# ALGAL BLOOMS AND ZOOPLANKTON STANDING CROP ALONG THE SOUTHWEST COAST OF INDIA

Thesis submitted to the

COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

MARINE BIOLOGY

UNDER THE FACULTY OF MARINE SCIENCES

BY

**PADMAKUMAR K. B.**

DEPARTMENT OF MARINE BIOLOGY, MICROBIOLOGY AND BIOCHEMISTRY
SCHOOL OF MARINE SCIENCES
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
KOCHI- 682 016

November 2010

# CERTIFICATE

This is to certify that the thesis entitled "**Algal blooms and zooplankton standing crop along the southwest coast of India**" is an authentic record of the research work carried out by Mr. Padmakumar. K. B, under my scientific supervision and guidance in the School of Marine Sciences, Cochin University of Science and Technology, in partial fulfilment of the requirements for the degree of Doctor of Philosophy of the Cochin University of Science and Technology and that no part thereof has been presented before for the award of any other degree, diploma or associateship in any University.

**Prof. Dr. N.RAVINDRANATHA MENON**
Emeritus Professor
School of Marine Sciences
Cochin University of Science and Technology
Kochi - 16

Kochi-16
November 2010

# DECLARATION

I hereby declare that the thesis entitled **“Algal blooms and zooplankton standing crop along the southwest coast of India”** is an authentic record of research work done by me under the supervision of Prof. Dr. N. R. Menon, Emeritus Professor, School of Marine Sciences, Cochin University of Science and Technology and no part of this has been presented for any other degree or diploma earlier.

Kochi-16
November, 2010

**Padmakumar K. B**

# Acknowledgement

***Guru Brahma Guru Vishnu Guru Devo Maheshwarah |***
***Guru Saakshaat Par-Brahma Tasmei Shree Gurave Namah ||***

*Indian tradition has given a great place for Guru. As the creator of knowledge he takes the place of Brahma, as the protector of our intellectual faculty he takes the place of Vishnu and as the destroyer of our ignorance he takes the place of Maheshwara. He is the Supreme Being, the Para Brahma, in binding us all with the feeling of universal oneness hence I offer my salutation to my Guru, Prof. (Dr.) N. R. Menon, Emeritus Professor, School of Marine Sciences, Cochin University of Science and Technology, for suggesting the topic of research, inspiring supervision, encouragement, scrupulous scrutiny of the manuscript and decisive suggestions during the entire tenure of the work without which it would have been a separate tale.*

*I am obliged to Prof. Dr. Aneykutty Joseph, Head, Department of Marine Biology, Microbiology and Biochemistry, for the encouragement and support I received throughout the tenure of my doctoral programme and for providing necessary facilities.*

*I am grateful to Dr. A. V. Saramma, Principal Investigator, 'Harmful Algal Blooms in the Indian EEZ' Dept. of Marine Biology, Microbiology and Biochemistry, School of Marine Sciences, CUAST, for the financial support as JRF in the project during the course of my Ph.D programme.*

*I gratefully acknowledge Dr. V. N. Sanjeevan, Director, Centre for Marine Living Resources & Ecology, Ministry of Earth Sciences, Kochi, for the encouragement and also giving all the amenities for sampling. I also thank Dr. T. Shunmugaraj and all other staffs of CMLRE for their cooperation.*

*I am thankful to Dr. H. Ram Mohan, Dean and Director and K. Mohan Kumar, former Dean, School of Marine Sciences, for their constant encouragement and for providing necessary facilities to carry out my research.*

*I wish to pronounce my gratitude to Prof. Dr. Babu Philip, Dr. Rosamma Philip, Dr. S. Bijoy Nandan and Dr. A. A. Mohamed Hatha, faculty members of the department for their support and encouragement.*

*Dr. K. J. Joseph, Professor (Retd.) Department of Marine Biology., was a source of inspiration, I sincerely thank him. I sincerely thank Prof. Dr. K. T. Damodaran, former Director and Prof Dr. R. Damodaran, former Dean, School of Marine Sciences for their valuable suggestions. I also wish to express my gratitude to Prof Dr. C. K. Radhakrishnan, former head of the department for his encouragement.*

*Dr. Sanilkumar M. G, was in the midst of me through out the tenure of the study as a co-worker and friend of all times. I thank him for all the helps offered to me. Mr. K.R. Abhilash, my colleague, has been very helpful to me in the collection of samples and I am thankful to him.*

*I thank the crew members of FORV Sagar Sampada for their help during the cruises. Service provided by fishing hands Mr. Tapan kumar, Mr. Sunil, Mr. Ratinavel, Mr. Prakash, Mr. Pradeep and Mr. Binoy are thankfully acknowledged.*

*Special thanks must also go to Dr. A. K. S. K. Prasad, Secretary, International Phycological Society, Department of Biological Sciences, Florida State University, USA who gave me valuable advice on diatom identification and took some good SEM pictures of the diatom species for this thesis.*

*I am thankful to my dear friends Dr. Nandini Menon, Dr. Soja Louise, Mrs. Cilla Abraham, Ms. Lathika Cicily Thomas, Mr. Niaz, Mr. Abdul Jaleel and Mr. M. Mohandas for their help.*

*I sincerely thank Mrs. K. Sreedevi, Mrs. T. Komalavally Nessiar former Section Officers, Mrs. Nazeem, K. K Section Officer, Mrs. Mr. C. J. Antony Ferdenend, Mrs. V. C. Shobhini and other staffs of the Department of Marine Biology, Microbiology and Biochemistry, for their timely service. I thank Mr. P. J. Manuel, librarian, and other staff, School of Marine Sciences Library for their valuable cooperation.*

*I thank Dr. A. Jeevanand, Reader, Department of Mathematics, Union Christian College, Aluva, for the statistical analysis.*

*Finally I wish to express my love and affections to my beloved Father, Mother and my sister for their kind understanding, endurance, prayers and sacrifices.*

*Padmakumar K B*

*……. to my beloved Parents and Sister*

# CONTENTS

# General Introduction

Phytoplankton or micro algae play a cardinal role as primary producers in the marine ecosystem forming the base of marine food web. The organic matter so produced ultimately determines the secondary and tertiary production among which fish, prawns, mussels etc. that we harvest. Although invisible to the naked eye they play an outstanding role in scavenging atmospheric carbon dioxide and the production of about 80% of the oxygen. The important components of marine phytoplankton are the diatoms (Bacillariophyceae), dinoflagellates (Dinophyceae), green micro algae (Chlorophyceae), blue green algae (Cyanophyceae), silicoflagellates, coccolithophores and the very minute nannoplankters. Favourable environmental conditions can result in the proliferation of these microalgae into enormous concentration (millions of cells per liter) and often leading to discoloration of the surface of the sea. These natural phenomena are termed as ‘harmful algal blooms (HABs)’ or ‘red tides’. In many cases the proliferation of planktonic algae is beneficial for aquaculture and wild fisheries operations especially in the case of ‘spring blooms’ of higher latitudes. However, algal blooms can have negative effects, causing severe economic loss to aquaculture, fisheries and tourism operations, and also cause major environmental disturbances and significantly human health impacts. The International Council for the Exploration of Seas (ICES, 1984) has defined the phytoplankton blooms as ‘those which are noticeable, particularly to the general public, directly or indirectly through their *effects* such as visible discolouration of the water, foam production, fish or invertebrate mortality or toxicity to humans'.

Among around 5000 species (the number is still rising with recent advances in technology) of extant marine phytoplankton (Sournia *et al.*, 1991), approximately 300 species including diatoms, dinoflagellate, raphidophytes, prymnesiophytes, cyanophytes and silicoflagellates can at times cause algal blooms. Only a few dozen of these species have the ability to produce potent toxins which can find their way through fish and shellfish to humans. These toxins accumulate in shellfish while feeding on these algae, resulting in poisonous syndromes like paralytic shell fish poisoning (PSP), diarrhoeic shell fish poisoning (DSP), amnesic shell fish poisoning (ASP) and neurotoxic shell fish poisoning (NSP) in human consumers. Fish may be contaminated as well, causing ciguatera fish poisoning (CFP), which results in human illness or death followed by consumption of the contaminated fin fish (Richardson, 1997).

It is believed that the first written reference (1000 years B.C.) to a harmful algal bloom appears in the Bible (Exodus 7: 20-21): "..... *all the waters that were in the river were turned to blood. And the fish that was in the river died; and the river stank, and the Egyptians could not drink of the water of the river*……" In this case, a non-toxic bloom-forming alga proliferated in such a fashion that it resulted in anoxic conditions leading to indiscriminate kills of both fish and invertebrates. Oxygen depletion can be due to high rates of respiration by the algae (at night or in dim light conditions) but more commonly caused by bacterial respiration during decay of the bloom. Though HABs are natural phenomena and have occurred throughout the recorded history, recent studies around the world indicate that they have increased in frequency and geographic distribution over the past few decades (Daranas *et al*., 2001). According to Ho and Hodgkiss (1991) in a review on red tides in subtropical coastal waters from 1928 to 1989, the number of HABs increased from 1- 2 every ten years at the beginning of the period to over 220 between 1980 to 1989. Maclean (1989) noted the spread of toxic dinoflagellate bloom *Pyrodinium bahamense* var. *compressa* to new locations in the coastal waters of Philippines, with increased occurrence of human fatality by PSP caused by this species. Increase in frequency of HABs have been reported along the South African coasts (Horstman, 1981), Dutch coastal waters (Cadee, 1986), Seto inland Sea, Japan (Imai and Itoh, 1987), Hong Kong (Lam and Ho, 1989), Black Sea (Turkoglu and Koray, 2002), in Chinese coastal waters (Qi *et al*., 1995), in the coastal waters of North America (Horner *et al*., 1997) and in the Gulf of Oman (Thangaraja *et al*., 2007) and Anderson (2004).

One of the first recorded fatal cases of human poisoning after eating shellfish contaminated with dinoflagellate toxins happened in 1793, when Captain George Vancouver and his crew landed in British Columbia in an area now known as Poison Cove. He noted that for local Indian tribes it was a taboo to eat shellfish when the seawater became phosphorescent due to dinoflagellate blooms (Dale and Yentsch, 1978). The causative alkaloid toxins, now called paralytic shellfish poisons (PSP), are so potent that a pinhead-size quantity (about 500 micrograms), which can easily accumulate in just one 100 gram serving of shellfish, could be fatal to humans. On a global scale, close to 2000 cases of human poisoning (15% mortality) through fish or shellfish consumption are reported each year and, if not controlled, the economic damage through reduced local consumption and reduced export of seafood products can be considerable. Whales and porpoises can also become victims when they receive toxins through the food chain via contaminated zooplankton or fish (Geraci *et al.,* 1989). Poisoning of manatees by dinoflagellate brevetoxins contained in salps attached to sea grass (Anderson and White, 1989), and of pelicans by domoic acid harbouring diatoms in anchovies have also been reported (Work *et al*., 1993).

Herbivorous zooplankton through consumption of phytoplankton are important converters of plant material to animal matter forming the most important link in the food web as a resource for consumers of higher trophic levels and in the trophic chain function as a conduit for packaging the organic material in the biological pump. Zooplanktons are important to the pelagic ecosystems in the Arabian Sea (Barrs and Oosterhius, 1997; Smith *et al*., 1998; Roman *et al.,* 2000). Understanding of zooplankton biomass important for gaining an insight into the fish production of the oceans (Lenz, 1973; Santhakumari and Saraswathy, 1981). Zooplankton communities support higher trophic levels and are essential determinant on the potential size of the fishery. The zooplankton and phytoplankton pulses are generally considered to be coincident or immediately following each other. In general, it is usually stated that the abundance of the zooplankton is dependent upon the abundance of the phytoplankton, but the zooplankton production is slower, hence the peak of zooplankton production lags behind the peak of phytoplankton production (Riley *et al*., 1949).Grazing rate of zooplankton is one of the major factor influencing the size of the standing crop of phytoplankton and also the development of algal blooms. A decline in the quantum of herbivorous zooplankton has been suggested as causative factor influencing certain type of phytoplankton blooms in the coasts of some sub tropical areas and certain regions of the Arabian Sea (Balakrishnan Nair and Thampy, 1980).

The transfer of toxins through marine food web is an important aspect of the dynamics of HABs. Toxins associated with marine phytoplankton can enter pelagic food webs through ingestion by phytoplanktivorous zooplankton and these organisms serve as vectors for toxin transfer to higher trophic levels, including humans (Lefebvre *et al*., 1999; Turner and Tester, 1997; Turner *et al*., 1998). In the case of paralytic shellfish poisoning in Massachusetts Bay (Turner *et al*., 2000) larger zooplankton of size fractions (200–500 mm, 4500 mm), dominated by *Calanus finmarchicus* and *Centropages typicus*, were found to accumulate large quantities of the relevant toxin. These copepods represent potential vectors for the direct transfer of PSP toxins to zooplanktivorous baleen whales, such as the north Atlantic right whale, as reported from the Bay of Fundy (Durbin *et al*., 2002; Doucette *et al*., 2005). However, toxin levels were low or undetectable in the smaller zooplankton (64-100 mm), containing primarily protists and other smaller copepod taxa. This emphasizes the importance of spatio-temporal variations in zooplankton community structure and their potential influence on the routes of toxin transfer in the trophic chain. Low numbers of zooplankton were observed along with a high concentration of monospecific bloom of *Karenia brevis* in the Gulf of Mexico (Lester, 2008). In the bloom area where the phytoplankton assemblage was mixed with less dense harmful species, greater abundance of certain zooplankton genera were observed. Dense blooms of dinoflagellates, which frequent the coastal waters, are unpredictable, patchy and almost monospecific (Sweeney, 1979). Reduction of grazing mortality due to the behavioral responses of zooplankton grazers simulates the dinoflagellate blooms in coastal waters (Wyatt and Horwood, 1974). This statement was well explained by Fiedler (1982) during a *Gymnodinium splendens* bloom and associated zooplankton avoidance accompanied by reduced grazing response in the coastal waters of southern California. Reduced zooplankton grazing on *Ceratium* dominated bloom was assigned to the poor food value (Graneli *et al.*, 1989). According to Smetacek (1981) the development of *Ceratium* blooms has been associated with a decline in mesozooplankton.

Copepods tend to avoid certain diatom species which harbour toxins. *Calanus pacificus* seemed most averse to diatom of the genus *Thalassiosira*, often avoiding them when they were the most dominant unicells, both numerically and by carbon content. By causing either reproductive harm to the copepods or reduced copepod rate of growth and reproduction, these toxic diatoms may be indirectly influencing the entire food web (Leising *et al.*, 2005).

The success of cyanobacterial blooms in brackish water ecosystems is due to their physiological adaptations that favour them competitively over other primary producers and their poor utilization by filtering zooplankton (Paerl, 1988; Sterner, 1989). According to Engstrom (2001) mysid, *Mysis mixta* fed actively on the non-toxic cyanobacteria and at low rates on the toxic strains. In nature, grazers avoid harmful algae by switching (Turner *et al.*, 1998), selective feeding (DeMott and Moxter, 1991) or vertical migration (Forsyth *et al.*, 1990).

The harpacticoid copepods, *Microsetella gracilis* and *Macrosetella gracilis* depend on *Trichodesmium* (a recurrent bloom forming cyanobacteria in warm tropical oceans) for its food and may be regarded as one pathway by which the elemental carbon and nitrogen of the blue green algae are introduced into the marine food web (Bjornberg, 1965; Roman, 1978). From the Indian waters only a few reports are available on impact/ relation between harmful algal blooms and zooplankton and when available are only restricted to *Trichodesmium* red tides (Pant *et al.,* 1984; Santhanam *et al*., 1994).

The toxins or metabolites produced by certain species of phytoplankton have a poisonous influence on the herbivorous zooplankton. The resulting break in the food chain upsets the balance between phytoplankton and zooplankton, which results in the spectacular growth of the phytoplankton. The success of a phytoplankton species is not only dependent on their specific growth rate, but also the difference between growth and loss. Mesozooplankton, one of the main grazers on phytoplankton, could play a key role in the control, structure and development of dinoflagellate blooms (Sandra *et al*., 2006). The effect of HABs on grazers is variable and appears to be situation specific. Some grazers are adversely affected by phycotoxins, whereas there are no apparent effects on others.

There have been three main theories to explain the phytoplankton-zooplankton relationship; viz theory of grazing, theory of animal exclusion and theory of differential growth rate. These three theories are not necessarily in opposition to each other and perhaps all three are partly valid. The theory of grazing was proposed by Harvey *et al*. (1935), and they opined that according to this theory, in those places where the zooplankton population is greater to begin with, the consumption of the phytoplankters take place at such a rate that they are not able to build up to large numbers. In those places where the initial population of zooplankton is lower, the phytoplankters have a chance to multiply rapidly, and thus result in a great local phytoplankton production. According to the theory of animal exclusion (Hardy and Gunther, 1935) animals avoid water rich in phytoplankton because the plants have some effect on the quality of the water which animals find unpleasant. The nature of the excluding influence is uncertain, but it might perhaps be due to the presence of secondary metabolites of the plants present in the water. Small zooplankters could avoid this water by controlling their depth so as to remain at deeper levels until the relative movement of the different layers of water carries them to areas where the surface water is less objectionable. The theory of differential growth rate was proposed by Steeman Nielsen (1937). Since reproductive cycle of phytoplankters is relatively very short and the rate of reproduction, ontogenic development and production of high-density zooplankton population is less rapid and often species dependent the standing crop of phytoplankton could be affected. The occurrence of phytoplankton and zooplankton population in abundance at different locations could be due to discontinuous distribution, which could be incidental, accidental or limiting factor dependent.

Approximately 2000 cases of human poisoning with an overall mortality rate of 15% have been reported world wide, is mainly caused by the consumption of fish/ shell fish contaminated by algal toxins (Hallegraeff, 1995). From Indian waters HABs and their negative impacts have been reported by many researchers (Hornell, 1917; Aiyer, 1936; Bhimachar and George, 1950; Prasad, 1953; Subrahmanyan, 1954; Subramanian and Purushothaman, 1985; Jugnu and Kripa, 2009; Gopakumar *et al*., 2009). Shell fish poisoning and related human fatalities have been reported from the Indian coats. PSP poisoning due to consumption of bloom infected *Meretrix casta* resulted in three death and hospitalization of many peoples in Tamilnadu in 1981 and in Mangalore (Karnataka) during 1983 (Bhat, 1981; Karunasagar, 1984; Devassy and Bhat, 1991). But the toxic species could not be identified. In Vizhinjam (Kerala) five children died and 300 peoples were hospitalized in 1997 due to shell fish poisoning by *Gymnodinium* (Karunasagar *et al*., 1998). In 2004, a massive fish kill and hospitalization of people especially childrens in Kollam and Trivandrum coasts was by consumption of intoxicated sea food. The bloom that occurred along the south west coast was due to species belonging to the genera *Gonyaulax*, *Cochlodinium* and *Karenia* (Sahayak *et al*., 2005, Iyer *et al*., 2008).

HABs have now become a global phenomenon, spreading across the seas of 30 countries including India. Number of HABs, economic losses from them, the types of resources affected and number of toxins and toxic species have also increased dramatically in recent years (Anderson, 1989; Smayda, 1990; Hallegraeff, 1993). The Arabian Sea especially Southwest coast of India is one of the most productive regions of the world and is important in commercial fishery, accounting for about 53% of the total exploited catch from the country. Recently, the occurrence of HABs and their negative impacts on fishery and marine ecosystem have increased along the west coast of India. Early warning on HABs is the most widely used management strategy, which helps in implementing specific plans to avoid health problems and to minimize the economic loss. In view of this, Centre for Marine Living Resources and Ecology (CMLRE), Ministry of Earth Sciences has been initiated a National programme on Harmful Algal Bloom monitoring in the EEZ of India and the present work is a part of this programme. Considering the importance of reduced zooplankton grazing on HAB initiation and also their role in transfer of toxins to higher trophic levels, the present study on “Harmful Algal Blooms and zooplankton standing crop along the south west coast of India” gains importance.

# Chapter 1

# Materials and Methods

## 1.1 Study area

Regular and continuous monitoring of Harmful algal blooms were conducted at four stations for a period of two years (2006- 08) along the coastal waters of south west coast of India. The stations were selected by a preliminary survey and discussions with the fisher folks for the occurrence of algal blooms along the south west coast. Algal blooms have appeared in all these stations during the recent past. Station 1 Vadi (off Kollam, Lat. 08°52.01 N, Long. 76°34.26 E); station 2 Punnapara (off Alapuzha, Lat. 09°25.23 N, Long. 76°19.41 E); station 3 Azheekode (off Kochi, Lat. 10°11.02 N, Long. 76°09.22 E) and station 4 Kodikkal (off Calicut, Lat. 11°28.43 N, Long. 75°36.10 E). The sampling stations are shown in figure 1. Samples for the estimation of physico-chemical and biological parameters were made on a seasonal basis (Pre-monsoon, Monsoon and Post-monsoon) from all these stations for a period of two years (2006-2008). For the ease of representation ellipsis PRM, MON and POM are used for premonsoon, monsoon and postmonsoon respectively.

Besides regular, seasonal coastal sampling, algal blooms observed during FORV Sagar Sampada cruises (FORV SS cruise no. 253 March

2007, trial cruise August 2008, cruise no. 264 March 2009, cruise no. 267 May-June 2009 and cruise no. 272 Sept- Oct 2009) along the Arabian Sea were also included. Figure 2 shows the location of algal blooms observed during the Sagar Sampada cruises.

