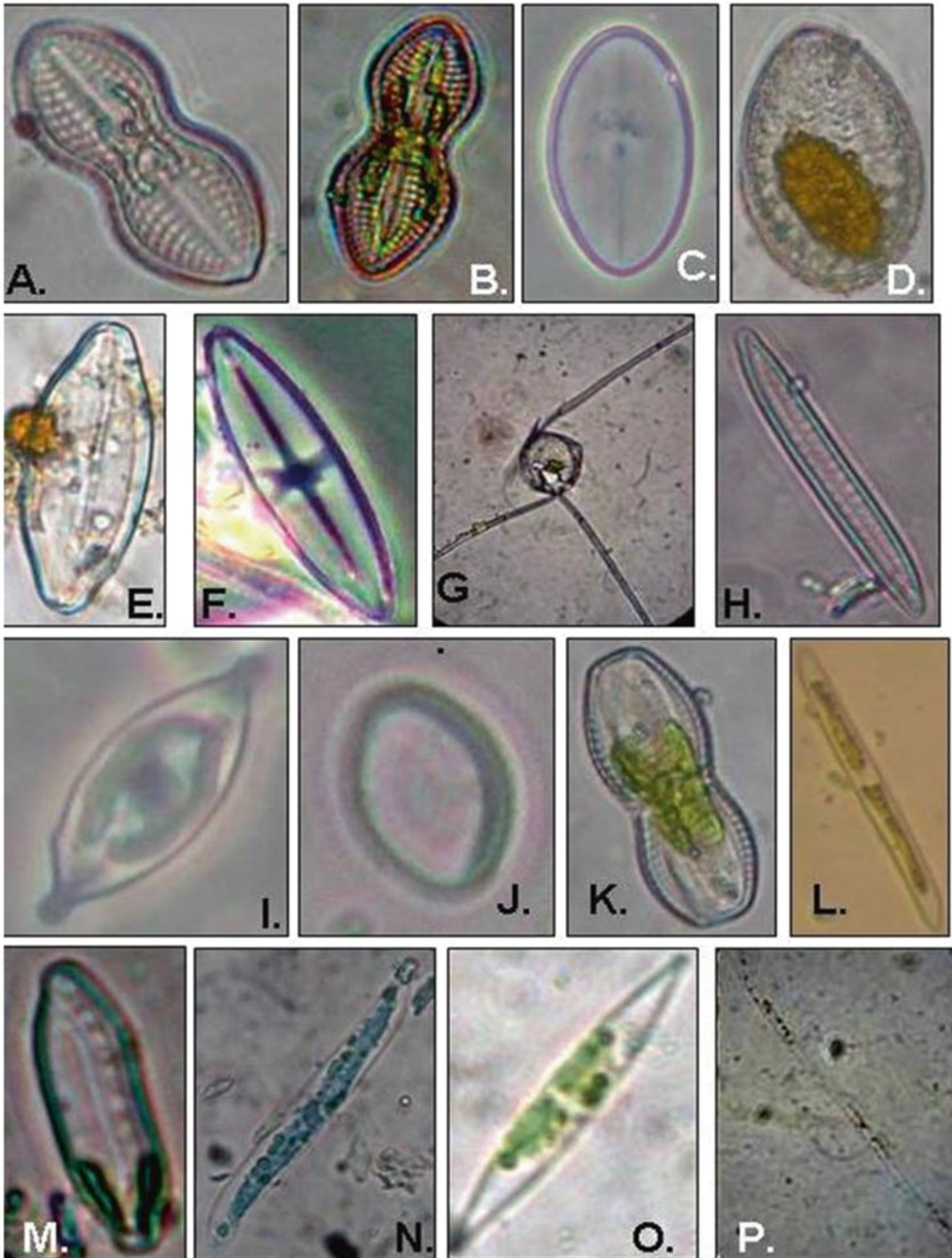
Plate 5.13 (**A**) *Diploneis weissflogii* (A. Schmidt) Cleve, (**B**) *Diploneis interrupta* (Kutzing) Cleve, (**C**) *Cocconeis dirupta* Greg., (**D**) *Surirella fastuosa* var. *recedens* (A. Schmidt) Cleve, (**E**) *Navicula quadripartita* Hustedt, (**F**) *Navicula minima* Grunow, (**G**) *Bacteriastrum delicatulum* Cleve (*top view*), (**H**) *Nitzschia ignorata* Kresske, (**I**) *Cymbella naviculiformis* Allerswald, (**J**) *Navicula mutica* Kutz. fo. *Cohni*, (**K**) *Nitzschia bilobata* var. *minor* Grunow, (**L**) *Nitzschia obtusa* Smith, (**M**) *Nitzschia punctata* W. Smith, (**N**) *Bacillaria paxillifer* (O. F. Müller) Hendy, (**O**) *Nitzschia amphibia* Grunow, (**P**) *Nitzschia pacifica* n. sp

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Glossary

Algae Algae are polyphyletic group of simple, oxygenic photosynthetic organisms that have chlorophyll as their main photosynthetic pigment and lack sterile covering of cells around the reproductive cells.