## 1.2 Hydrographic parameters

### 1.2.1 Physical parameters

Hydrographic parameters such as temperature, salinity of the surface sea water were measured immediately after the collection of water sample during the field survey. Temperature was measured using an alcohol thermometer with an accuracy ± 0.01°C. Salinity was measured using a hand held refractometer (*ATAGO-Smill-E*, Japan) and was expressed in psu. During onboard FORV Sagar Sampada cruises CTD profiler (*Seabird 911 plus CTD*) was used for measuring temperature and salinity.

**Figure 1. Map showing the location of regular field sampling stations**

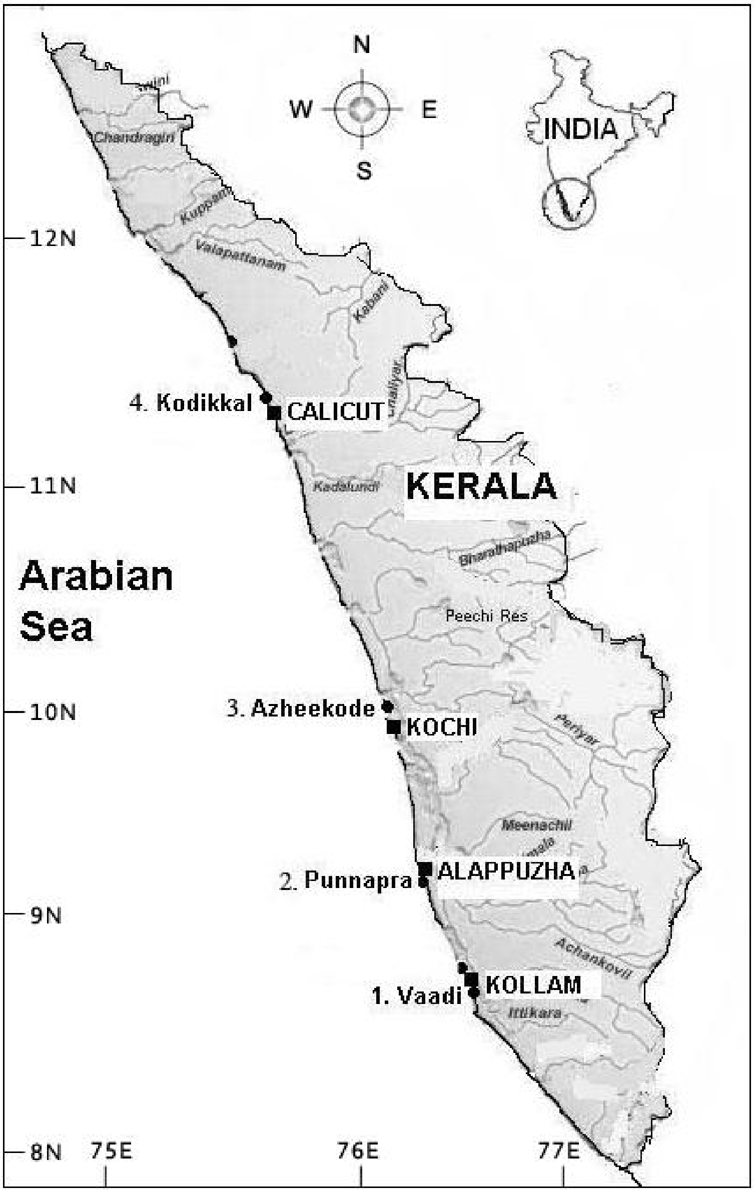
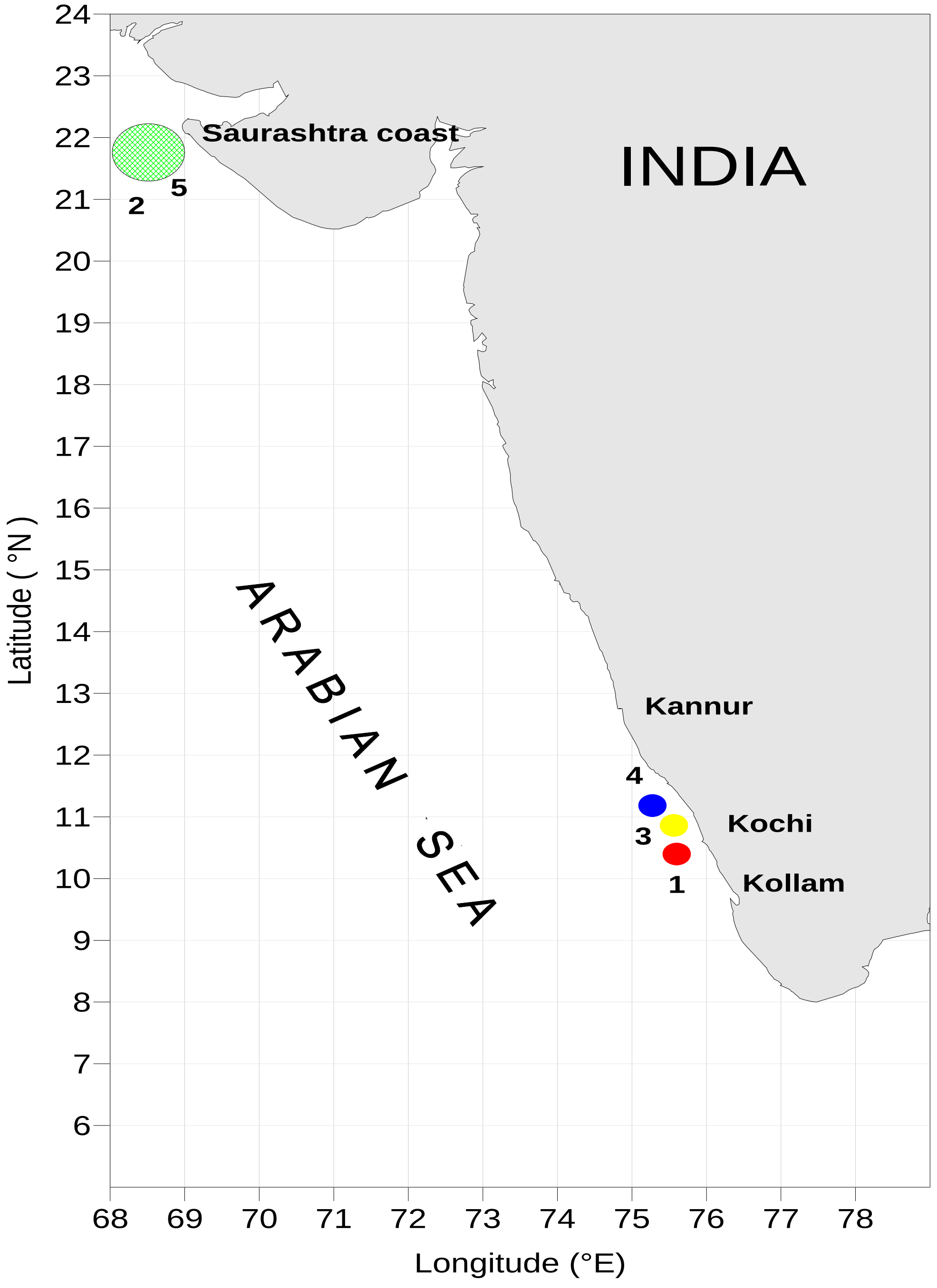


**Figure 2. Map showing the locations of algal blooms observed during FORV Sagar Sampada cruises (2006- 2009)**



### 1.2.2 Chemical parameters

#### 1.2.2.1 Dissolved oxygen

Dissolved oxygen was estimated by Winkler method (1888).

#### 1.2.2.2 pH

pH was measured using a portable digital pH meter (*Eutech pH Scan1* with accuracy ± 0.1 pH) and was calibrated with standard buffers prior to the field sampling.

#### 1.2.2.3 Nutrients

Major nutrients like nitrate, phosphate and silicate of surface water samples were analysed in the laboratory using standard procedures. Nitrite was first reduced to nitrate by the cadmium- copper column reduction method and nitrate estimated by sulphanilamide method by Morris and Riley (1963) with modifications suggested by Grasshoff (1964) and Wood *et al* (1967). Phosphate was analysed by the ascorbic acid method by Murphy and Riley (1962). Silicate was estimated by following Strickland and Parsons (1972). During FORV Sagar Sampada cruises nutrients were analysed using a segmented flow Auto Analyzer (SKALAR) onboard the vessel by following UNESCO- JGOFS protocol (1994).

### 1.2.3 Biological parameters

#### 1.2.3.1 Chlorophyll *a*

Chlorophyll *a* is taken as the index of Algal Blooms during the present study. Acetone extraction method was used for the chlorophyll estimation (Parsons *et al*., 1984). One litre of water samples free of zooplankton were filtered through Whatman GF/F filter paper of porosity 0.45μm. Before the filtration of water samples, 1 ml of 1% $MgCO_3$ suspension was added on to the filter paper to form a thin bed which will serve as a precaution against the development of any acidity and subsequent degradation of pigments in the extract. For the extraction of pigments the filter paper with filtrate was placed in a stoppered test tube containing 10ml of 90% aqueous acetone. To accelerate the extraction of pigments, the filtrate was gently ground with a homogenizer or glass rod and the test tube was then stoppered. This operation must be carried out in a semi-darkened area. The test tube with the solution was subsequently transferred to a dark colored cloth bag, and placed in a refrigerator for 24 hours in order to facilitate the complete extraction of pigments. After the extraction period the extract was transferred to a graduated centrifuge tube and the volume made up to 10ml by adding fresh 90% acetone. The solution was centrifuged for about 20 minutes at 5000 rpm and the supernatant solution was used for determination of optical density using *HITACHI U-2001* UV-visible spectrophotometer. The supernatant solution was then transferred to 1 cm (path length) cuvette of the spectrophotometer for the determination of optical densities at different wavelengths, viz. 750, 664, 647 and 630 nm, the maximum absorption wave length of the pigments. All the extinction values were corrected for a small turbidity blank by subtracting the optical density of 750nm from the 665, 645 and 630nm absorptions.

The following equation was used to calculate the chlorophyll *a* concentration.

$$\text{Chlorophyll } a\ (\mathrm{C}a) = 11.85\ \mathrm{E}_{665} - 1.54\ \mathrm{E}_{645} - 0.08\ \mathrm{E}_{630}$$

Where ‘E’ is the absorbance at different wavelengths in the respective wavelengths.

$$\text{Chlorophyll } a\ \mu\text{g/ litre} = \frac{\mathrm{Ca} \times \mathrm{v}}{\mathrm{V} \times 1}$$

Where ‘v’ is volume of acetone (ml), ‘V’ is volume of water (litre) filtered and ‘I’ is the path length (cm) of cuvette.

### 1.2.3.2 Phytoplankton analysis

Phytoplankton samples for quantitative and qualitative analyses were collected by filtering ~50 litres of surface water through 20□ bolting silk and the filtrate preserved in 1-3% neutralized formaldehyde/ Lugol’s iodine solution. Qualitative analysis involved calculation of the number of cells of each species of phytoplankton in one liter of sea water. Quantitative estimation of phytoplankton was found out by employing Sedgewick-Rafter counting cell. Species identification was done employing Nikon E200 light microscope using standard identification keys (Allen and Cupp, 1935; Venkataraman, 1939; Cupp, 1943; Desikachary, 1959; Hendey, 1964; Desikachary *et al.*, 1987b; Subrahmanyan, 1946, 1959a, 1959b, 1968, 1971; Subrahmanyan and Sharma, 1960; Hallegraeff *et al.*, 1995; Tomas, 1997; Karlson *et al.*, 2010).

### 1.2.3.3 Primary productivity

Primary productivity experiments were conducted under *in situ* condition for three hours by light and dark bottle- oxygen method and the values obtained were extrapolated for the day hours in which photosynthetic quotient was taken as 1.25 (Gaarder and Gran, 1927). The following calculations were done to estimate gross and net production.

Gross prod. = $O_2$ content of light bottle-$O_2$ content of dark bottle →A

Net prod.= $O_2$ content of light bottle-$O_2$ content of control bottle → B

Respiration=$O_2$ content of control bottle- $O_2$ content of dark bottle →C

The period of incubation was 3 hours,

Gross production (mgC/L/Hr) = A x 0.375/ PQ x 3.....................D

Net Production (mgC/L/Hr) = B x 0.375/ PQ x 3..........................E

Gross or net production (mgC/L/Day) = D or E x12 ....................F

Gross or net production (gC/ $m^3$/day) = F x 1000 x1000

### 1.2.3.4 Zooplankton analysis

Zooplankton samples were collected employing a standard zooplankton net. Horizontal and oblique hauls were made to collect the samples. The filtering cone of the net was made of 200µ bolting silk. The speed of the haul was always maintained at 2 knots. The duration of the haul was always 5 minutes. During FORV Sagar Sampada cruises Bongo net (mesh size 200µ) was used for collecting surface zooplankton samples. The biomass was expressed as wet weight of zooplankton in $m^3$ of sea water. The value obtained was used to evaluate the secondary productivity and fishery potentials of the study area. Estimation of biomass was by standard methods, volume was obtained by displacement method, wet weight and dry weight by gravimetric method. Normally prior to determination of biomass, larger zooplankters such as medusae, ctenophores, salps, siphonophores and fish larvae were separated and their biomass estimated separately. The total biomass would be the biomass of bigger forms plus the biomass of the rest of the zooplankton. In displacement volume method the zooplankton sample was filtered through a piece of clean, dried netting material. The mesh size of netting material was smaller than the mesh size of the net used for collecting the samples. The water adhering to the zooplankton was removed with blotting paper. The filtered zooplankton was transferred to a measuring cylinder with a known volume of 4-5 % buffered formalin. To avoid interference of large zooplankton on the biomass volume they were sorted and removed before finding out the volume. Volume was determined by displacement method.

The weight measurements were done in shore laboratory. Zooplankton was filtered using the net material similar to the one used for the zooplankton net. The water adhering to the plankters was removed by blotting paper. While blotting, only mild pressure was used to prevent damage of delicate organisms. The weight of zooplankton was measure in an electronic balance. The wet weight is expressed in mg $m^{-3}$. Dry weight of the zooplankton was expected to be more dependable to express biomass. An aliquot of the zooplankton sample was dried for 24 hours at 60ºC in an electric oven. The dried samples were kept in a desiccator until weighing. Dry weight is represented as mg $m^{-3}$. Major zooplankton species were identified with the help of standard keys (Raymont 1963; Newell and Newell, 1963; Steedman, 1976; Omori and Ikeda, 1984; Todd *et al*., 1996; Harris *et al*., 2000).

The faunal composition and the relative abundance of different zooplankton taxa are obtained by counting the plankters present in the samples. The quality of the sample was estimated only from a sub sample of reasonable volume. However, rare groups were identified and enumerated from the whole sample. Required aliquots were obtained using Folsom plankton splitter. As a rule four aliquots were made, one was used for estimation of dry weight, another for enumeration, the third for finding out relative abundance. The fourth aliquot was kept as reference sample in the archive. The Stempel pipette was used to obtain a representative sample from the zooplankton suspension.

The zooplankton samples were examined for qualitative abundance on a major taxa basis. Counting was done following standard protocol. All the specimens present in the sub sample were counted with proper records on the data sheet. The quantity of zooplankton for volume and weight was expressed as ml $m^{-3}$ or mg $m^{-3}$ was obtained by the following method.

$$\text{Volume of zooplankton (ml/ m}^3\text{)} = \frac{\text{Total volume of zooplankton}}{\text{Volume of water filtered (V)}}$$

$$\text{Wet weight of zooplankton (mg/ m}^3\text{)} = \frac{\text{Total wet weight of zooplankton}}{\text{Volume of water filtered (V)}}$$

$$\text{Dry weight of zooplankton (mg/ m}^3\text{)} = \frac{\text{Total dry weight of zooplankton}}{\text{Volume of water filtered (V)}}$$

## 1.3 Statistical analysis

PRIMER, SPSS, MS Excel and Grapher softwares were used for statistical interpretation of data. First the bivariate correlation of environmental parameters with the biological parameters and phytoplankton density was done. Secondly the correlation between environmental parameters was calculated. The Pearson correlation coefficient was found in both the cases using SPSS (7.5) software.

Diversity indices were calculated using PRIMER v5 software (Clarke and Warwick, 1994).

**1.3.1 Margalef’s species richness:** Margalef’s species richness is a measure of the number of species present, making some allowance for the number of individuals belonging to each species. It was calculated according to the formula,

$$\text{Species richness (Margalef): } d = (S-1)/ \log_e (N)$$

Where, S= Number of species, N= Number of individuals

**1.3.2 Shannon- Wiener's diversity index:** Shannon-Wiener's diversity was calculated for measuring the variation in phytoplankton species diversity of the region over the two year period. This was calculated according to the formula,

$$H' = {}^{s}\sum_{i} \log_{e}(Pi)$$

Where *s*, is the number of species, and P*i* is the proportion of the total number of individuals consisting of the *i*th species

### 1.3.3 Cluster analysis:

Cluster analysis was done to find seasons with similar composition of phytoplankton and zooplankton. SIMPER analysis (analysis of similarity percentages) was then performed to identify the species/ groups which contributed to this clustering (Clarke, 1993). Seasonal abundance data were fourth root transformed and a triangular matrix of similarities between samples was derived using the Bray-Curtis similarity coefficient. The similarity matrix was then subjected to cluster analysis. Clustering was by hierarchical agglomerative method using group average linking, resulting in a dendrogram. In the resulting dendrogram, the seasons in the same cluster have more similar species/ group composition than seasons in different clusters. All these analysis were performed using PRIMER v5 (Clarke and Warwick, 1994) software.

# Chapter 2

# Hydrographic parameters

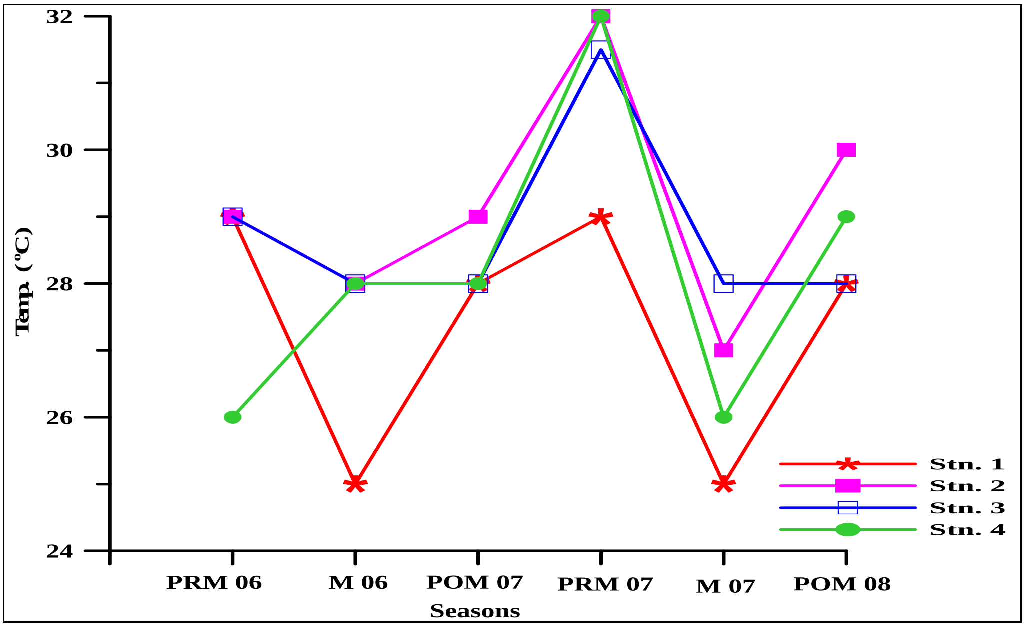
Generating roughly half the primary production, marine phytoplankton affect the abundance and diversity of marine organisms. It is argued that there has been an increase in the incidence of phytoplankton blooms. It is often argued that the apparent increase in the occurrence of harmful algal blooms is due to eutrophication. Environmental features such as temperature, salinity, dissolved oxygen and nutrients play a vital role in this production, initially at the primary and subsequently at the secondary and tertiary levels (Morris *et al.*, 1981; Gopinathan *et al.*, 2001). Along the Southwest coast of India the reversal of two monsoons (SW and NE monsoons) plays a critical role in triggering environmental features. Among these, SW monsoon is of importance in the production of phyto and zooplankton especially in the inshore upwelling areas (Qasim and Reddy, 1967; Subrahmanyan *et al.*, 1975; Silas, 1972; Mathew *et al.*, 1989; Satya Prakash and Ramesh, 2006). It is well known that an intense monsoon triggers off strong upwelling along the southwest coast of India. The interaction of hydrographical parameters and micro algae (phytoplankton) in a defined time may cause blooms in marine ecosystem, which can persist over a long period or occur from time to time. Initiation of harmful algal blooms (red tides) needs a seed population; in the case where the seed population is composed of resting cysts, environmental factors can cause resuspension and/ or excystment, creating a motile population capable of asexual divisions (Steidinger and Haddad, 1981). The relationship between the occurrence of harmful phytoplankton blooms and environmental conditions is complicated and anthropogenic perturbation is certainly not a prerequisite for all harmful phytoplankton blooms. The concentration and distribution of hydrographical parameters like sea surface temperature (SST), salinity, pH, Dissolved oxygen and inorganic nutrients (nitrite, nitrate, phosphate and silicate) were measured seasonally over a period of two years (2006- 08) to study their seasonal and spatial variations along the SW coast of India. The periods of the different years are mentioned as M (Monsoon), POM (Postmonsoon) and PRM (Premonsoon) for uniformity.

## 2.1 Physical parameters

### 2.1.1 Sea Surface Temperature

Spatial and seasonal variation of SST is given in figure 3. SST ranged between 25°C to 32°C during the study period. The lowest SST 25°C was recorded during the monsoon in station 1 and the highest SST of 32°C was recorded during the premonsoon period at stations 2 and 4. A dip in SST during monsoon was quiet well pronounced during the study period. SST showed an impound trend after southwest monsoon reaching its peak during the premonsoon. Two way ANOVA showed 1% level of significance with temperature and seasons. However, no significant correlation was noticed between temperature and stations.

**Figure 3. Temperature: Seasonal and spatial variations at various stations during the period 2006 to 2008**



### 2.1.2 Salinity

Seasonal and spatial variation of surface salinity is shown in figure 4. Salinity ranged between 22 to 37 psu. Highest salinity of 37 psu was observed in station 4 during the post monsoon period and the lowest 22 psu at station 3 during the monsoon. The low value observed in station 3 (off Kochi) might be due to the heavy inflow of fresh water through Azheekode barmouth into Arabian Sea during the monsoon season. Statistically, no significant relation was found between salinity with stations and seasons.

## 2.2 Chemical parameters

### 2.2.1 pH

Seasonal and spatial variation of surface pH is shown in figure 5. pH ranged between 7.5 to 8.3 during the study period. The highest value of 8.3 was observed at station 3 and 4 during post monsoon and the lowest at station 4 during the monsoon period of 2007. Two way ANOVA showed that the variation in pH was significant at 1% level between stations and seasons.

**Figure 4. Salinity: Seasonal and spatial variations at various stations during the period 2006 to 2008**

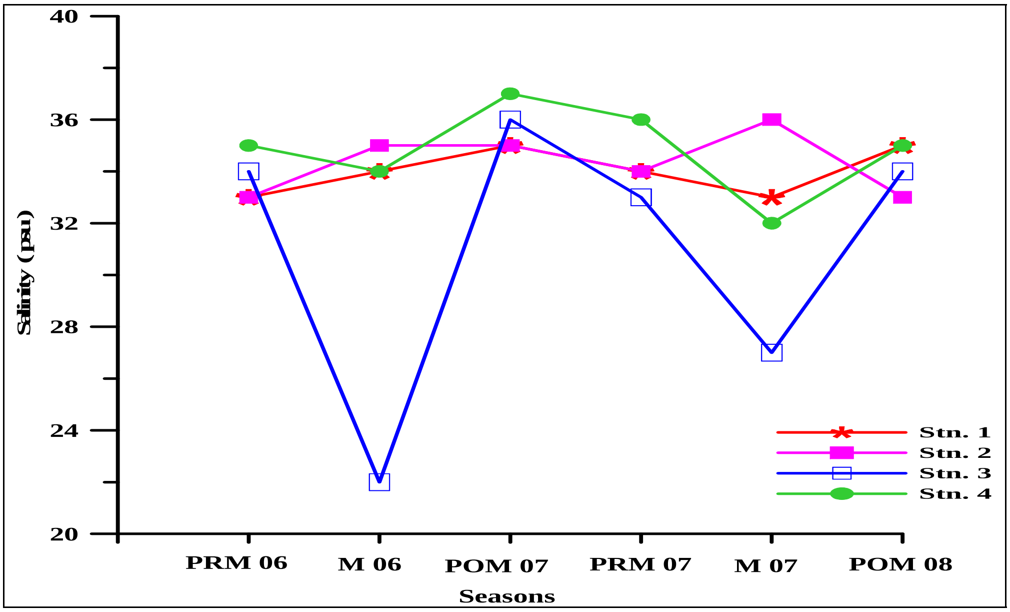
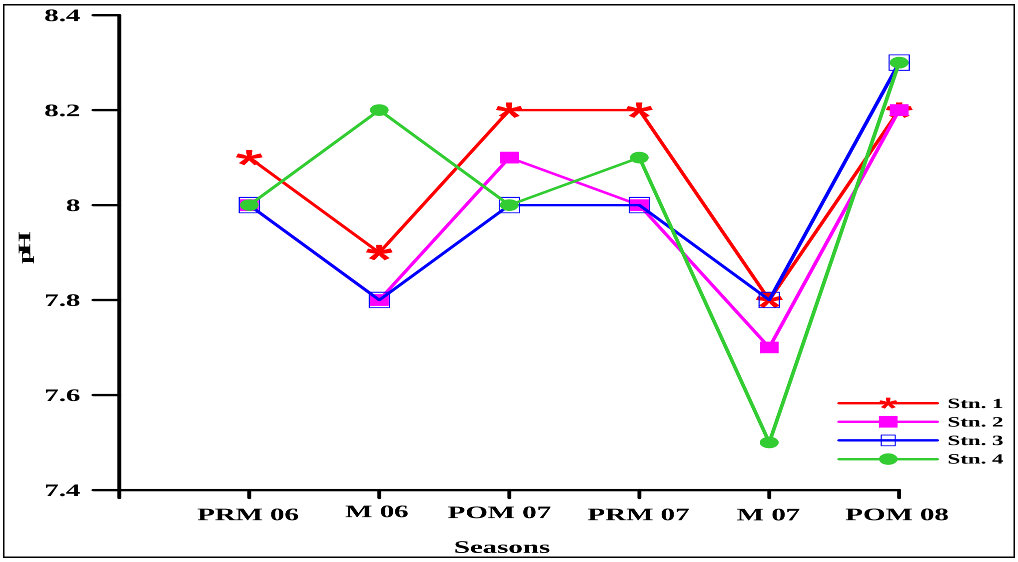


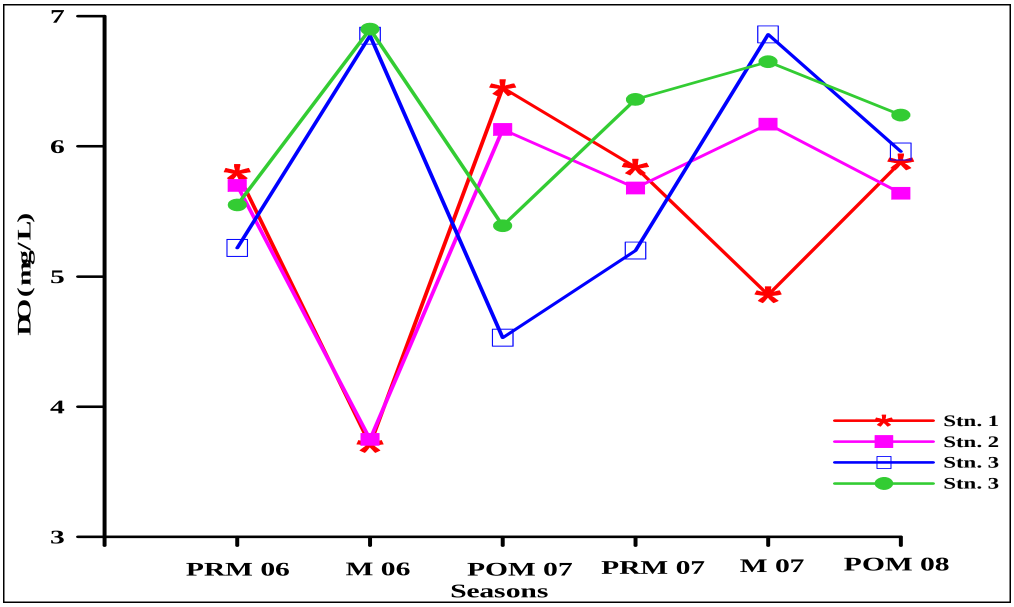
**Figure 5. pH: Seasonal and spatial variations at various stations during the period 2006 to 2008**



### 2.2.2 Dissolved oxygen

The result of surface dissolved oxygen estimation and their seasonal and spatial variation are presented in figure 6. During the study period DO values varied between 3.71 mg $L^{-1}$ to 6.9 mg $L^{-1}$. Highest DO was recorded at station 4 during the monsoon of 2006 and the lowest in station 1 during monsoon of 2006. Dissolved oxygen values were generally higher during monsoon at all the stations. It is assumed that heavy production of phytoplankton and enhanced fresh water run off during monsoon could be the reason for higher concentration of DO. Reduced DO in station 1 and 2 during monsoon season of 2006 was due to heavy turbidity and low phytoplankton production. This was an episodel event. There was no significant relation between seasons and stations with reference to DO.

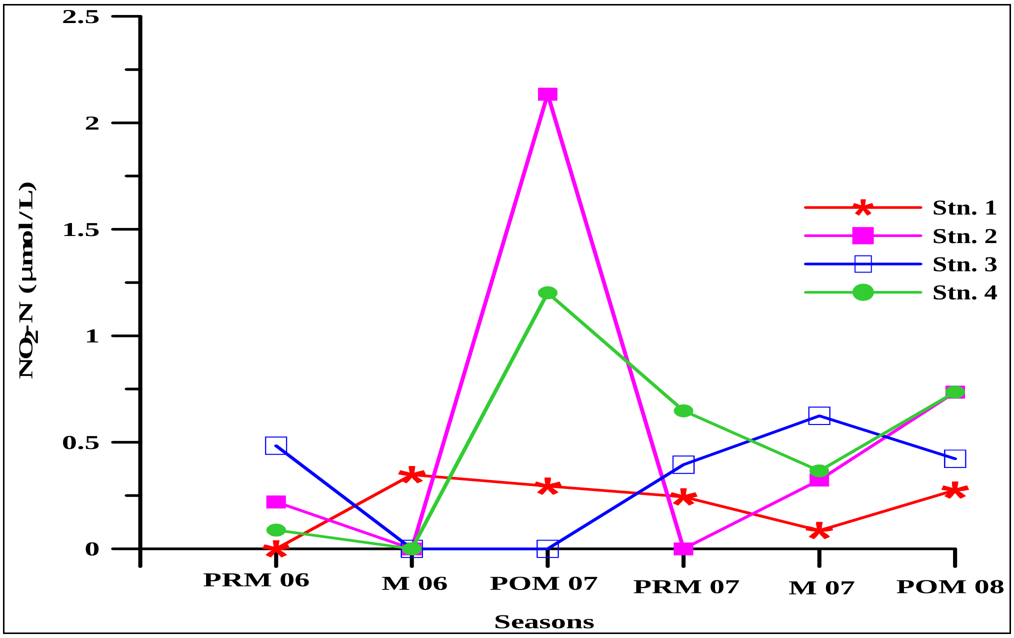
**Figure 6. Dissolved Oxygen: Seasonal and spatial variations at various stations during the period 2006 to 2008**



### 2.2.3 Nitrite

Seasonal and spatial distribution of nitrite of surface water is shown in figure 7. Nitrite concentration ranged from non-detectable levels to 2.13 µ mol $L^{-1}$. Highest nitrite concentration of 2.13 µmol $L^{-1}$ was observed at station 2 (off Alapuzha) during postmonsoon of 2007. During monsoon of 2006 nitrite concentration was below detectable range at station 2, 3 and 4. The nitrite value obtained at station 2 during the postmonsoon season of 2007 was unusually high and the reason for this could not be recognized. Statistical analyses indicated that the variations in nitrite content between seasons and stations were not significant.

**Figure 7. Nitrite: Seasonal and spatial variations at various stations during the period 2006 to 2008**



## 2.2.4 Nitrate

Nitrate concentrations of surface waters observed during the study period are shown in figure 8 and the values were in the range 0.73 µ mol $L^{-1}$ to 40 µ mol $L^{-1}$. High concentration of nitrate was noticed in station 1 and 3 during the monsoon season of 2007. Highest value of nitrate was recorded from station 1 (40 µmol $L^{-1}$) during monsoon of 2007. Station 2 recorded the lowest value for nitrate (0.73 µmol $L^{-1}$) during post monsoon of 2008. Two way ANOVA indicated that the variations are significant at 1% between stations and periods.

## 2.2.5 Phosphate

The seasonal and spatial variation of phosphate concentration is shown in figure 9. During the study period the phosphate concentration was in the range 0 to 3.21 µmol $L^{-1}$. Nil value was recorded during the pre monsoon period. Highest phosphate concentration was recorded at station 3 during monsoon of 2006. Surface waters were depleted of $PO_4$-P during the premonsoon season. However, monsoon seasons show predominantly phosphate rich surface waters. The observed concentration of $PO_4$-P was not significant statistically between seasons and stations indicating that the $PO_4$-P content of the surface waters showed comparable levels during seasons at all the stations sampled.

**Figure 8. Nitrate: Seasonal and spatial variations at various stations during the period 2006 to 2008**

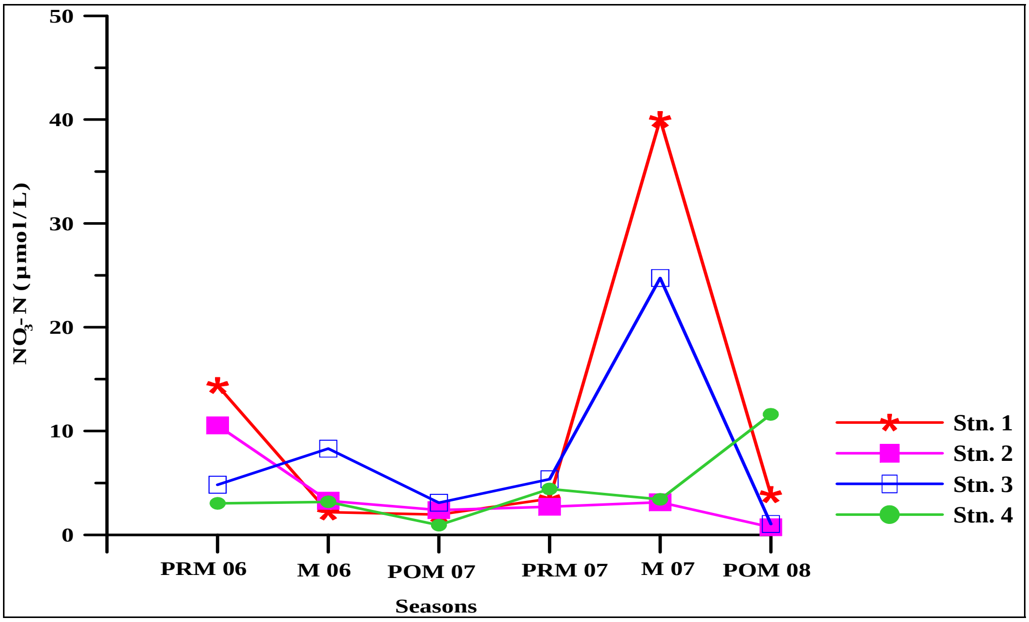
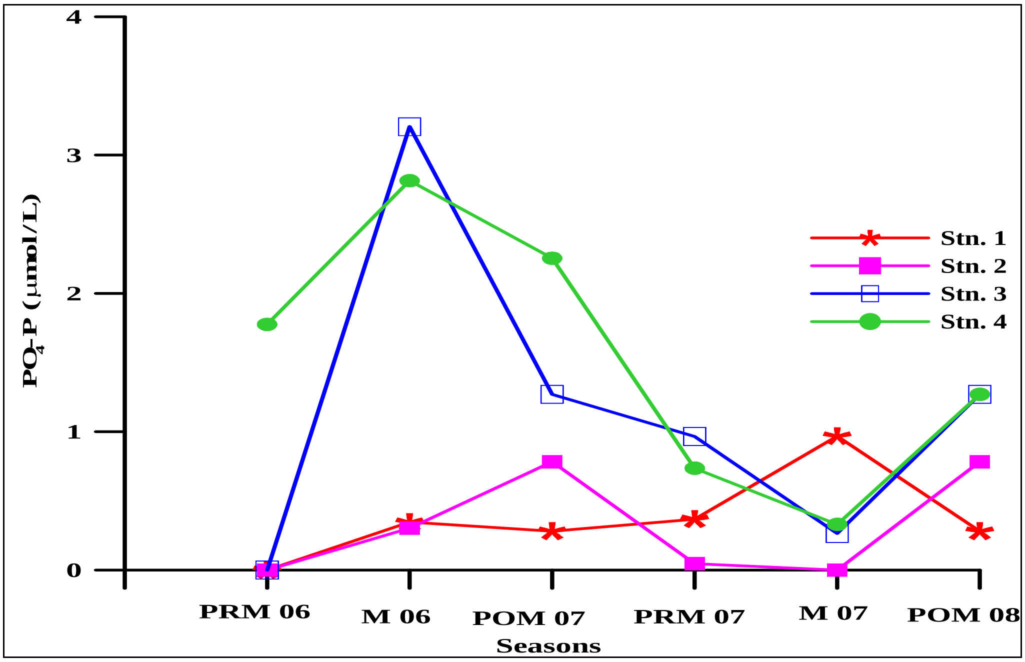


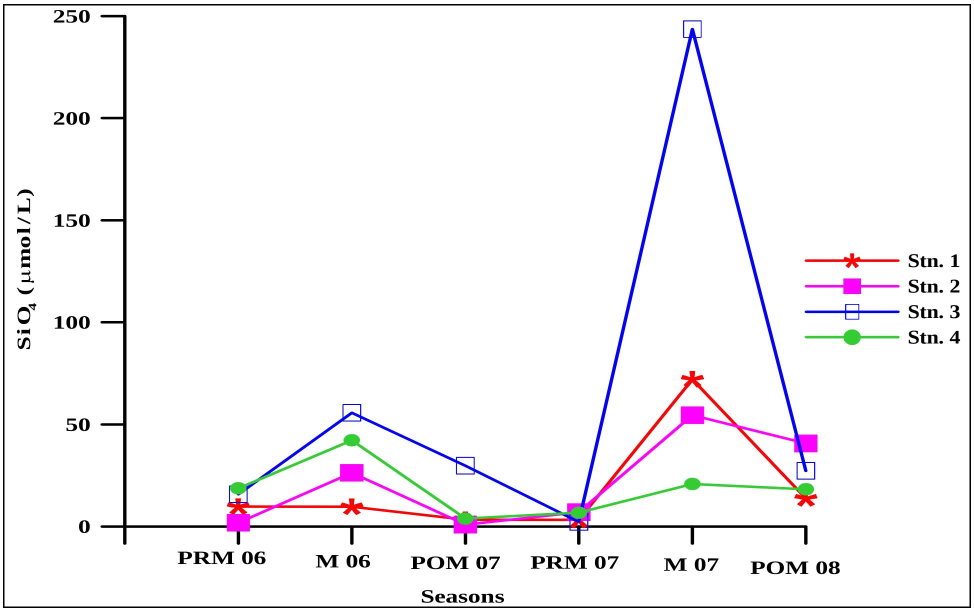
**Figure 9. Phosphate: Seasonal and spatial variations at various stations during the period 2006 to 2008**



## 2.2.6 Silicate

The seasonal and spatial variation of silicate ($SiO_4$) concentration is shown in figure 10. During the study period the silicate concentration was in the range 0.96 µmol $L^{-1}$ to 243.6 µmol $L^{-1}$. Silicate concentration was high during monsoon season compared to those of premonsoon and postmonsoon. The highest value was recorded at station 3 (243.6 µmol $L^{-1}$) during the monsoon of 2007 and lowest (0.961µmol $L^{-1}$) at station 2 during the postmonsoon of 2007. The changes in the distribution of $SiO_4$ observed in the study area were significant at 1% level between seasons and stations. This indicates that all the stations exhibited a similar trend spatially. The variations in distribution at the stations were controlled by seasons.

**Figure 10. Silicate: Seasonal and spatial variations at various stations during the period 2006 to 2008**

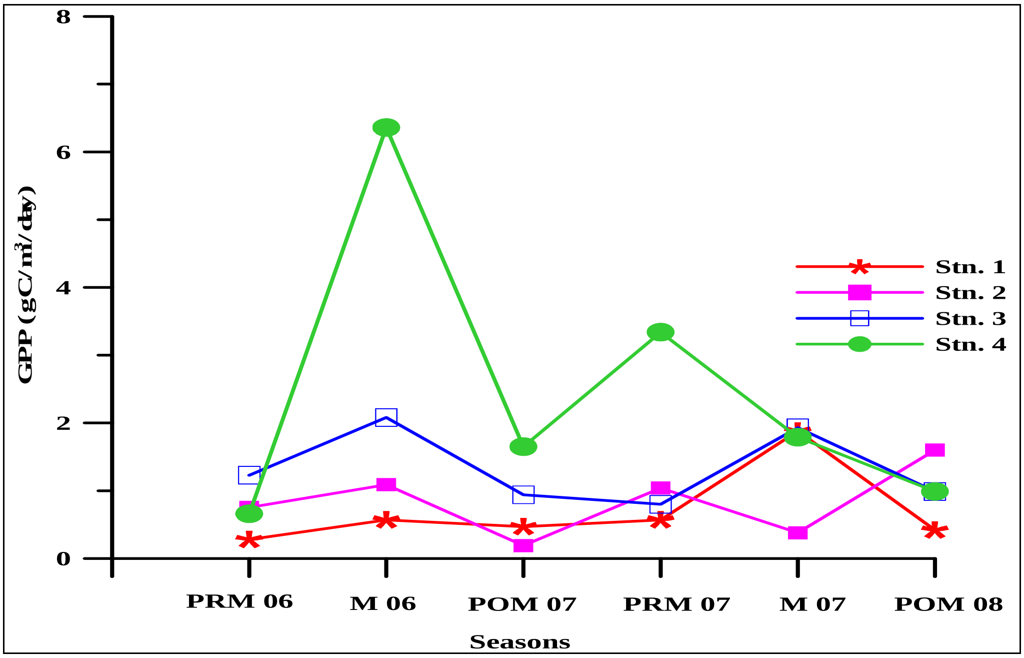


## 2.3 Biological parameters

### 2.3.1 Gross primary production (GPP)

Seasonal and spatial variation of gross primary production of surface waters of the study area is illustrated in figure 11. Surface primary productivity values were in the range of 0.19 gC/ $m^3$/ day to 6.36 gC/ $m^3$/ day. Highest gross primary production (6.36 gC/ $m^3$/ day) was recorded in station 4 (off Kodikkal) during the monsoon of 2006 and the lowest (0.19 gC/ $m^3$/ day) in station 2 during the postmonsoon of 2007. The whole area studied depicted high primary production during the monsoon season. Two way analyses however, did not indicate any statistical significant relationship between seasons and stations.