Algal bloom Dense population of planktonic algae or cyanobacteria that distinctly colours the water and may form scum on the surface.

Algal trophic index Quantitative expression of algal species counts, providing a measure of the trophic (nutrient) status of the aquatic environment.

Allochthonous Materials (usually organic) produced within a water body.

Apochlorotic Colourless or without chlorophyll.

Autotroph Organism capable of synthesizing organic matter by means of photosynthesis.

Bathyal zone Ocean water over continental slope.

Biofilm Community of microorganisms occurring at a physical (e.g. water/solid) interface that is typically present within a layer of extracellular polysaccharide that is secreted by the community.

Bioluminescence Emission of light by a living organism.

Biovolume Volume of single algae and algal populations in a particular population. It may be measured either for a single genus or for a mixed population (volume of individual taxa should be measured).

Brackish Saline water with a salinity less than that of seawater (33 0/$_{00}$).

Calcification Deposition of calcium carbonate, usually in association with smaller amounts of other carbonate.

Carotenoid Yellow, orange or red hydrocarbon or fat-soluble pigment.

Chlorophyll Fat-soluble, green, porphyrin-type pigment.

Chloroplast Plastid with chlorophyll.

Chloroplast endoplasmic reticulum or chloroplast ER One or two membranes surrounding the chloroplast envelope; ribosomes are usually attached to the outside of the outer membrane.

Chromatic adaptation Change in the proportion of different photosynthetic pigments enabling optimum absorption of the available wavelengths of light.

Circadian rhythm Repeated sequence of metabolic activities that occur at about 24 h intervals.

Coccoid Spherical structure.

Coccolith Calcified scale in a coccolithophorid (Prymnesiophyceae).

Coenobium Spherical colony of algal cells with central hollow and number that is fixed at the time of origin and is not subsequently augmented.

Compensation depth Depth of water at which sufficient light is penetrated so that photosynthesis equals respiration over a 24 h period.

Compensation point Particular light intensity at which respiration equals photosynthesis over a 24 h period of a specific area.

Coralline Calcified algae.

Cryptomonads Group of unicellular motile eukaryote algae of the division Cryptophyta.

Cyanelle Endosymbiotic blue-green alga that gave rise to chloroplast.

Cyanome Host cell containing a cyanelle that gave rise to eukaryotic algae.

Cyanophage Virus that infects the cells of the Cyanophyceae.

Cyanophycin granule Polypeptide storage granules within the cells of Cyanophyceae.

Diatom indices Use of diatom species counts to assess the trophic status of a water body.

Dystrophic Brown or yellow coloured waters rich in organic matter where the rate of decay of that organic matter is slow having a low pH.

Ecosystem Self-regulating biological community living in a defined habitat.

Environmental stress factor External change that impairs biological function at the level of individual organisms and molecular systems of an ecosystem.

Epilithic Organisms living on rock surfaces.

Epipelic Organisms growing on mud.

Epiphyte One plant living on other plant.

Epontic Organisms living on the bottom of ice.

Estuary The junction of a river and ocean where tidal effects are evident and where freshwater and seawater mix.

Euphotic or photic zone Regions of water body above the compensation depth.

Eurysaline (euryhaline) Organisms tolerant of a wide salinity range.

Eutrophic A body of water that receives large amounts of nutrients, usually resulting in a large growth of algae.

Eutrophication An increase in the concentration of soluble inorganic nutrients such as phosphates and nitrates in aquatic ecosystem.

Gas vacuole Gas-filled vacuum found in some aquatic blue-green algae and bacteria that increases buoyancy. It is composed of gas vesicles which are made of protein.

Habitat The living place of an organism or community, characterized by its physicochemical and biotic properties.

Holoplanktonic Aquatic organisms which are present in the water column over most of the annual cycle.

Hydrology All aspects of water flow connected with an aquatic system, including inflow and outflow of water.

Hypertrophic Water body with extremely high levels of dissolved inorganic nutrients, also called hypereutrophic.