**Figure 11. Gross Primary Production: Estimated GPP of the various stations in the study area during the period Premonsoon of 2006 to Postmonsoon of 2008**



### 2.3.2 Net primary production (NPP)

Seasonal and spatial variation of net primary production of surface waters of the study area is illustrated in figure 12. The net primary production ranged from 0.09 gC/ $m^3$/ day to 5.61 gC/ $m^3$/ day. Highest surface net primary production (5.61 gC/ $m^3$/ day) was recorded at station 4 (off Calicut) during the monsoon season of 2006 and the lowest (0.09 gC/ $m^3$/ day) at station 2 during the postmonsoon season of 2007. In the case of net primary production the whole region behaved uniformly in the sense that monsoon season was characterised by uniformly high rates of net primary production. Evidently statistical analyses using analyses of variance method indicated no significant correlation between seasons and stations.

**Figure 12. Net Primary Production: Estimated NPP of the various stations in the study area during the period Premonsoon of 2006 to Postmonsoon of 2008**

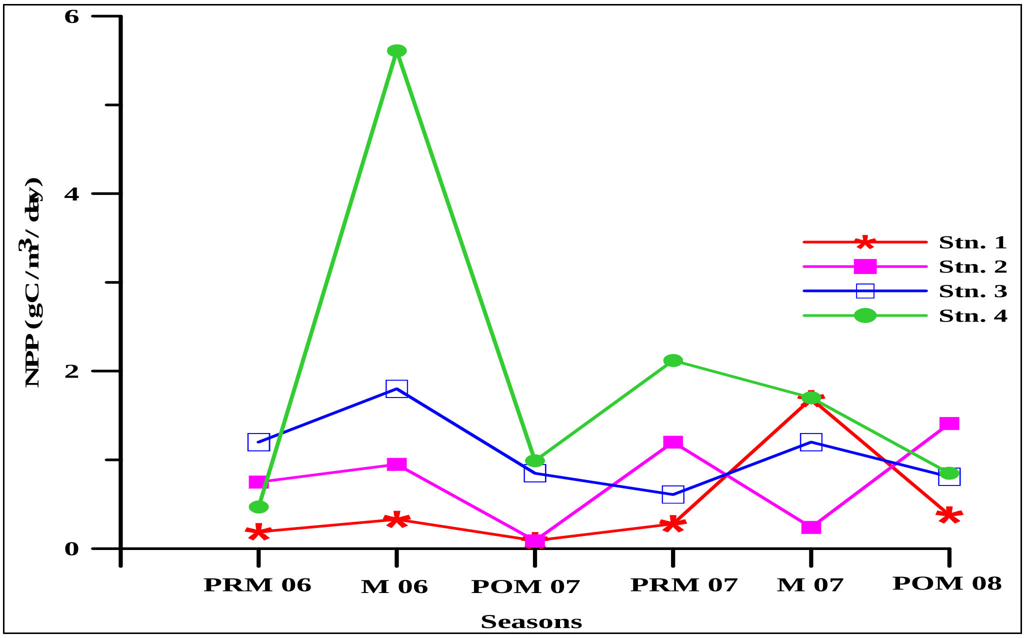


Table 1(a) to 1(h): ANOVA of the hydrographic parameters between the various stations during the study period premonsoon of 2006 to postmonsoon of 2008.

**Table 1**

| **(a)** | **Temperature** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 11.365 | 3.788 | 3.378 | 0.046 |
| Seasons | 5 | 50.052 | 10.01 | 8.926 | <0.001 |
| Residual | 15 | 16.823 | 1.122 | | |
| Total | 23 | 78.24 | 3.402 | | |

| **(b)** | **Salinity** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 53.792 | 17.931 | 2.319 | 0.117 |
| Seasons | 5 | 54.208 | 10.842 | 1.402 | 0.279 |
| Residual | 15 | 115.958 | 7.731 | | |
| Total | 23 | 223.958 | 9.737 | | |

| **(c)** | **pH** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 0.035 | 0.0117 | 0.854 | 0.486 |
| Seasons | 5 | 0.678 | 0.136 | 9.927 | <0.001 |
| Residual | 15 | 0.205 | 0.0137 | | |
| Total | 23 | 0.918 | 0.0399 | | |

| **(d)** | **Dissolved Oxygen** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 2.082 | 0.694 | 0.772 | 0.527 |
| Seasons | 5 | 1.702 | 0.34 | 0.379 | 0.856 |
| Residual | 15 | 13.481 | 0.899 | | |
| Total | 23 | 17.265 | 0.751 | | |

| **(e)** | **Nitrite ($NO_2$-N)** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 0.498 | 0.166 | 0.818 | 0.504 |
| Seasons | 5 | 1.701 | 0.34 | 1.676 | 0.201 |
| Residual | 15 | 3.045 | 0.203 | | |
| Total | 23 | 5.244 | 0.228 | | |

| **(f)** | **Nitrate ($NO_3$-N)** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 199.715 | 66.572 | 1.05 | 0.399 |
| Seasons | 5 | 665.305 | 133.061 | 2.098 | 0.122 |
| Residual | 15 | 951.14 | 63.409 | | |
| Total | 23 | 1816.16 | 78.963 | | |

| **(g)** | **Phosphate ($PO_4$- P)** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 6.414 | 2.138 | 4.559 | 0.018 |
| Seasons | 5 | 4.95 | 0.99 | 2.111 | 0.12 |
| Residual | 15 | 7.034 | 0.469 | | |
| Total | 23 | 18.398 | 0.8 | | |

| **(h)** | **Silicate ($SiO_4$-Si)** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 457.624 | 152.541 | 0.585 | 0.634 |
| Seasons | 5 | 3975.27 | 795.054 | 3.047 | 0.043 |
| Residual | 15 | 3914.06 | 260.937 | | |
| Total | 23 | 8346.95 | 362.911 | | |

Table 2 (a) and 2 (b). Primary production: Results of analysis of variance obtained between the variables at the four stations during the period of monsoon 2006 to postmonsoon 2008

**Table 2**

| **(a)** | **Gross Primary Production** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 11.548 | 3.849 | 3.169 | 0.055 |
| Seasons | 5 | 8.81 | 1.762 | 1.451 | 0.263 |
| Residual | 15 | 18.22 | 1.215 | | |
| Total | 23 | 38.577 | 1.677 | | |

| **(b)** | **Net Primary Production** | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 7.24 | 2.413 | 2.453 | 0.103 |
| Seasons | 5 | 7.085 | 1.417 | 1.44 | 0.267 |
| Residual | 15 | 14.76 | 0.984 | | |
| Total | 23 | 29.085 | 1.265 | | |

# Table 3. Pearson correlation analysis of Physico-chemical variables

| | | Temp | Salinity | pH | DO | $NO_2N$ | $NO_3N$ | $PO_4$ | $SiO_4$ | Chl a | NPP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp | Pearson Correlation | 1 | | | | | | | | | |
| | Sig. (2-tailed) | | | | | | | | | | |
| | N | 24 | | | | | | | | | |
| Salinity | Pearson Correlation | .071 | 1 | | | | | | | | |
| | Sig. (2-tailed) | .742 | | | | | | | | | |
| | N | 24 | 24 | | | | | | | | |
| pH | Pearson Correlation | .428(*) | .348 | 1 | | | | | | | |
| | Sig. (2-tailed) | .037 | .096 | | | | | | | | |
| | N | 24 | 24 | 24 | | | | | | | |
| DO | Pearson Correlation | .208 | -.378 | .119 | 1 | | | | | | |
| | Sig. (2-tailed) | .329 | .069 | .578 | | | | | | | |
| | N | 24 | 24 | 24 | 24 | | | | | | |
| $NO_2N$ | Pearson Correlation | .164 | .203 | .182 | .163 | 1 | | | | | |
| | Sig. (2-tailed) | .444 | .342 | .395 | .448 | | | | | | |
| | N | 24 | 24 | 24 | 24 | 24 | | | | | |
| $NO_3N$ | Pearson Correlation | -.277 | -.354 | -.268 | .023 | -.156 | 1 | | | | |
| | Sig. (2-tailed) | .190 | .090 | .206 | .917 | .467 | | | | | |
| | N | 24 | 24 | 24 | 24 | 24 | 24 | | | | |
| $PO_4$ | Pearson Correlation | -.128 | -.295 | .122 | .242 | .003 | -.069 | 1 | | | |
| | Sig. (2-tailed) | .551 | .162 | .569 | .254 | .988 | .750 | | | | |
| | N | 24 | 24 | 24 | 24 | 24 | 24 | 24 | | | |
| $SiO_4$ | Pearson Correlation | -.373 | -.373 | -.363 | .036 | -.345 | .449(*) | .375 | 1 | | |
| | Sig. (2-tailed) | .073 | .073 | .081 | .867 | .099 | .028 | .071 | | | |
| | N | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | | |
| Chl *a* | Pearson Correlation | -.143 | .018 | -.159 | -.112 | -.173 | -.180 | .215 | .422(*) | 1 | |
| | Sig. (2-tailed) | .505 | .934 | .457 | .602 | .420 | .399 | .313 | .040 | | |
| | N | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | |
| NPP | Pearson Correlation | .038 | -.173 | -.001 | .329 | -.215 | .076 | .540(**) | .394 | .466(*) | 1 |
| | Sig. (2-tailed) | .860 | .418 | .996 | .116 | .313 | .724 | .006 | .057 | .022 | |
| | N | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed)

# Chapter- 3

# Harmful Algal Blooms and phytoplankton standing crop along the southwest coast of India

## 3.1 Introduction and review of literature

Marine phytoplanktons are microscopic, single-celled algae that inhabit the surface waters. They are found across all oceans in high concentrations of cells per litre. Their existence is critical to virtually all the other organisms found in the sea, as they are the primary producers of organic material and are right at the very start of the marine food chain. Presence of sufficient light and nutrients can lead to proliferation of these algae to enormous concentrations of up to millions of cells per litre. A phytoplankton bloom (also called micro algal bloom, toxic algae, red tides and harmful algal blooms) is a naturally occurring phenomena when rapid growth of one or more species occurs leading to increase in biomass of the species. About 300 species of micro algae are reported to cause such blooms. Nearly one fourth of these species are known to produce toxins. A very small number of these species are potentially harmful. These can contaminate seafood with toxins and can cause serious human health problems, proliferate and kill fish, or otherwise alter ecosystems in ways that we perceive as harmful. The scientific community refers to these events with the generic term ‘harmful algal blooms’, or HABs. In most cases these proliferations are beneficial for aquaculture and fisheries operations, but in some situations algal blooms can have a negative effect, causing severe economic losses to aquaculture, fisheries and tourism operations and also have major environmental and human health impacts (Hallegraeff, 1995). According to Daranas (2001) the negative impacts of HAB events appear to have increased in frequency, intensity and geographic distribution in the past two decades.

Seasonal blooms occur annually, as a result of changes in temperature and nutrient availability whereas red tides are localized outbreaks and occur due to a variety of reasons which are characteristics of species and region (Richardson, 1997). According to Cushing (1959), spring and autumn diatom blooms are typical of temperate waters, which occur during the period when the waters column become well mixed, allowing the surface phytoplankton to get sufficient nutrients and light prior to the development of grazing populations. Harmful micro algal species are probably ubiquitous, and they become hazardous only when their concentration exceeds a certain threshold. Marine ecosystem provides many different niches that can be exploited by different phytoplankton species and that each species has its own specific combination of requirements to the external environment (temperature, salinity and nutrients). The degree of ecophysiological requirements of a species when matched by the physico-chemical environment determines the proliferation of the species. Studies on bloom dynamics will thus help in developing predictive models for early warning of HABs, which helps in implementing specific plans to avoid health problems and to minimize the economic loss.

HABs of autotrophic algae and some heterotrophic protists are increasingly frequent in coastal waters around the world. The aggregation of these organisms can discolor the sea surface to red, mahogany, brown and yellow, can float on the surface as scums, cover beaches with biomass or foam and deplete oxygen levels through excessive respiration and decomposition (Sellner *et al*., 2003).

Generally the HAB outbreaks often follow a period of intense rainfall and runoff which increases water mass stratification, possibly enclosing a patch of chemically modified surface layer of water favourable for phytoplankton growth (Smayda, 1995). According to Paerl (1988), in stratified waters, motility allows a red tide organism to orient itself near the surface during the photosynthetically active day light hours while having the option of seeking deeper nutrient rich waters during potentially photo inhibitory mid day or night time hours. This favours their bloom over the less motile phytoplankton taxa which coexist during the initiation of bloom.

Physical factors such as wind driven currents, tides, upwelling and downwelling, convergence and divergence and related frontal boundaries have also been indicated as initiation factors for red tide formation (Carreto *et al.,* 1986; Franks and Anderson, 1992; Tester and Steidinger, 1997). According to Marasovic (1991) development of *Gonyaulax polyedra* bloom in Katsela bay, Adriatic Sea was linked to the increased phytoplankton density to lowered salinities and higher temperatures. Relationship between *Noctiluca* swarming and hydrological features of the western coast of Brittany was studied by LeFevre *et al* (1970).

Nutrient enrichment in coastal waters is generally regarded as one of the major reason for the increased occurrence of algal blooms. Increased input of nitrogen and phosphorous, to the coastal waters as a result of anthropogenic activities makes the coastal waters eutrophic.

This has been accompanied by a corresponding increase in the appearance and persistence of algal blooms. Eutrophication from anthropogenic inputs has been linked to the increased recurrence of blooms in Tolo harbour, Hong Kong (Lam and Ho, 1989) and in Seto inland sea (Kotani *et al*., 2001). Increased ground water and atmospheric deposition of nitrogen to coastal waters derived mainly from urban, industrial and agricultural sources has been linked to expansion of HABs by Paerl (1997). Changes in major nutrient ratios have been found to be more significant than the total concentration of nutrients for the increased occurrence of HABs because it results in selective stimulation HAB species over the others (Smayda, 1990).

Eutrophication by natural processes such as coastal upwelling, circulation, convective mixing and river flow and also by anthropogenic activities are the primary factors responsible for algal bloom. The latter is generally assumed to be the primary cause of all blooms. It is usually acknowledged that occurrences of these phenomena are increasing throughout the world oceans. The reasons for this obvious increase remain debated and include not only eutrophication but increased observation efforts in coastal zones of the world.

According to Steidinger (2010) benthic- pelagic coupling is an obvious key component in HAB species- such as dinoflagellates- that produce pellicle (thin-walled) cysts or resting cysts (thick-walled) that settle to the benthos. Resuspension events may therefore be important to inoculate surface waters (Kirn *et al*., 2005; Kremp, 2001), though germination directly from the sediment surface also occurs. A meroplanktonic alternation in generations between 1N and 2N stages of phytoplankton, e.g., dinoflagellates, diatoms, and others, is often thought of as an adaptation to survive two different niches seasonally. Triggers for transition between these stages may be gradients in temperature, light, turbulence, sheer, nutrients, cell abundance, endogenous and exogenous infochemicals or nutrients, and even gases.

According to the problems caused, Hallegraeff (1995) classified HABs into four major groups. They are species which cause water discolouration; species non-toxic to humans but harmful to filter feeding invertebrates and fishes; species which produce toxins causing illness to humans through aerosols from bloom area to the coast and species producing potent toxins that can affect human through seafood. The first two are formed by the non-toxic species which discolour the water. However, under some conditions the growth is so high that it generates anoxic conditions resulting in indiscriminate killing of both fish and invertebrates. Oxygen depletion can be due to high respiration by the algae (at night or in dim light during the day) but more commonly is caused by bacterial respiration during decay of the bloom. Dinoflagellates that cause these problems are *Gonyaulax*, *Noctiluca* and *Scrippsiella* and Cyanophycean species like *Trichodesmium* (Hallegraeff, 1995).

The third group, which can seriously damage fish gills, either mechanically or through production of hemolytic substances. While wild fish stocks have the freedom to avoid such problem areas, caged fish appear to be extremely vulnerable to such noxious algal blooms. Potent ichthyotoxins called prymnesin- 2 1 and prymnesin-1 2 have been isolated from *Prymnesium parvum* cultures (Igarashi *et al*., 1996; Murata and Tasumoto, 2000). Other species that fall in this group are diatoms like *Chaetoceros convolutus*, dinoflagellates like *Gymnodinium* *mikimotoi,* prymnesiophytes *Chrysochromulina polylepis, Prymnesium patelliferum* and raphidophytes *Heterosigma carterae* or *Chattonella marina* and *C. antiqua* which killed 500 million US dollars' worth of caged yellowtail fish in the Seto Island Sea in 1972 (Okaichi, 1989).

The fourth group produces potent toxins which can find their way through the food chain to humans, causing a variety of gastrointestinal and neurological illnesses. According to the symptoms observed in human intoxication by the secondary metabolites of the so called toxins, produced by microalgae, it is likely to consider six illnesses caused by groups of marine toxins: Amnesic Shellfish Poisoning (ASP), Paralytic Shellfish Poisoning (PSP), Neurotoxic Shellfish Poisoning (NSP), Diarrhetic Shellfish Poisoning (DSP), Ciguatera Poisoning (CFP), and Azaspiracid Poisoning (AZP).

According to Anderson (2009) globally, the nature of the HAB problem has changed considerably over the last several decades. The number of toxic blooms, the resulting economic losses, the types of resources affected, and the number of toxins and toxic species have all increased dramatically. Some of this expansion has been attributed to storms, currents and other natural phenomena, but human activities are also frequently implicated. Humans have contributed by transporting toxic species in ballast water, and by adding massive and increasing quantities of industrial, agricultural and sewage effluents to coastal waters. In many urbanized coastal regions, these inputs have altered the size and composition of the nutrient pool which has, in turn, created a more favorable nutrient environment for certain HAB species. The steady expansion in the use of fertilizers for agricultural production represents a large and worrisome source of nutrients in coastal waters that promote some HABs.

In recent decades there is an increase in the frequency, intensity and spreading of harmful and toxic algal blooms in the World Oceans and are now considered as global epidemic (Hallegraeff *et al*., 1995). The main constrain in the study of these blooms are lack of historical data and the restricted number of good long-term data series. The first written record of a harmful algal blooms appears in Bible (Exodus 7: 20-21). The first recorded fatal cases of human poisoning had happened in 1793 after eating shellfish contaminated with dinoflagellate toxins when Captain George Vancouver and his crew landed in British Columbia in an area now known as Poison Cove. He noted that for local Indian tribes it was taboo to eat shellfish when the seawater became phosphorescent due to dinoflagellate blooms (Dale and Yentsch, 1978).

However, there is fossil evidence that HABs were occurring long before this. Noe- Nygaard *et al* (1987) have suggested, on the basis of the distribution of dinoflagellate cysts and bivalve shells in fossil sediments taken from the Island of Bornholm in Baltic Sea, that toxic dinoflagellate caused mass mortalities of bivalves on several occasions dating back to about 130 million years ago. Dale *et al* (1993) have also studied the distribution of fossil dinoflagellate cysts and present evidence suggesting bloom formation by the toxic dinoflagellate *Gymnodinium catenatum* in the Kattegat- Skagerrak long before anthropogenic activities can have influenced these waters.

Arising from growing concerns of such an increase in the occurrence of HABs, a number of national, regional and international programs namely the Intergovernmental Oceanographic Commission on

Harmful Algal Blooms (IOC-HAB), Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB), the Northwest Pacific Action Plan (NOWPAP), the Korean Harmful Algal Bloom Research Group (KORHAB), have hence recently been implemented to understand the features and mechanisms underlying the population dynamics of HABs, and to improve and develop management and amelioration strategies.

In the Indian EEZ, occurrences of algal blooms are more prevalent along the west than on the east coast. Diatoms blooms have been observed regularly along the Indian coast during summer monsoon period (June- September). Bloom of the diatoms has been reported by Nair and Subrahmanyan (1955); Ramamirtham and Jayaraman (1963); Devassy (1974) Devassy and Bhattathiri (1974) and by Padmakumar *et al* (2007). Phytoplankton blooms which occurred along the Indian coast during the period from 1982 to 1987 have been documented by Mathew *et al* (1988). Algal blooms particularly HAB occurrences along the Indian coast has been reviewed by Karunasagar and Karunasagar (1990).

Dinoflagellate blooms mainly by *Noctiluca* sp. has been reported from the coastal waters of southwest coast of India by Bhimachar and George (1950); Prasad and Jayaraman (1954); Subramanyan (1959a); Venugopal *et al* (1979); Devassy and Nair (1987); Mathew *et al* (1988); Katty *et al* (1988); Naqvi *et al* (1998); Nayak *et al* (2000) and by Eashwar *et al* (2001). Along the East coast, *Noctiluca* blooms along with associated mortality have been reported as early as 1935 by Aiyar (1936) and recently *Noctiluca* bloom and associated mortality of marine organisms were reported in Gulf of Mannar by Gopakumar *et al.* (2009). Algal blooms and associated fish mortality was reported by Sasikumar *et al* (1989) in Kalpakkam waters along the Tamilnadu coast. Mohanty *et al*

(2007) reported *Noctiluca* bloom and its impact on the coastal water quality of near shore waters of Bay of Bengal. Blooms of other dinoflagellates, *Gonyaulax polygramma* was recorded along southwest coast by Prakash and Sharma (1964) and along the coastal waters off Cochin by Gopinathan and Pillai (1976). Dinoflagellate bloom events of *Gymnodinium mikimotoi* and associated shrimp and benthic fish mortality were reported from the South west coast of India (Karunasagar and Karunasagar, 1992; Karunasagar and Karunasagar, 1993; Karunasagar *et al.,* 1993).

Diazotrophic filamentous blue green alga *Trichodesmium erythraeum* is the most common red tide organism in tropical seas and is a recurrent phenomenon in Arabian Sea during pre monsoon months. Bloom of *Trichodesmium* has been reported off the Mangalore coast by Prabhu *et al* (1965), around Minicoy Island by Naghabhushanam (1967), by Qasim (1970) in Laccadive Sea, along the Goa coast by Ramamurthy *et al* (1972) and Devassy *et al* (1978), from southwest coast by Anoop *et al* (2007). Investigation by Sreekumaran *et al* (1992) has shown that the algae regularly bloom in the Arabian Sea during the pre-monsoon season every year.

Another harmful algae which regularly blooms along the Calicut coast of Kerala is the marine raphidophyte *Chattonella marina*. Eventhough blooms and associated mortalities due to a phytoflagellate off the Calicut coast were reported as early as 1917 by Hornell and by Jacob and Menon (1948), it was identified *as Hornellia marina* by Subrahmanyan in 1954. Its nomenclature has been now changed to *Chattonella marina* (Hara et Chihara 1982). Jugnu and Kripa (2009) reported massive fish kills due to *C. marina* bloom along the Kerala coast during 2002. The concentration of major nutrients was monitored and related to a bloom of *Fragilaria oceanica* by Devassy (1974). Physical and chemical parameters during a *Trichodesmium* bloom was studied by Qasim (1970) and Devassy *et al* (1978). Reasons for the red tide along the south Kerala coast was studied by Venugopal *et al* (1979). Bacteriological and physicochemical factors associated with *Noctiluca miliaris* bloom along Mangalore, southwest coast of India was done by Nayak *et al* (2000). In all these studies, physicochemical and biological parameters at the time of the bloom are monitored and presented.

Along the West coast of India, upwelling is the most important factor triggering the algal blooms during the monsoon period. The extensive southwest monsoon upwelling in conjunction with winter mixing makes the Arabian Sea one of the most productive regions in the world’s ocean (Madhupratap *et al*., 2001). The Arabian Sea is one of the most biologically productive regions of the world oceans. Being in the tropical region and subjected to seasonally reversing monsoonal wind system, the biological productivity of the basin shows strong seasonality with blooms occurring in summer monsoon (June- August) and winter monsoon (December- February). The summer bloom is driven by upwelling along the coasts of Somalia, Arabia and the southern parts of the west coast of India (Banse *et al*., 1996). In addition to coastal upwelling, processes such as wind-mixing, lateral advection, Ekman pumping, mesoscale eddies and filaments also play an important role in supplying nutrients to the euphotic zone during summer. The winter bloom occurs due to winter cooling and convective mixing.

Nutrient availability together with light and temperature are primary determinants of phytoplankton growth and biomass accumulation. There is growing evidence that the reported increase in HAB events and the increased magnitude of these events is linked to nutrient availability, and these events are often directly or indirectly linked to anthropogenic eutrophication (Glibert *et al*., 2005; 2006). The nutrient most often implicated in the limitation of phytoplankton growth in the sea and in particular in coastal upwelling systems is nitrogen (N) (Wilkerson and Dugdale, 2008), though clearly silica (Si) may shape community dynamics through limitation or co-limitation of diatoms (Kudela, 2008).

Biomass of phytoplankton in the seas in terms of chlorophyll *a* concentration is one of the most widely accepted methods in the study of primary production. Chlorophyll *a* indicates total plant material available in the water at primary stages of food chain. Phytoplankton blooms can color the water when chlorophyll concentrations reach >20 mg $L^{-1}$. The chlorophyll *a* concentration is one of the indicators of the phytoplankton biomass in the sea and is responsible for the photosynthesis. The standing crop of phytoplankton indicates the availability of food for animals at the primary stage. Chlorophyll a concentration has been measured during various expeditions and cruises in different areas of Indian sea. Qasim (1978) has described the distribution of chlorophyll *a* in the Indian Ocean. Chlorophyll *a* was selected as an indicator of water quality because it is an indicator of phytoplankton biomass, with concentrations reflecting the integrated effect of many of the water quality parameters that may be altered by restoration activities.

Chlorophyll *a* is taken as the index of HABs during the present study. There is a long history of the application of chlorophyll *a* as an index of the productivity and trophic condition of estuaries, coastal and oceanic waters. Initially, Steele (1962) summarized the application of Chlorophyll *a* as an indicator of photoautotrophic biomass as related to primary productivity. Cullen (1982) further addressed the use of chlorophyll *a* as an index for biomass of primary producers. Sakshaug (1989) termed algal blooms with chlorophyll *a* concentration >100 µg $L^{-1}$ as “Super blooms”. If blooms of such magnitude were occurring in coastal regions of the more densely populated area, they would almost certainly be considered as exceptional. Smetacek *et al* (1992) observed a super bloom of centric diatoms, *Thalassiosira antarctica*, *Porosira pseudodenticulata* and *Stellarima microtrias* in Weddell Sea. Chlorophyll *a* biomass reflects the net result (standing stock) of both growth and loss processes in pelagic waters. Chlorophyll *a* is considered as the principal variable to use as a trophic state indicator. There is generally a good agreement between planktonic primary production and algal biomass, and algal biomass is an excellent trophic state indicator. Furthermore, algal biomass is associated with the visible symptoms of eutrophication, and it is usually the cause of the practical problems resulting from eutrophication.

## 3.2 Materials and methods

Chlorophyll *a* and phytoplankton samples were collected on seasonal basis from the selected coastal stations during the study period 2006-08. Along with this, sampling was also done at locations where the visible appearance of bloom was observed during FORV Sagar Sampada cruises. Samples for the analysis of physicochemical and biological parameters were collected in both the cases and estimated according to the methodology described in Chapter I.

## 3.3 Results

### 3.3.1 Chlorophyll *a*

Seasonal and spatial variation of surface chlorophyll *a* concentration was studied for six seasons (from Premonsoon of 2006 to Postmonsoon of 2008) in four coastal stations along the southwest coast of India (Figure 13). Chlorophyll *a* concentration varied temporally and spatially. In general, surface chlorophyll *a* was elevated during monsoon and post monsoon seasons. During this study period five algal blooms were observed with high chlorophyll *a* concentration along the southwest coast of India and these algal blooms occurred during the monsoon seasons of 2006 and 2007.

In station 1 (off Kollam) highest chlorophyll *a* concentration was observed during the post monsoon of 2007 (52.42 mg $m^{-3}$) and lowest during the pre monsoon of 2006 (1.42 mg $m^{-3}$). In station 2 (off Alapuzha) highest chlorophyll *a* concentration was recorded during monsoon of 2006 (225.26 mg $m^{-3}$) and monsoon of 2007 (127.61 mg $m^{-3}$). The lowest value of chlorophyll *a* was observed during premonsoon of 2006 (4.65 mg $m^{-3}$). During post monsoon of 2007 and 2008 moderately high value of chlorophyll *a* was recorded in station 2 (52.27 mg $m^{-3}$ and 91.4 mg $m^{-3}$ respectively). In station 3 (off Kochi) highest chlorophyll *a* concentration was observed during monsoon of 2006 (66.18 mg $m^{-3}$), postmonsoon of 2007 (61.58 mg $m^{-3}$) and during monsoon of 2007 (30.82 mg $m^{-3}$). The lowest chlorophyll *a* was recoded during premonsoon of 2007 (3.36 mg $m^{-3}$). In station 4 (off Calicut) highest chlorophyll *a* was observed during monsoon of 2006 (206. 5 mg $m^{-3}$) and lowest during postmonsoon of 2008 (4.32 mg $m^{-3}$). Two way ANOVA between chlorophyll *a*, stations and seasons are shown in table

4. In some seasons significant variation was observed in chlorophyll *a* content temporally and spatially.

**Figure 13. Seasonal and spatial variation of Chlorophyll *a* at the four stations during the study period 2006 to 2008**

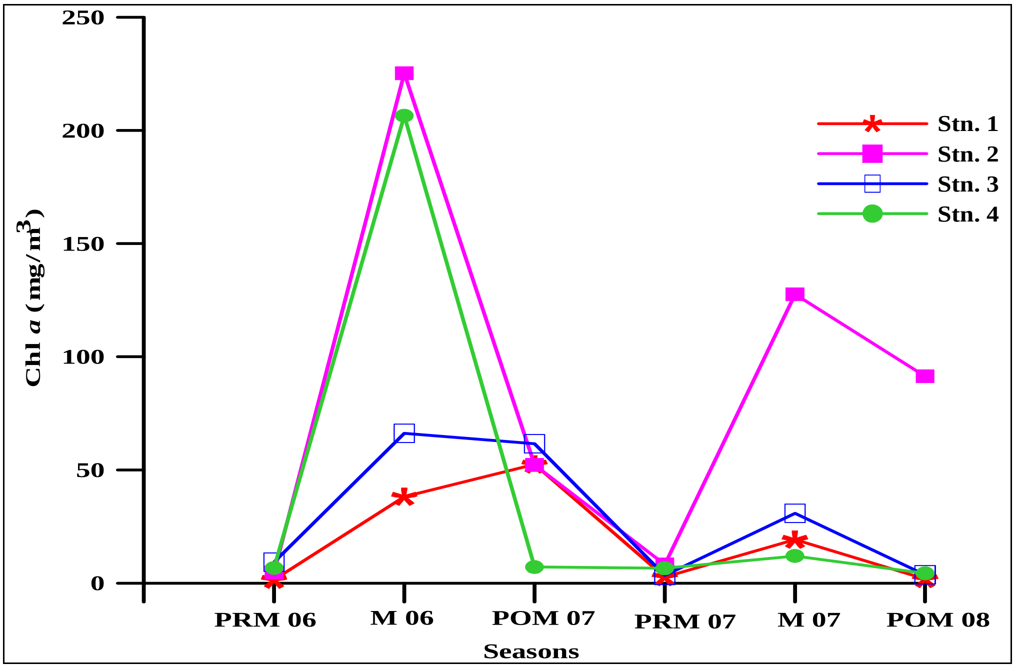


**Table 4. ANOVA of Chlorophyll *a* between the various stations during the study period premonsoon of 2006 to postmonsoon of 2008**

| Chlorophyll *a* | | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 4 | 15089.8 | 5029.93 | 2.627 | 0.088 |
| Seasons | 6 | 45796.2 | 9159.23 | 4.783 | 0.008 |
| Residual | 15 | 28723.3 | 1914.89 | | |
| Total | 23 | 89609.3 | 3896.06 | | |

### 3.3.2 Chlorophyll *a* and nutrients

It is well known that sea water a variety of dissolved salts and gases. Some are present in high concentrations while others only in very minute quantities. Of these, from the biological point of view, the most important are phosphate, nitrate and silicates; these are the most essential nutrients for phytoplankton growth in the sea. Surface nutrients concentrations, such as nitrite, nitrate, phosphate and silicate were estimated from the study area along with surface chlorophyll *a*.

Figure 14 showing the seasonal variation of chlorophyll *a* and nutrients in station 1. In station 1 (off Kollam) highest nitrate concentration was recorded during monsoon of 2007 (40 µmol $L^{-1}$) and lowest during post monsoon of 2007 (1.95 µmol $L^{-1}$). During premonsoon of 2006 moderately high value of nitrate, 14.39 µmol $L^{-1}$ was observed. Lowest surface phosphate concentration (below detectable level) was recorded during pre monsoon of 2006 and the highest was 0.968 µmol $L^{-1}$ in monsoon of 2007. In both post monsoons of 2007 and 2008 phosphate concentration was around 0.28 µmol $L^{-1}$. In station 1 highest surface silicate concentration was observed during monsoon of 2007 (72.1 µmol $L^{-1}$) and the lowest value in pre monsoon of 2007 (3.205 µmol $L^{-1}$). In post monsoon of 2008 moderately high silicate value of 13.78 µmol $L^{-1}$ was recorded.

Seasonal variation of surface chlorophyll *a* and nutrients in station 2 (off Alapuzha) are shown in figure 15. In station 2 highest nitrate concentration was recoded during premonsoon of 2006 (10.54 µmol $L^{-1}$) and lowest during postmonsoon of 2008 (0.725 µmol $L^{-1}$). During the monsoon season of 2006 and 2007 nitrate concentration was 3.29 µmol $L^{-1}$ and 3.134 µmol $L^{-1}$ respectively. Surface phosphate concentration was below detectable level during premonsoon of 2006 and monsoon of 2007. Phosphate concentration was highest during postmonsoon of 2007 and 2008 (0.782 µmol $L^{-1}$) and lowest during premonsoon of 2007 (0.046 µmol $L^{-1}$). Higher surface silicate concentration was observed in station 2 during monsoon of 2007 (54.5 µmol $L^{-1}$). In monsoon of 2006 silicate concentration was 26.34 µmol $L^{-1}$. Among postmonsoon seasons, highest silicate concentration was observed during postmonsoon of 2008 (40.71 µmol $L^{-1}$) and lowest during 2007 (0.961 µmol $L^{-1}$).

**Figure 14: Station 1. Figure showing the distribution of nutrients during the various seasons along with chlorophyll *a* obtained during the period**

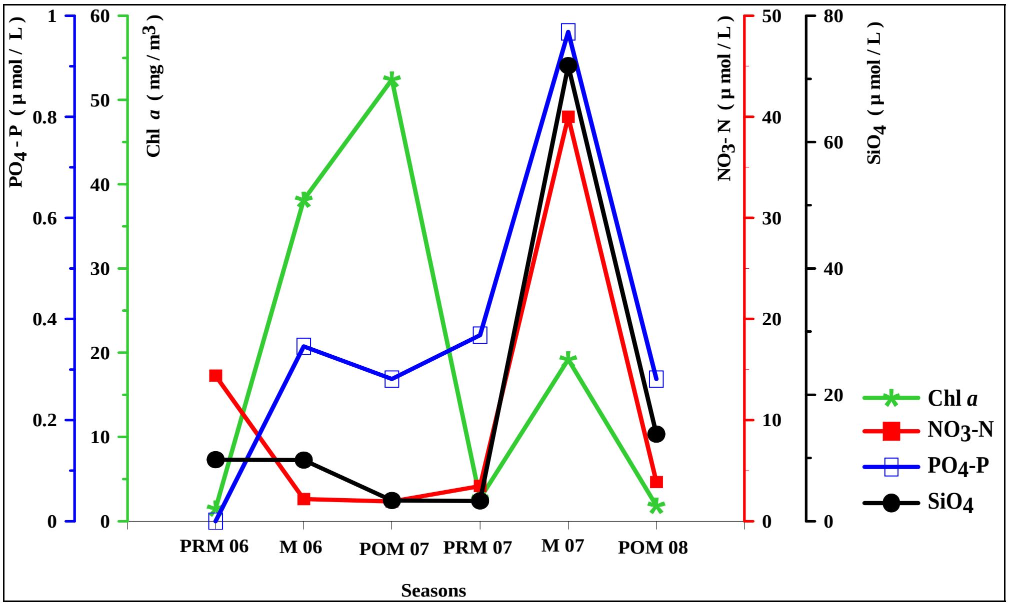
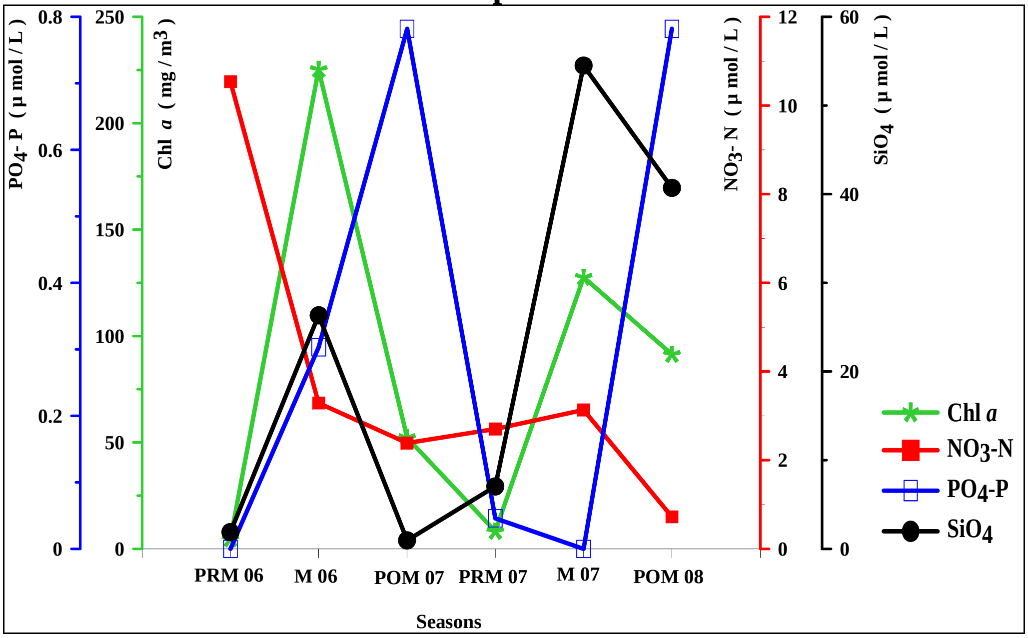
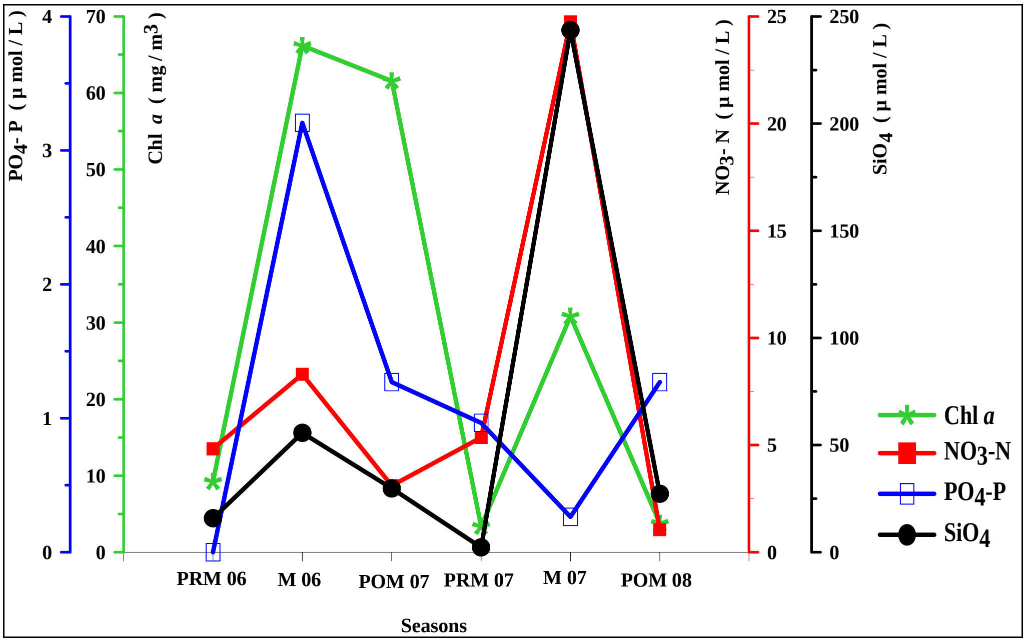


**Figure 15: Station 2. Figure showing the distribution of nutrients during the various seasons along with chlorophyll *a* obtained during the period**



Seasonal variation of surface chlorophyll *a* and nutrients in station 3 (off Kochi) are shown in figure 16. Peak nitrate concentrations were recorded during monsoon seasons with highest value during monsoon of 2007 (24.746 µmol $L^{-1}$). Lowest nitrate concentration during postmonsoon of 2008 was 1.05 µmol $L^{-1}$. Surface phosphate concentration was below detectable level during premonsoon of 2006 and lowest value was detected during monsoon of 2007 (0.264 µmol $L^{-1}$). Highest surface phosphate concentration was recorded during monsoon of 2006 (3.205 µmol $L^{-1}$). During postmonsoon of 2007 and 2008 phosphate concentration of 1.27 µmol $L^{-1}$ was recorded. In station 3 highest silicate concentration was observed during monsoon of 2007, 243.6 µmol $L^{-1}$ and lowest during the premonsoon of 2007 (2.243 µmol $L^{-1}$). In monsoon of 2006 silicate concentration was also high, 55.7 µmol $L^{-1}$. Moderately high values of silicate were recorded during postmonsoon of 2007 and 2008 with values 29.78 µmol L$^{-1}$ and 27.25 µmol L$^{-1}$ respectively.