Hypolimnion Region of water body beneath the thermocline in thermally stratified water bodies with low light intensity.

Intertidal Occurring between the low and high tide marks.

Iridescence The play of colours caused by refraction and interference of light waves at the surface.

K-selected species (K-strategist) Organisms adapted to high levels of competition in a crowded environment where they survive, grow and reproduce.

Lentic Related to a pond or lake habitat.

Limnology Study of aquatic systems in relation to physicochemical and biotic factors.

Littoral zone Peripheral shoreline at the edge of lakes and rivers.

Lotic Related to rivers or stream habitat.

Macroplankton Planktons larger than 75 μm in diameter. Also called net plankton.

Meroplanktonic Algae with only a limited planktonic existence in the water column. Most of the annual cycle is spent on sediments as a resting stage.

Mesotrophic Water body with moderate levels of inorganic nutrients and moderate primary productivity – intermediate state between oligotrophic and eutrophic condition.

Microplankton Unicellular and multicellular planktonic organisms in the size range of 20–200 μm.

Mixotrophy Organisms having the ability to combine both autotrophic (using inorganic carbon sources) and heterotrophic (organic carbon sources including phagotrophy) nutrition.

Nannoplankton or nanoplankton Plankton smaller than 75 μm but larger than 2 μm.

Nephelometer Submerged instrument used to measure the particulate concentration (turbidity) of water by collecting light scattering from suspended matter.

Oligotrophic Water body with less dissolved inorganic nutrients (particularly nitrogen and phosphorous) resulting in low levels of biological productivity.

Organotroph (osmotrophy, saprotrophy) Organisms that either use reduced organic compounds as its sources of electrons or carry out organotrophy.

Pelagic All organisms normally present in the water column of water bodies like plankton and nekton.

Pelagic zone The central main part of a lake.

Periphyton Plantlike organisms present in a community mainly on underwater substrata – including algae, bacteria and fungi.

Photic zone Upper part of water column on aquatic ecosystem in which net photosynthesis can occur (also known as the euphotic zone).

Phototroph Organisms that use solar energy to fix inorganic carbon to organic compounds by photosynthesis.

Phragmoplast Wall formation by the coalescence of Golgi vesicles between spindle microtubules.

Phytoplankton Free-floating plants that float aimlessly or swim too feebly to maintain a constant position against water current.

Picoplankton Plankton with a diameter of 0.2–2 μm.

Plankton Organisms that float aimlessly or swim too feebly to maintain a constant position against water current.

Plankton sedimentation Gravitational force-induced sinking of nonmotile plankton in the water column.

Primary production Synthesis of biomass by photosynthetic organisms – higher plants, algae and photosynthetic bacteria.

Productivity The rate of increase in biomass (growth rate) in a population of organism. Can be expressed as $mgC/m^2/day$.

r-selected species (r-strategist) Organism adapted to an uncrowded environment, with low competition.

Saline lakes Lakes with highly concentrated salts often resulting in white salt 'crusts' round their margins where evaporation from the surface greatly exceeds the inputs.

Saprobic pollution High concentration of soluble organic nutrients.

Secchi depth A particular depth of a water column at which a suspended sectored plate (Secchi disc) can no longer just be seen indicating the measure of water turbidity and phytoplankton biomass.

Sedgwick rafter cell counter A grooved slide with counting chamber commonly used for phytoplankton samples.

Stratification Vertical structuring of static or very slow moving water bodies into three distinct layers – epilimnion, metalimnion and hypolimnion. Determined by temperature and circulatory differences with the water column.

Sublittoral zone In the freshwater region, the zone from the end of rooted vegetation (about 6 m) to the compensation depth and in the marine ecosystem the zone from the lowest low tide mark to 200 m depth.

Succession Temporal sequence of organism that occurs in a developing community such as biofilm or lake pelagic community.

Supralittoral zone In marine ecosystem the zone above the high tide mark in the ocean and in freshwater region above the standing water mark, which receives splash during windy periods.

Trophic The term 'trophic' is used to describe the inorganic nutrient status of different water bodies (oligotrophic to eutrophic) and the feeding relationships (trophic interactions) of freshwater biota.

Turbidity Opacity of water caused by suspended particulate matter used as measure of phytoplankton biomass.

Tychoplankton Organisms circumstantially carried into the plankton often from plant or rock surfaces. Also referred to as 'accidental plankton' or 'pseudoplankton'.

Water bloom See algal bloom.

Zooplankton Assemblage of invertebrate planktonic organism.

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