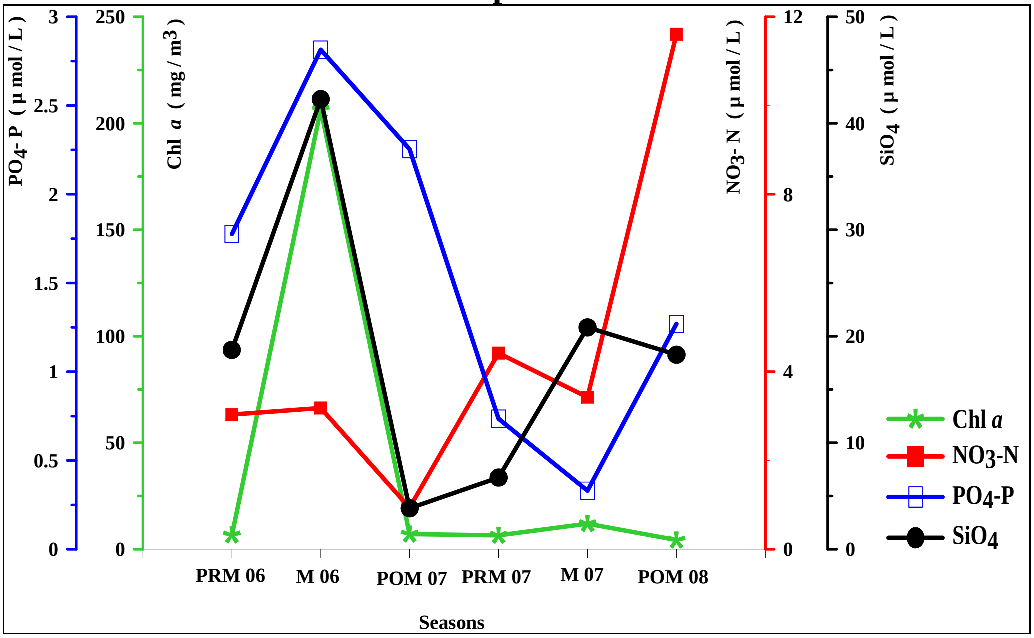
**Figure 16: Station 3. Figure showing the distribution of nutrients during the various seasons along with chlorophyll *a* obtained during the period**



Seasonal variation of surface chlorophyll *a* and nutrients in station 4 (off Calicut) are shown in figure 17. In station 3 highest surface nitrate concentration was observed during the postmonsoon of 2008 (11.61 µmol L$^{-1}$) and lowest during the postmonsoon of 2007 (0.938 µmol L$^{-1}$). During monsoon of 2006 and of 2007 nitrate concentration was 3.185 µmol L$^{-1}$ and 3.426 µmol L$^{-1}$ respectively. Phosphate concentration was highest during the monsoon of 2006 (2.815 µmol L$^{-1}$) and lowest during monsoon of 2007 (0.33 µmol L$^{-1}$). During postmonsoon of 2007 moderately high value (2.254 µmol L$^{-1}$) of surface phosphate was also recoded. Surface silicate concentration was highest during monsoon periods, monsoon of 2006 and of 2007 (42.27 µmol L$^{-1}$ and 20.835 µmol

L$^{-1}$ respectively). Lowest silicate concentration was recorded during postmonsoon of 2007 (3.846 µmol L$^{-1}$).

**Figure 17: Station 4. Figure showing the distribution of nutrients during the various seasons along with chlorophyll *a* obtained during the period**



### 3.3.3 Phytoplankton composition and diversity

Quantitative and qualitative variation of micro algae was studied for a period of two years (from Premonsoon of 2006 to Post monsoon of 2008). There was considerable seasonal and spatial variation of micro algal density (Figure 18).

During the study period, in station 1 (off Kollam), highest cell density was observed during postmonsoon of 2008 (2366 cell L$^{-1}$) and lowest (153 cells L$^{-1}$) during monsoon of 2006. The results of qualitative and quantitative analysis of phytoplankton of station 1 are represented in table 5. During monsoon of 2007 moderately high cell density was recorded (604 cells L$^{-1}$). During postmonsoon of 2007 phytoplanktonpopulation was represented by diatoms only (157 cells $L^{-1}$) and dinoflagellates were completely absent. Diatoms were represented by five genera *vis Pleurosigma*, *Hantzschia*, *Cyclotella*, *Coscinodiscus* and *Campylodiscus*. Figure 19 shows the seasonal variations of major phytoplankton groups in station 1. Diatoms and dinoflagellates were present in all the seasons with highest diatom cell density (2018 cells $L^{-1}$) during postmonsoon of 2008. During postmonsoon of 2008, diatoms belonging to 12 genera were recorded. The genera are *Asterionella*, *Bacteriastrum, Biddulphia, Chaetoceros, Coscinodiscus, Ditylum, Guinardia, Navicula, Pleurosigma, Proboscia, Rhizosolenia* and *Thalassiosira*. Dinoflagellates were represented by two genera *Ceratium* and *Protoperidinium*. Potentially toxic dinoflagellate like *Dinophysis acuminata*, *Gonyaulax moniliana* and *Prorocentrum micans* were recorded in very low density from this station during the study period. The result of analysis of diversity indices are presented in table 6. At station 1 (off Kollam) species richness and diversity indices were high during monsoon of 2007 and postmonsoon of 2008.

The dendrogram of cluster analysis of phytoplankton composition during different seasons at station 1 is given in figure 20. The cluster analysis grouped the seasons into two clusters with 20% similarity in phytoplankton composition. These were cluster I consisted of premonsoon of 2006 and monsoon of 2007 and the cluster II consisted of monsoon of 2006 and premonsoon of 2007.

Figure 18: Seasonal and spatial variation of phytoplankton cell density along the southwest coast during the period 2006 to 2008

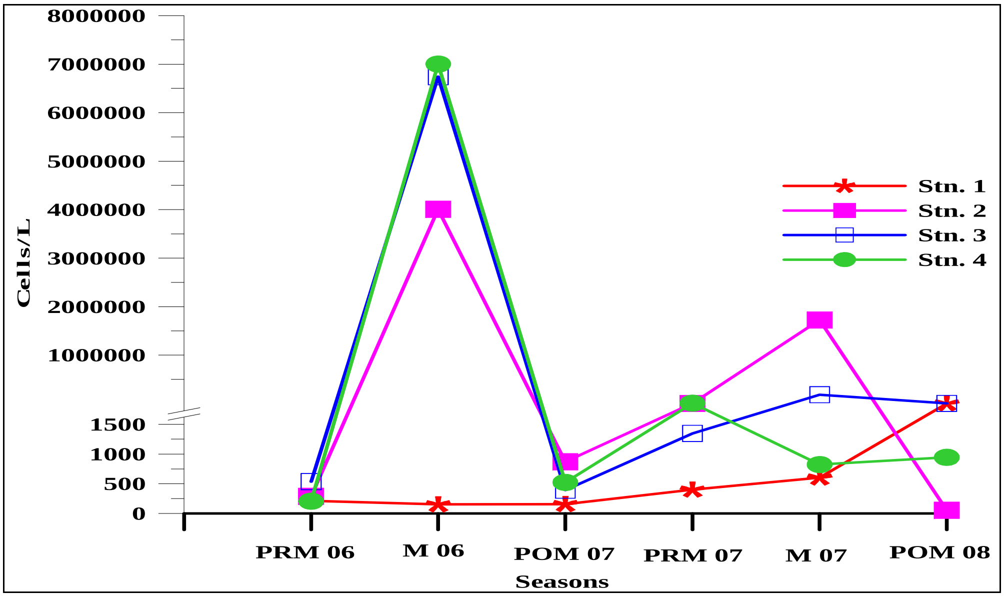
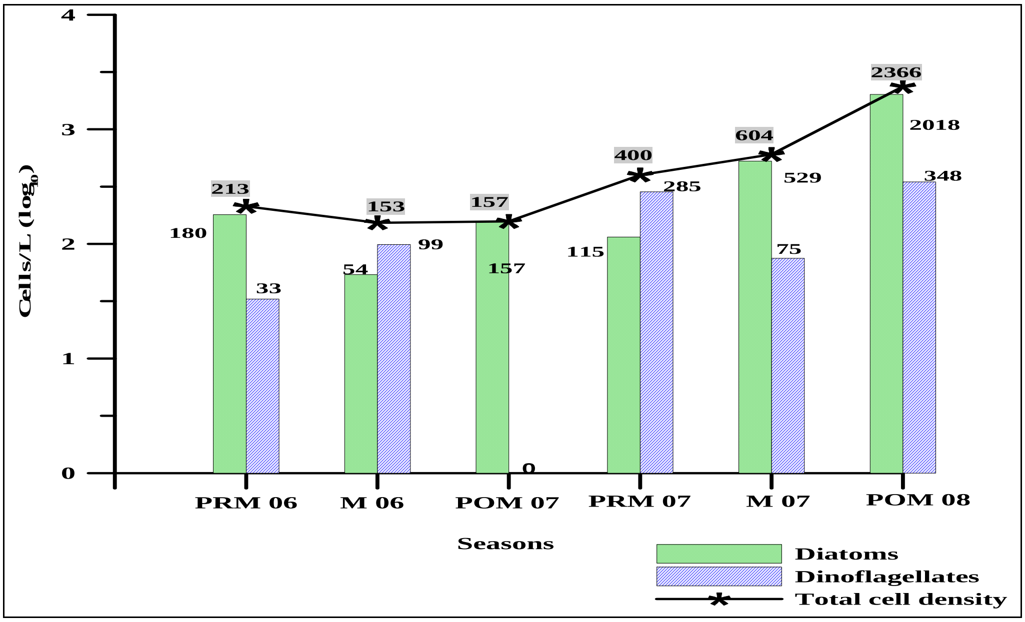


Figure 19: Seasonal variation of major phytoplankton groups at Station 1 during the period 2006 to 2008



## Table 5: Qualitative and quantitative composition of phytoplankton at Station 1 during different seasons of 2006 to 2008

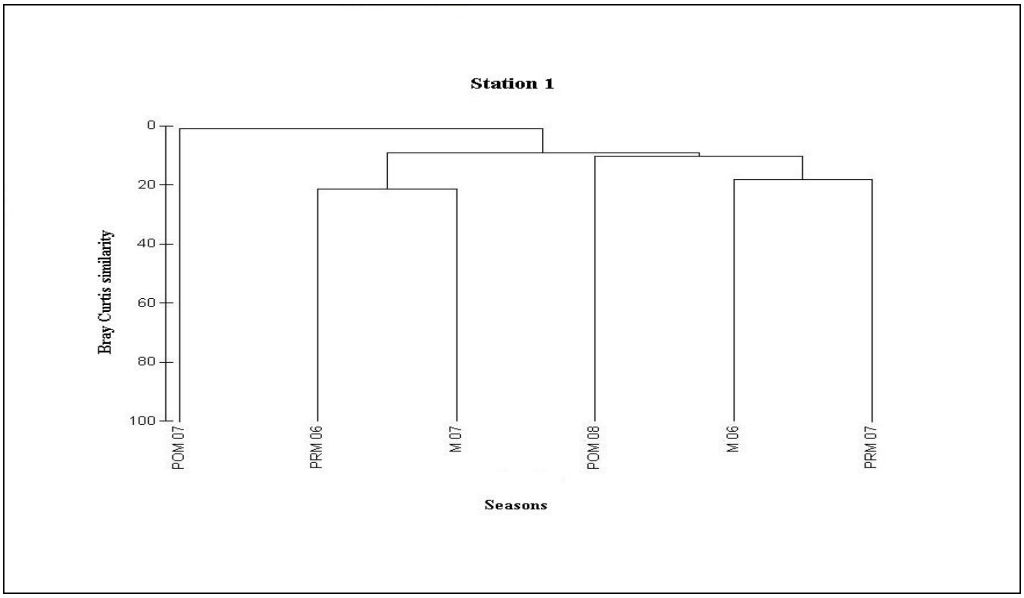
| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 1 | *Asterionella japonica* | 0 | 14 | 0 | 50 | 0 | 288 |
| 2 | *Bacteriastrum comosum* | 0 | 0 | 0 | 0 | 0 | 264 |
| 3 | *Biddulphia aurita* | 0 | 0 | 0 | 0 | 0 | 60 |
| 4 | *Biddulphia mobiliensis* | 0 | 12 | 0 | 0 | 0 | 0 |
| 5 | *Calonies permagna* | 0 | 0 | 0 | 0 | 25 | 0 |
| 6 | *Campylodiscus ecclesianus* | 0 | 0 | 29 | 0 | 0 | 0 |
| 7 | *Cerataulina bicornis* | 12 | 0 | 0 | 0 | 0 | 0 |
| 8 | *Chaetoceros affinis* | 30 | 0 | 0 | 0 | 0 | 252 |
| 9 | *Chaetoceros decipiens* | 0 | 28 | 0 | 0 | 0 | 0 |
| 10 | *Chaetoceros socialis* | 0 | 0 | 0 | 0 | 0 | 360 |
| 11 | *Chaetoceros teres* | 0 | 0 | 0 | 0 | 0 | 180 |
| 12 | *Coscinodiscus eccentricus* | 0 | 0 | 0 | 0 | 0 | 36 |
| 13 | *Coscinodiscus marginatus* | 0 | 0 | 13 | 0 | 55 | 0 |
| 14 | *Coscinodiscus radiatus* | 12 | 0 | 0 | 0 | 50 | 0 |
| 15 | *Coscinodiscus rothii* | 0 | 0 | 0 | 0 | 50 | 0 |
| 16 | *Cyclotella striata* | 0 | 0 | 21 | 0 | 0 | 0 |
| 17 | *Diploneis bombus* | 0 | 0 | 0 | 20 | 0 | 0 |
| 18 | *Ditylum brightwelli* | 0 | 0 | 0 | 0 | 20 | 96 |
| 19 | *Eucampia cornuta* | 6 | 0 | 0 | 0 | 0 | 0 |
| 20 | *Guinardia flaccida* | 0 | 0 | 0 | 0 | 0 | 24 |
| 21 | *Hantzschia marina* | 0 | 0 | 23 | 0 | 0 | 0 |
| 22 | *Leptocylindrus danicus* | 39 | 0 | 0 | 0 | 0 | 0 |
| 23 | *Navicula cinta* | 0 | 0 | 0 | 0 | 20 | 0 |
| 24 | *Navicula lyra* | 0 | 0 | 0 | 0 | 0 | 38 |
| 25 | *Navicula maculosa* | 0 | 0 | 0 | 0 | 14 | 0 |
| 26 | *Navicula pygmoea* | 0 | 0 | 0 | 0 | 0 | 12 |
| 27 | *Navicula tuscula* | 12 | 0 | 0 | 0 | 0 | 0 |
| 28 | *Pleurosigma angulatum* | 0 | 0 | 13 | 0 | 0 | 0 |
| 29 | *Pleurosigma attenuatum* | 0 | 0 | 24 | 0 | 0 | 0 |
| 30 | *Pleurosigma elongatum* | 0 | 0 | 0 | 0 | 35 | 0 |
| 31 | *Pleurosigma falx* | 0 | 0 | 0 | 0 | 0 | 72 |
| 32 | *Pleurosigma intermedium* | 6 | 0 | 0 | 0 | 0 | 0 |

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 33 | *Pleurosigma naviculaceum* | 0 | 0 | 0 | 30 | 0 | 0 |
| 34 | *Pleurosigma strigosum* | 0 | 0 | 34 | 0 | 0 | 0 |
| 35 | *Podosira montagnei* | 6 | 0 | 0 | 0 | 30 | 0 |
| 36 | *Proboscia alata* | 0 | 0 | 0 | 0 | 0 | 192 |
| 37 | *Rhizosolenia castracanei* | 0 | 0 | 0 | 0 | 0 | 72 |
| 38 | *Rhizosolenia imbricata* | 9 | 0 | 0 | 0 | 0 | 0 |
| 39 | *Thalassionema nitzschioides* | 48 | 0 | 0 | 0 | 40 | 0 |
| 40 | *Thalassiosira coramandeliana* | 0 | 0 | 0 | 0 | 0 | 72 |
| 41 | *Thalassiosira decipiens* | 0 | 0 | 0 | 0 | 75 | 0 |
| 42 | *Thalassiosira subtilis* | 0 | 0 | 0 | 15 | 50 | 0 |
| 43 | *Triceratium dubium* | 0 | 0 | 0 | 0 | 35 | 0 |
| 44 | *Tropidonies longa* | 0 | 0 | 0 | 0 | 30 | 0 |
| | Total | 180 | 54 | 157 | 115 | 529 | 2018 |
| | Class: Dinophyceae | | | | | | |
| 1 | *Ceratium concilians* | 0 | 0 | 0 | 10 | 25 | 0 |
| 2 | *Ceratium furca* | 6 | 29 | 0 | 50 | 0 | 36 |
| 3 | *Ceratium gibberum* | 0 | 0 | 0 | 0 | 0 | 84 |
| 4 | *Ceratium symmetricum* | 9 | 9 | 0 | 0 | 0 | 120 |
| 5 | *Dinophysis accuminata* | 0 | 16 | 0 | 0 | 0 | 0 |
| 6 | *Dinophysis ovum* | 0 | 0 | 0 | 25 | 0 | 0 |
| 7 | *Diplopsalis lenticula* | 0 | 27 | 0 | 0 | 0 | 0 |
| 8 | *Gonyaulax moniliana* | 0 | 0 | 0 | 60 | 0 | 0 |
| 9 | *Prorocentrum arcuatum* | 0 | 0 | 0 | 50 | 0 | 0 |
| 10 | *Prorocentrum micans* | 12 | 0 | 0 | 55 | 50 | 0 |
| 11 | *Protoperidinium asymmetricum* | 0 | 12 | 0 | 0 | 0 | 0 |
| 12 | *Protoperidinium leonis* | 0 | 6 | 0 | 0 | 0 | 0 |
| 13 | *Protoperidinium oceanicum* | 6 | 0 | 0 | 0 | 0 | 108 |
| 14 | *Pyrophacus steinii* | 0 | 0 | 0 | 35 | 0 | 0 |
| | Total | 33 | 99 | 0 | 285 | 75 | 348 |
| | Grand Total | 213 | 153 | 157 | 400 | 604 | 2366 |

**Table 6: Phytoplankton diversity indices of Station 1 during the period 2006 to 2008**

| Diversity indices of phytoplankton at Station 1 | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | Lambda' |
| PRM 06 | 14 | 213 | 2.425 | 0.8871 | 3.377 | 0.1202 |
| M 06 | 9 | 153 | 1.59 | 0.9467 | 3.001 | 0.1315 |
| POM 07 | 7 | 157 | 1.187 | 0.973 | 2.732 | 0.152 |
| PRM 07 | 11 | 400 | 1.669 | 0.9521 | 3.294 | 0.1078 |
| M 07 | 16 | 604 | 2.342 | 0.9691 | 3.876 | 7.18E-02 |
| POM 08 | 19 | 2366 | 2.317 | 0.8985 | 3.817 | 8.56E-02 |

**Figure 20. Dendrogram showing Bray Curtis similarity of phytoplankton composition at station 1 during the various seasons of 2006 to 2008.**



In station 2 (off Alapuzha), highest cell densities of $4x10^6$ cells $L^{-1}$ and 1.7x $10^6$ cells $L^{-1}$ were observed during monsoon of 2006 and 2007 respectively. Lowest cell density of 54 cells $L^{-1}$ was recorded during postmonsoon of 2008. The results of qualitative and quantitative analysis of phytoplankton of station 2 are represented in table 7 and seasonal variation of major phytoplankton groups are presented in figure 21. Diatoms were dominant during monsoon of 2006 (3.9x $10^6$ cells $L^{-1}$) and monsoon of 2007 (1.67x $10^6$ cells $L^{-1}$). Dinoflagellates cells density was also high during monsoon of 2006 and 2007 (7.5x$10^4$ cells $L^{-1}$ and 5x$10^4$ cells $L^{-1}$ respectively). The highest cell density observed during the monsoon of 2006 was due to the bloom of diatom *Thalassiosira partheneia* (3932710 cells $L^{-1}$) and the heterotrophic dinoflagellate *Noctiluca scintillans* (73583 cells $L^{-1}$). Scanning Electron Micrographs of *Thalassiosira partheneia* cells is given in figure 22. Other diatoms present along with the bloom were *Coscinodiscus* spp., *Cylindrotheca gracilis*, *Diploneis smithii*, *Navicula elegans*, *Nitzschia closterium*, *Pleurosigma acuminatum*, *Skeletonema costatum* and *Thalassiosira nordenskioldii*. In station 2, during monsoon of 2007 a multi species bloom, dominated diatom *Thalassiosira partheneia* (1675490 cells $L^{-1}$) and dinoflagellate *Ceratium* spp. (42155 cells $L^{-1}$) and *Noctiluca scintillans* (7356 cells $L^{-1}$) was observed. The genus *Ceratium* was represented by eight species, such as *C. furca, C. gibberum, C. horridum, C. kofoidii, C. pentagonum, C. symmetricum, C. trichoceros* and *C. vulture*. Toxic species like *Dinophysis accuminata* and *D. caudata* were recorded in small numbers along with this bloom. During premonsoon of 2006 and post monsoon of 2008 diatoms dominated in the phytoplankton biomass. Dinoflagellates was completely absent during this period. The result of analysis of diversity indices are presented in table 8. Shannon-Wiener's diversity index (H') and Margalef species richness (d) was low during the phytoplankton blooms in 2006 and 2007.

The dendrogram of cluster analysis of phytoplankton composition during different seasons at station 2 (off Alapuzha) is given in figure 23.

The cluster analysis resulted in grouping the seasons into two clusters. Cluster I consisted of monsoon of 2006 and monsoon of 2007 with 65% similarity in phytoplankton composition during which there was blooms of *Thalassiosira partheneia*. The cluster II consisted of postmonsoon of 2007 and premonsoon of 2007.

**Figure 21: Seasonal variation of major phytoplankton groups at Station 2 during the period 2006 to 2008**

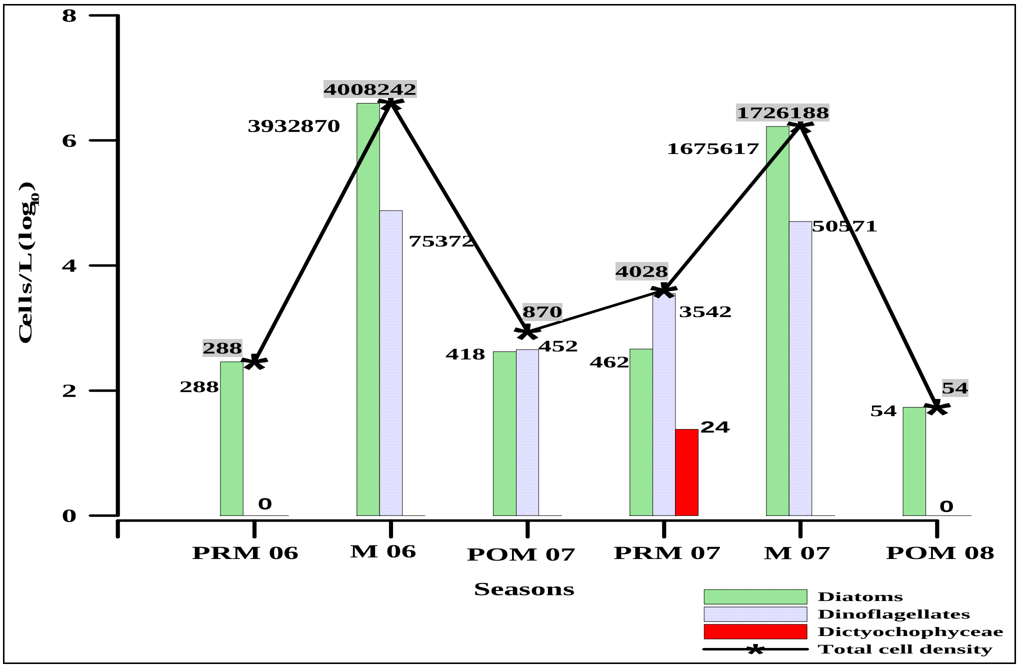


**Table 7: Qualitative and quantitative composition of phytoplankton at Station 2 during different seasons of 2006 to 2008**

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 1 | *Achnanthes brevipes* | 0 | 0 | 0 | 0 | 12 | 0 |
| 2 | *Achnanthes hauckiana* | 0 | 0 | 0 | 0 | 20 | 0 |
| 3 | *Amphora turgida* | 0 | 0 | 20 | 0 | 0 | 0 |
| 4 | *Biddulphia aurita* | 12 | 0 | 0 | 0 | 0 | 0 |
| 5 | *Biddulphia regia* | 0 | 0 | 0 | 20 | 0 | 0 |
| 6 | *Biddulphia reticulata* | 0 | 0 | 0 | 44 | 0 | 0 |
| 7 | *Biddulphia rhombus* | 5 | 0 | 0 | 0 | 0 | 0 |
| 8 | *Biddulphia sinensis* | 0 | 0 | 0 | 16 | 0 | 0 |
| 9 | *Calonies brevis* | 0 | 0 | 12 | 0 | 0 | 0 |

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 10 | *Calonies westii* | 0 | 0 | 10 | 0 | 0 | 0 |
| 11 | *Cerataulus turgidus* | 0 | 0 | 0 | 0 | 0 | 16 |
| 12 | *Chaetoceros affinis* | 41 | 0 | 72 | 0 | 0 | 0 |
| 13 | *Chaetoceros breve* | 29 | 0 | 0 | 0 | 0 | 0 |
| 14 | *Chaetoceros decipiens* | 0 | 0 | 0 | 44 | 0 | 0 |
| 15 | *Coscinodiscus asteromphalus* | 0 | 0 | 0 | 0 | 35 | 0 |
| 16 | *Coscinodiscus centralis* | 0 | 10 | 0 | 0 | 0 | 0 |
| 17 | *Coscinodiscus marginatus* | 24 | 0 | 0 | 0 | 0 | 0 |
| 18 | *Coscinodiscus radiatus* | 35 | 0 | 0 | 64 | 0 | 0 |
| 19 | *Coscinodiscus subtilis* | 0 | 12 | 0 | 0 | 15 | 0 |
| 20 | *Cylindrotheca gracilis* | 0 | 15 | 0 | 0 | 0 | 0 |
| 21 | *Cymbella hustedtii* | 12 | 0 | 0 | 0 | 0 | 0 |
| 22 | *Diploneis smithii* | 0 | 16 | 0 | 0 | 0 | 0 |
| 23 | *Fragilaria oceanica* | 0 | 0 | 38 | 0 | 0 | 0 |
| 24 | *Grammatophora undulata* | 0 | 0 | 0 | 16 | 0 | 0 |
| 25 | *Leptocylindrus minimus* | 48 | 0 | 0 | 0 | 0 | 0 |
| 26 | *Mastogloia lanceolata* | 0 | 0 | 0 | 0 | 0 | 20 |
| 27 | *Navicula elegans* | 0 | 12 | 0 | 0 | 0 | 18 |
| 28 | *Navicula hasta* | 0 | 0 | 32 | 0 | 0 | 0 |
| 29 | *Navicula henneidyi* | 0 | 0 | 48 | 40 | 0 | 0 |
| 30 | *Navicula lyra* | 0 | 0 | 40 | 0 | 0 | 0 |
| 31 | *Nitzschia closterium* | 0 | 46 | 0 | 0 | 0 | 0 |
| 32 | *Nitzschia longissima* | 7 | 0 | 0 | 0 | 0 | 0 |
| 33 | *Nitzschia lorenziana* | 0 | 0 | 0 | 22 | 0 | 0 |
| 34 | *Nitzschia paduriformis* | 5 | 0 | 0 | 0 | 0 | 0 |
| 35 | *Nitzschia paduriformis* var. minor | 0 | 0 | 10 | 0 | 0 | 0 |
| 36 | *Nitzschia paleacea* | 0 | 0 | 44 | 0 | 0 | 0 |
| 37 | *Paralia sulcata* | 0 | 0 | 0 | 20 | 0 | 0 |
| 38 | *Pleurosigma acuminatum* | 0 | 15 | 0 | 0 | 0 | 0 |
| 39 | *Pleurosigma angulatum* | 0 | 0 | 0 | 0 | 15 | 0 |
| 40 | *Pleurosigma naviculaceum* | 0 | 0 | 0 | 28 | 0 | 0 |
| 41 | *Podosira montagnei* | 0 | 5 | 0 | 0 | 0 | 0 |
| 42 | *Skeletonema costatum* | 0 | 12 | 0 | 0 | 0 | 0 |
| 43 | *Surirella flumiensis* | 0 | 0 | 60 | 40 | 0 | 0 |
| 44 | *Thalassionema nitzschioides* | 34 | 0 | 0 | 80 | 30 | 0 |
| 45 | *Thalassionema frauenfeldii* | 36 | 0 | 0 | 0 | 0 | 0 |
| 46 | *Thalassiosira nordenskioldii* | 0 | 17 | 0 | 0 | 0 | 0 |
| 47 | *Thalassiosira partheneia* | 0 | 3932710 | 0 | 0 | 1675490 | 0 |
| 48 | *Thalassiosira subtilis* | 0 | 0 | 32 | 0 | 0 | 0 |
| 49 | *Trachyneis aspera* | 0 | 0 | 0 | 28 | 0 | 0 |
| | Total | 288 | 3932870 | 418 | 462 | 1675617 | 54 |
| | Class: Dinophyceae | | | | | | |
| 1 | *Ceratium furca* | 0 | 800 | 84 | 3390 | 8900 | 0 |
| 2 | *Ceratium gibberum* | 0 | 0 | 0 | 0 | 4435 | 0 |
| 3 | *Ceratium horridum* | 0 | 0 | 0 | 0 | 8150 | 0 |
| 4 | *Ceratium kofoidii* | 0 | 0 | 0 | 0 | 50 | 0 |
| 5 | *Ceratium pentagonum* | 0 | 0 | 0 | 0 | 40 | 0 |
| 6 | *Ceratium symmetricum* | 0 | 0 | 0 | 0 | 10600 | 0 |
| 7 | *Ceratium trichoceros* | 0 | 0 | 0 | 0 | 9900 | 0 |
| 8 | *Ceratium vulture* | 0 | 0 | 0 | 0 | 80 | 0 |
| 9 | *Dinophysis accuminata* | 0 | 0 | 0 | 0 | 285 | 0 |
| 10 | *Dinophysis caudata* | 0 | 0 | 0 | 0 | 135 | 0 |
| 11 | *Dinophysis fortii* | 0 | 36 | 12 | 60 | 0 | 0 |
| 12 | *Diplopsalis lenticula* | 0 | 920 | 32 | 0 | 45 | 0 |
| 13 | *Noctiluca scintillans* | 0 | 73583 | 0 | 0 | 7356 | 0 |
| 14 | *Prorocentrum compressum* | 0 | 0 | 0 | 0 | 80 | 0 |
| 15 | *Prorocentrum gracile* | 0 | 0 | 0 | 16 | 210 | 0 |
| 16 | *Prorocentrum lima* | 0 | 0 | 100 | 0 | 0 | 0 |
| 17 | *Prorocentrum micans* | 0 | 33 | 104 | 48 | 0 | 0 |
| 18 | *Protoperidinium oceanicum* | 0 | 0 | 120 | 0 | 305 | 0 |
| 19 | *Pyrophacus horologium* | 0 | 0 | 0 | 28 | 0 | 0 |

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| | Total | 0 | 75372 | 452 | 3542 | 50571 | 0 |
| | Class: Dictyochophyceae | | | | | | |
| 1 | *Dictyocha fibula* | 0 | 0 | 0 | 24 | 0 | 0 |
| | Total | 0 | 0 | 0 | 24 | 0 | 0 |
| | Grand total | 288 | 4008242 | 870 | 4028 | 1726188 | 54 |

## Table 8: Phytoplankton diversity indices of Station 2 during the period 2006 to 2008

| Diversity indices of phytoplankton at Station 2 | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | Lambda' |
| PRM 06 | 12 | 288 | 1.942 | 0.917 | 3.287 | 0.111 |
| M 06 | 16 | 4008242 | 0.987 | 0.035 | 0.139 | 0.963 |
| POM 07 | 18 | 870 | 2.512 | 0.918 | 3.828 | 0.081 |
| PRM 07 | 19 | 4028 | 2.168 | 0.297 | 1.263 | 0.709 |
| M 07 | 22 | 1726188 | 1.462 | 0.061 | 0.271 | 0.942 |
| POM 08 | 3 | 54 | 0.501 | 0.996 | 1.579 | 0.323 |

## Figure 23: Dendrogram showing Bray Curtis similarity of phytoplankton composition at station 2 during the various seasons of 2006 to 2008

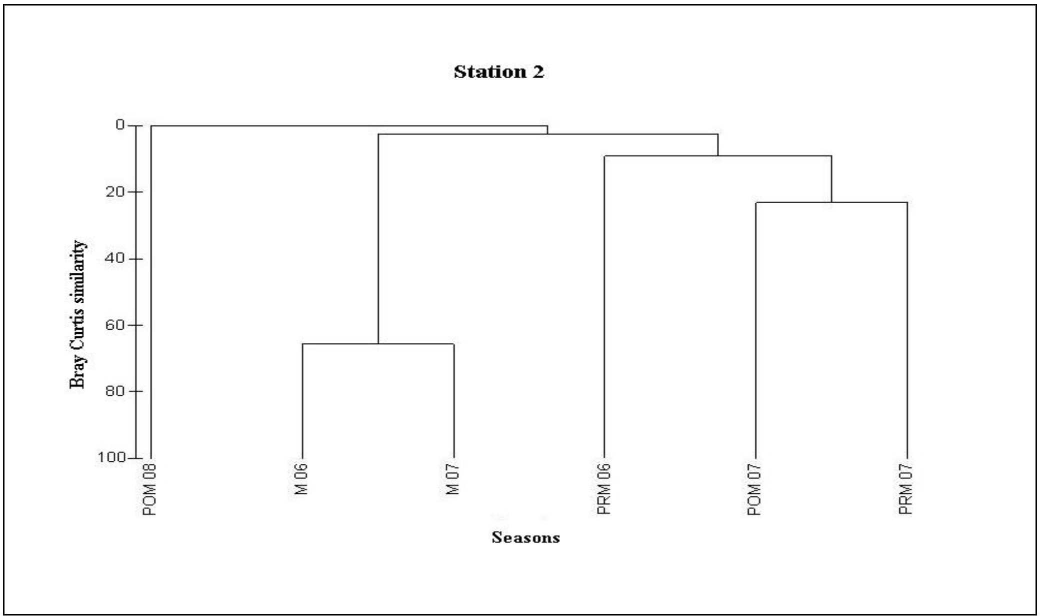
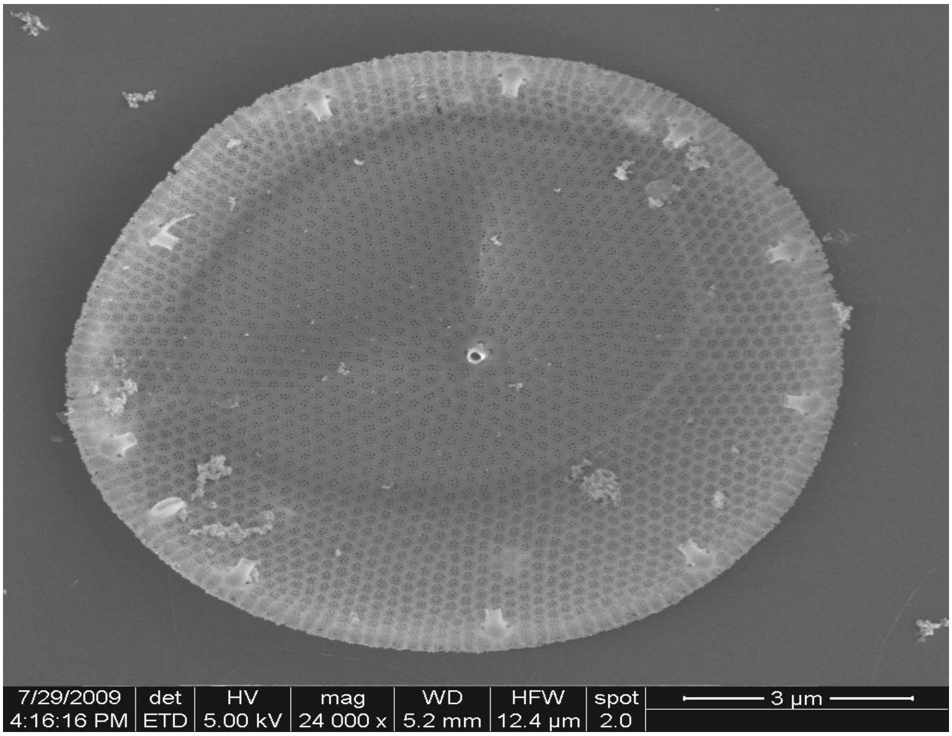
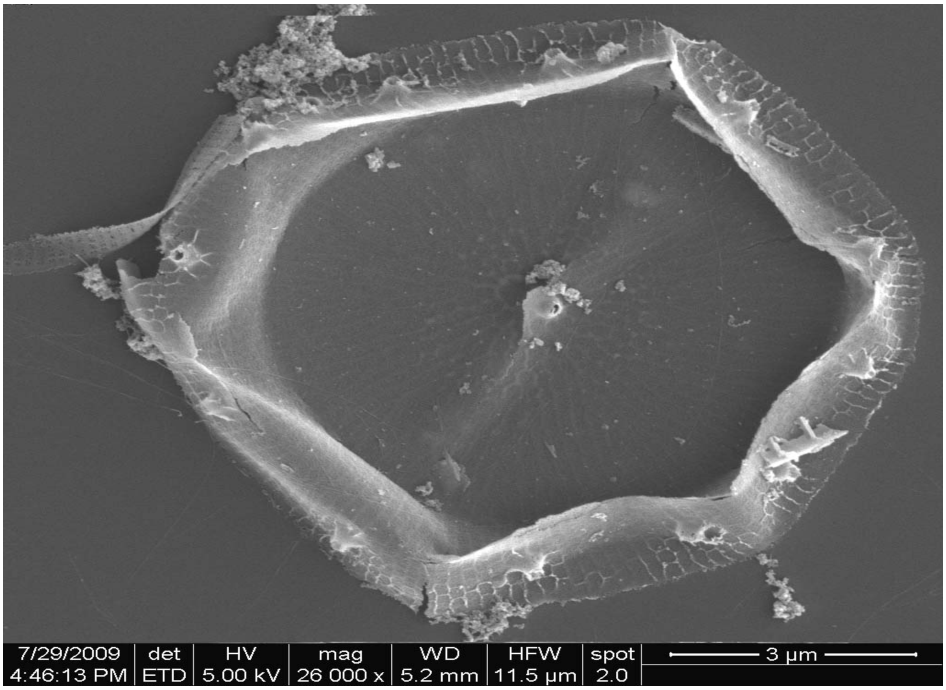


**Figure 22 Scanning Electron Micrograph of *Thalassiosira partheneia***



**(a) Internal view of valve**

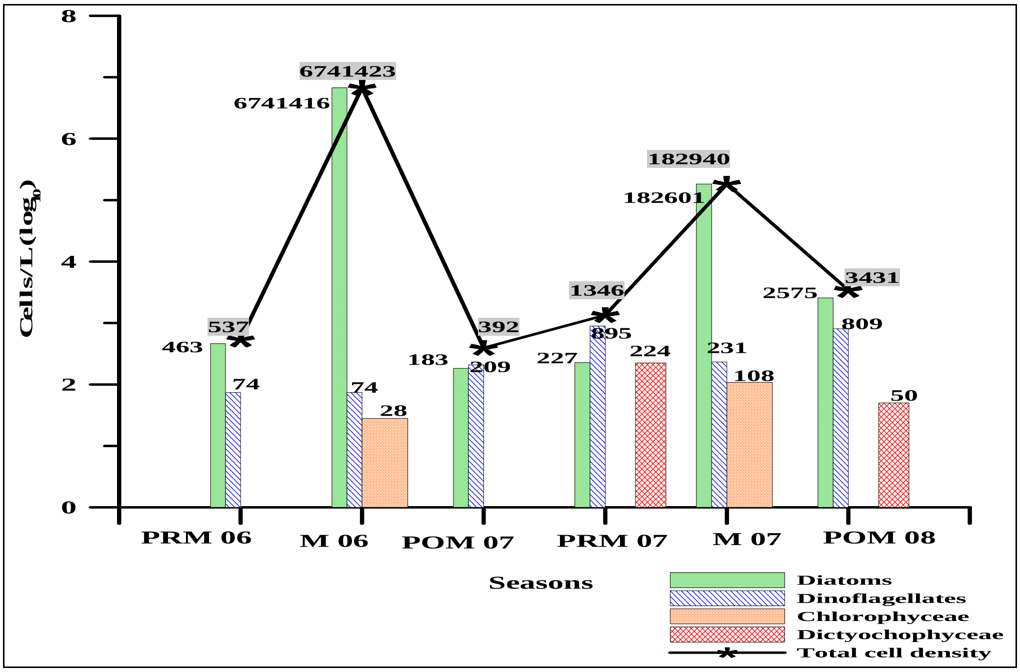


**(b) External view of valve**

In station 3 (off Kochi), high micro algal densities was observed during monsoon of 2006 and 2007 with values 6.7x $10^6$ cells $L^{-1}$ and 1.8x $10^5$ cells $L^{-1}$ respectively. Lowest cell density (392 cells $L^{-1}$) was recorded during the postmonsoon of 2007. The result of qualitative and quantitative analysis of phytoplankton of station 3 is given in table 9. Seasonal variations of major phytoplankton groups of station 3 were presented in figure 24. Diatoms and dinoflagellates were present in all the seasons. Diatoms were dominant in phytoplankton during monsoon of 2006 and 2007 with cell density 6.7x $10^6$ cells $L^{-1}$ and 1.8x $10^5$ cells $L^{-1}$ respectively. During monsoon of 2006 *Thalassiosira mala* a toxic diatom bloom was observed off Kochi with cell density of 6741230 cells $L^{-1}$. Figure 25 shows the Scanning Electron Micrograph of *Thalassiosira mala*. Other species diatoms were few in number when *T. mala* bloom occurred. The species were represented by *Amphora* spp., *Chaetoceros affinis, Ditylum sol, Eucampia zodiacus, Nitzschia sigma, Planktoniella sol, Surirella striatula* and *Thalassionema frauenfeldii*. Dinoflagellates were also negligible during *T. mala* bloom. The species of dinoflagellates were *Ceratium furca*, *Dinophysis accuminata* and *Protoperidinium leonis*. Chlorophyceaen members were recorded only during the monsoon seasons. Dictyochophyceae were present during the premonsoon of 2007 (224 cells $L^{-1}$) and postmonsoon of 2008 (50 cells $L^{-1}$). During monsoon of 2007, *Thalassiosira partheneia* bloom occurred with a cell density of 182100 cells $L^{-1}$. Other diatoms recorded were *Achnanthes brevipes, Biddulphia* spp., *Coscinodiscus* spp., *Navicula* spp., *Podosira montagnei* and *Thalassiosira subtilis*. Two chlorophycean members were also present along with this bloom in very low cell density, *Onychonema leave* and *Staurastrum leptocladium*. A toxic dinoflagellate *Alexandrium* sp. was observed with cells density 26 cells $L^{-1}$ along with this bloom. The result of analysis of diversity indices were presented in table 10. Shannon- Wiener's diversity index (H') and Margalef species richness (d) was low during the phytoplankton blooms in 2006 and 2007.

The dendrogram showing cluster analysis of phytoplankton composition during various seasons at station 3 (off Kochi) during the study period is given in figure 26. The cluster analysis grouped the seasons mainly into cluster I, consisted of postmonsoon of 2007 and premonsoon of 2007 at 30% similarity. Monsoon of 2006 and monsoon of 2007 behaved entirely different when compared to the other seasons. This was due to the bloom of *Thalassiosira mala* during the monsoon of 2006 and *T. partheneia* during monsoon of 2007. During monsoon of 2006 *T. mala* formed 99.99% of the total phytoplankton population and during monsoon of 2007 *T. partheneia* formed 99.54% of total phytoplankton population. Therefore, cluster analysis will be over showed by the abundance of a single species dominated population.

## Figure 24: Seasonal variation of major phytoplankton groups at Station 3 during the period 2006 to 2008



## Table 9. Qualitative and quantitative composition of phytoplankton at Station 3 during different seasons of 2006 to 2008

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class: Chlorophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 1 | *Coelasteum cambricum* | 0 | 12 | 0 | 0 | 0 | 0 |
| 2 | *Pediastrum tetras* | 0 | 16 | 0 | 0 | 0 | 0 |
| 3 | *Onychonema laeve* | 0 | 0 | 0 | 0 | 77 | 0 |
| 4 | *Staurastrum leptocladium* | 0 | 0 | 0 | 0 | 31 | 0 |
| | Total | 0 | 28 | 0 | 0 | 108 | 0 |
| | Class. Bacillariophyceae | | | | | | |
| | | | | | | | |
| 1 | *Achnanthes brevipes* | 0 | 0 | 0 | 0 | 21 | 0 |
| 2 | *Amphiprora alata* | 0 | 0 | 0 | 0 | 0 | 44 |
| 3 | *Amphipora gigantia var. sulcata* | 13 | 8 | 0 | 0 | 0 | 0 |
| 4 | *Amphora angusta* | 0 | 12 | 0 | 0 | 0 | 0 |
| 5 | *Asterionella japonica* | 0 | 0 | 0 | 0 | 0 | 127 |
| 6 | *Aulacodiscus orbiculatus* | 14 | 0 | 0 | 0 | 0 | 0 |
| 7 | *Bacteriastrum comosum* | 0 | 0 | 0 | 0 | 0 | 82 |
| 8 | *Biddulphia aurita* | 0 | 0 | 0 | 0 | 39 | 0 |

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class: Chlorophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 9 | *Biddulphia heteroceros* | 30 | 0 | 0 | 0 | 0 | 0 |
| 10 | *Biddulphia longicruris* | 0 | 0 | 0 | 0 | 0 | 110 |
| 11 | *Biddulphia mobiliensis* | 0 | 0 | 0 | 0 | 0 | 38 |
| 12 | *Biddulphia rhombus* | 0 | 0 | 0 | 0 | 32 | 0 |
| 13 | *Biddulphia sinensis* | 0 | 0 | 0 | 0 | 0 | 82 |
| 14 | *Calonies madraspatensis* | 0 | 0 | 0 | 14 | 0 | 0 |
| 15 | *Chaetoceros affinis* | 0 | 10 | 0 | 0 | 0 | 0 |
| 16 | *Chaetoceros constrictus* | 0 | 0 | 0 | 0 | 0 | 55 |
| 17 | *Chaetoceros lorenzianus* | 24 | 0 | 0 | 0 | 0 | 0 |
| 18 | *Corethron criophilum* | 0 | 0 | 0 | 0 | 0 | 55 |
| 19 | *Corethron enerme* | 0 | 0 | 0 | 0 | 0 | 60 |
| 20 | *Coscinodiscus asteromphalus* | 0 | 0 | 0 | 56 | 0 | 0 |
| 21 | *Coscinodiscus eccentricus* | 0 | 0 | 0 | 0 | 0 | 23 |
| 22 | *Coscinodiscus granii* | 0 | 0 | 0 | 0 | 64 | 0 |
| 23 | *Coscinodiscus marginatus* | 59 | 0 | 0 | 0 | 0 | 0 |
| 24 | *Coscinodiscus nitidus* | 54 | 0 | 0 | 0 | 12 | 0 |
| 25 | *Coscinodiscus radiatus* | 54 | 0 | 0 | 0 | 14 | 16 |
| 26 | *Coscinodiscus rothii* | 0 | 0 | 0 | 0 | 35 | 0 |
| 27 | *Cylindrotheca gracilis* | 41 | 0 | 16 | 0 | 0 | 0 |
| 28 | *Cymbella hustedtii* | 0 | 0 | 0 | 0 | 0 | 0 |
| 29 | *Diploneis elliptica* | 13 | 0 | 0 | 0 | 0 | 0 |
| 30 | *Ditylum brightwelli* | 0 | 0 | 0 | 22 | 0 | 275 |
| 31 | *Ditylum sol* | 0 | 5 | 0 | 0 | 0 | 0 |
| 32 | *Eucampia zodiacus* | 0 | 5 | 0 | 0 | 0 | 0 |
| 33 | *Grammatophora serpentina* | 0 | 0 | 0 | 0 | 0 | 55 |
| 34 | *Guinardia flaccida* | 0 | 0 | 0 | 0 | 0 | 56 |
| 35 | *Gyrosigma balticum* | 0 | 0 | 20 | 0 | 0 | 0 |
| 36 | *Gyrosigma hippocampus* | 0 | 0 | 0 | 45 | 0 | 0 |
| 37 | *Laudaria annulata* | 0 | 0 | 0 | 0 | 0 | 148 |
| 38 | *Mastogloia cochinensis* | 26 | 0 | 0 | 0 | 0 | 0 |
| 39 | *Mastogloia exigua* | 0 | 0 | 0 | 0 | 0 | 60 |
| 40 | *Navicula bicapitata* | 0 | 0 | 0 | 0 | 0 | 55 |
| 41 | *Navicula granulata* | 0 | 0 | 0 | 0 | 0 | 60 |
| 42 | *Navicula halophila* | 0 | 0 | 0 | 0 | 0 | 56 |
| 43 | *Navicula humerosa* | 0 | 0 | 0 | 0 | 30 | 0 |
| 44 | *Navicula inclementis* | 0 | 0 | 0 | 0 | 12 | 0 |
| 45 | *Navicula longa* | 0 | 0 | 0 | 0 | 0 | 50 |

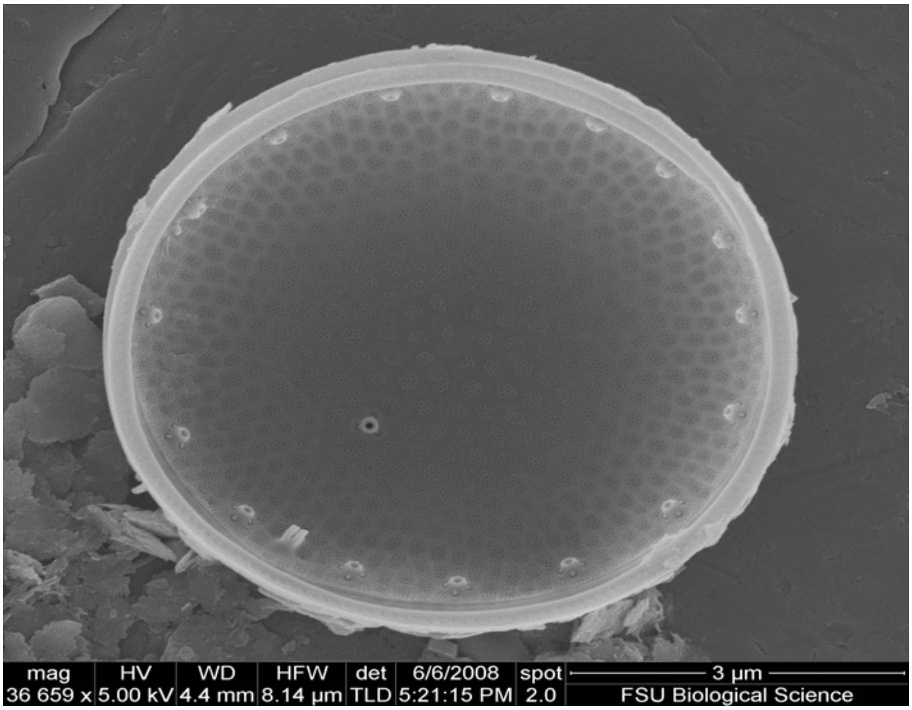
| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class: Chlorophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 46 | *Navicula marina* | 0 | 0 | 16 | 0 | 0 | 58 |
| 47 | *Nitzschia constricta* | 0 | 0 | 0 | 0 | 0 | 55 |
| 48 | *Nitzschia sigma* | 0 | 14 | 0 | 0 | 0 | 0 |
| 49 | *Paralia sulcata* | 13 | 0 | 0 | 0 | 0 | 0 |
| 50 | *Planktoniella sol* | 10 | 6 | 0 | 0 | 0 | 0 |
| 51 | *Pleurosigma angulatum* | 0 | 0 | 44 | 0 | 0 | 0 |
| 52 | *Pleurosigma aestuarii* | 10 | 0 | 0 | 0 | 0 | 22 |
| 53 | *Pleurosigma attenuatum* | 0 | 0 | 0 | 14 | 0 | 0 |
| 54 | *Pleurosigma falx* | 24 | 0 | 0 | 0 | 0 | 44 |
| 55 | *Pleurosigma intermedium* | 0 | 0 | 0 | 0 | 0 | 60 |
| 56 | *Pleurosigma normanii* | 0 | 0 | 0 | 0 | 0 | 66 |
| 57 | *Podosira montagnei* | 0 | 0 | 0 | 0 | 102 | 0 |
| 58 | *Proboscia alata* | 0 | 0 | 0 | 0 | 0 | 71 |
| 59 | *Rhizosolenia borealis* | 0 | 0 | 0 | 0 | 0 | 66 |
| 60 | *Rhizosolenia castracanei* | 0 | 0 | 0 | 0 | 0 | 61 |
| 61 | *Rhizosolenia robusta* | 0 | 0 | 0 | 0 | 0 | 55 |
| 62 | *Rhizosolenia setigera* | 0 | 0 | 0 | 17 | 0 | 0 |
| 63 | *Rhizosolenia styliformis* | 0 | 0 | 0 | 0 | 0 | 55 |
| 64 | *Surirella flumiensis* | 0 | 0 | 64 | 28 | 0 | 0 |
| 65 | *Surirella neumeyeri* | 0 | 0 | 0 | 0 | 0 | 60 |
| 66 | *Surirella striatula* | 17 | 14 | 0 | 0 | 0 | 82 |
| 67 | *Thalassionema bacillare* | 0 | 0 | 0 | 0 | 0 | 22 |
| 68 | *Thalassionema frauenfeldii* | 37 | 10 | 0 | 0 | 0 | 110 |
| 69 | *Thalassionema nitzschioides* | 24 | 0 | 0 | 0 | 0 | 99 |
| 70 | *Thalassiosira coramandeliana* | 0 | 0 | 13 | 31 | 0 | 0 |
| 71 | *Thalassiosira subtilis* | 0 | 0 | 10 | 0 | 140 | 0 |
| 72 | *Thalassiosira mala* | 0 | 6741230 | 0 | 0 | 0 | 0 |
| 73 | *Thalassiosira partheneia* | 0 | 0 | 0 | 0 | 182100 | 0 |
| 74 | *Triceratium dubium* | 0 | 0 | 0 | 0 | 0 | 82 |
| | Total | 463 | 6741314 | 183 | 227 | 182601 | 2575 |
| | Class: Dinophyceae | | | | | | |
| 1 | *Alexandrium sp.* | 0 | 0 | 0 | 0 | 26 | 0 |
| 2 | *Ceratium furca* | 27 | 27 | 83 | 588 | 0 | 148 |
| 3 | *Ceratium fusus* | 0 | 0 | 0 | 0 | 0 | 110 |
| 4 | *Ceratium gibberum* | 0 | 0 | 0 | 0 | 39 | 110 |
| 5 | *Ceratium horridum* | 0 | 0 | 0 | 0 | 32 | 0 |
| 6 | *Ceratium symmetricum* | 0 | 0 | 0 | 0 | 102 | 55 |

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class: Chlorophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 7 | *Coolia monotis* | 0 | 0 | 0 | 0 | 0 | 6 |
| 8 | *Dinophysis accuminata* | 0 | 24 | 0 | 0 | 0 | 0 |
| 9 | *Dinophysis caudata* | 0 | 0 | 0 | 28 | 0 | 0 |
| 10 | *Dinophysis tripos* | 0 | 0 | 0 | 0 | 0 | 12 |
| 11 | *Diplopsalis lenticula* | 24 | 0 | 19 | 59 | 0 | 0 |
| 12 | *Goniodoma sphaericum* | 0 | 0 | 0 | 17 | 0 | 0 |
| 13 | *Noctiluca scintillans* | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | *Prorocentrum gracile* | 0 | 0 | 43 | 0 | 0 | 0 |
| 15 | *Prorocentrum micans* | 0 | 0 | 0 | 70 | 0 | 110 |
| 16 | *Protoperidinium brochii* | 0 | 0 | 0 | 0 | 0 | 11 |
| 17 | *Protoperidinium cerasus* | 0 | 0 | 0 | 45 | 0 | 0 |
| 18 | *Protoperidinium conicum* | 0 | 0 | 0 | 0 | 32 | 0 |
| 19 | *Protoperidinium leonis* | 0 | 13 | 0 | 0 | 0 | 0 |
| 20 | *Protoperidinium mediterraneum* | 0 | 0 | 0 | 48 | 0 | 0 |
| 21 | *Protoperidinium minutum* | 0 | 0 | 0 | 12 | 0 | 0 |
| 22 | *Protoperidinium oblongum* | 0 | 0 | 38 | 0 | 0 | 0 |
| 23 | *Protoperidinium oceanicum* | 13 | 10 | 26 | 28 | 0 | 0 |
| 24 | *Pyrophacus horologium* | 10 | 0 | 0 | 0 | 0 | 0 |
| 25 | *Pyrophacus steinii* | 0 | 0 | 0 | 0 | 0 | 247 |
| | Total | 74 | 74 | 209 | 895 | 231 | 809 |
| | Class: Dictyochophyceae | | | | | | |
| 1 | *Dictyocha fibula* | 0 | 0 | 0 | 224 | 0 | 50 |
| | Total | 0 | 0 | 0 | 224 | 0 | 50 |
| | Grand total | 537 | 6741416 | 392 | 1346 | 182940 | 3431 |

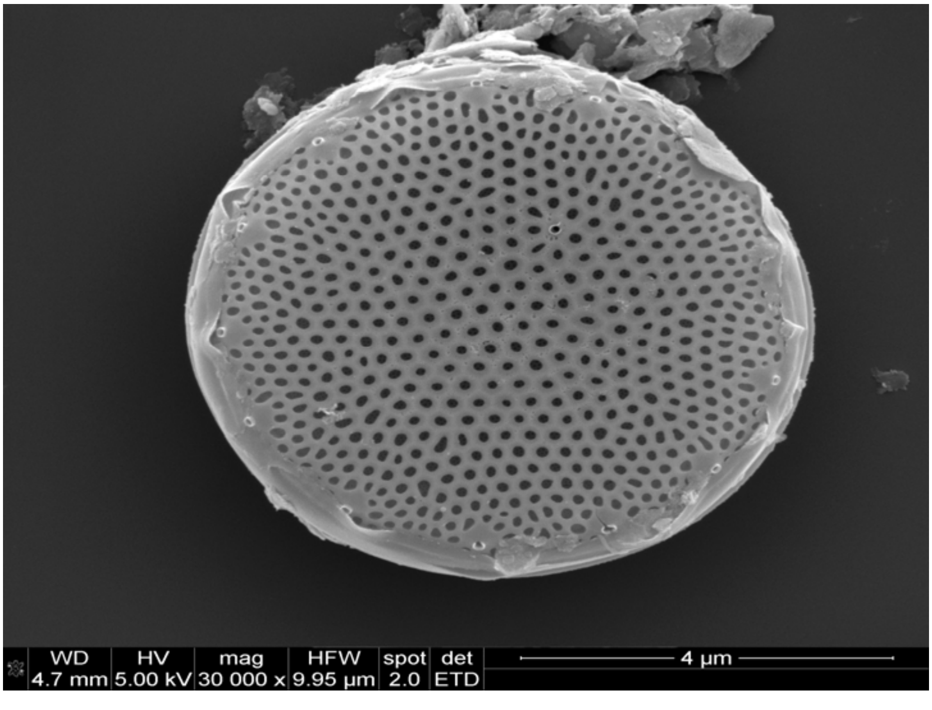
## Table 10: Phytoplankton diversity indices of Station 3 during the period 2006 to 2008

| Diversity indices of phytoplankton at Station 3 | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | Lambda' |
| PRM 06 | 21 | 537 | 3.182 | 0.948 | 4.164 | 0.062 |
| M 06 | 16 | 6741416 | 0.954 | 0.0001 | 0.0006 | 0.999 |
| POM 07 | 12 | 392 | 1.842 | 0.919 | 3.296 | 0.118 |
| PRM 07 | 18 | 1346 | 2.359 | 0.717 | 2.990 | 0.231 |
| M 07 | 19 | 182940 | 1.486 | 0.014 | 0.0598 | 0.991 |
| POM 08 | 47 | 3434 | 5.650 | 0.946 | 5.254 | 0.032 |

**Figure 25: Scanning Electron Micrograph of *Thalassiosira mala***

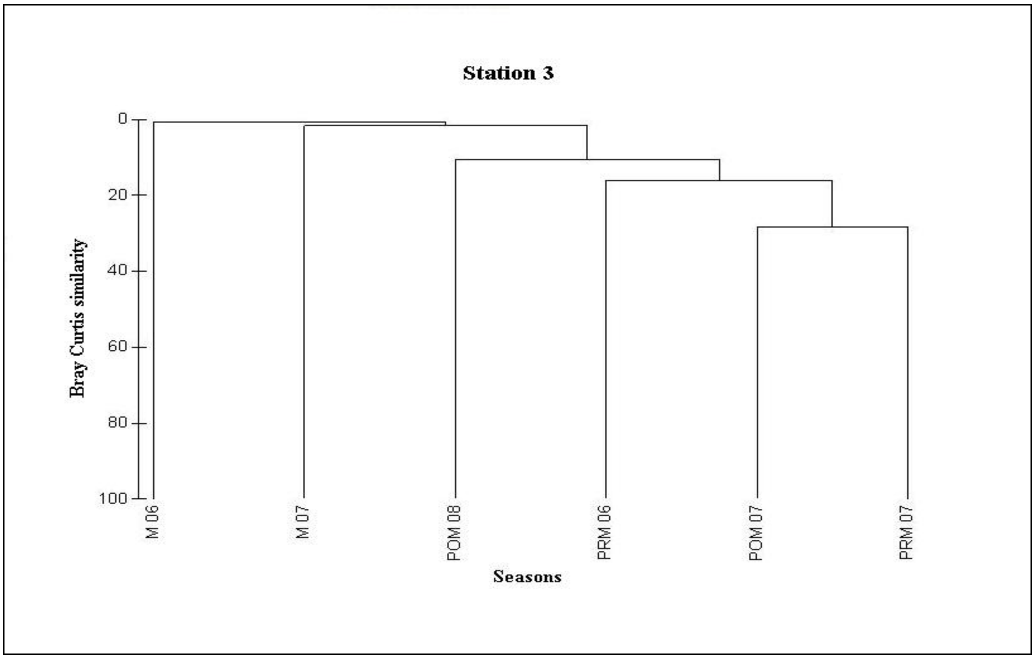


**(a) Internal view of valve**



**(b) External view of valve**

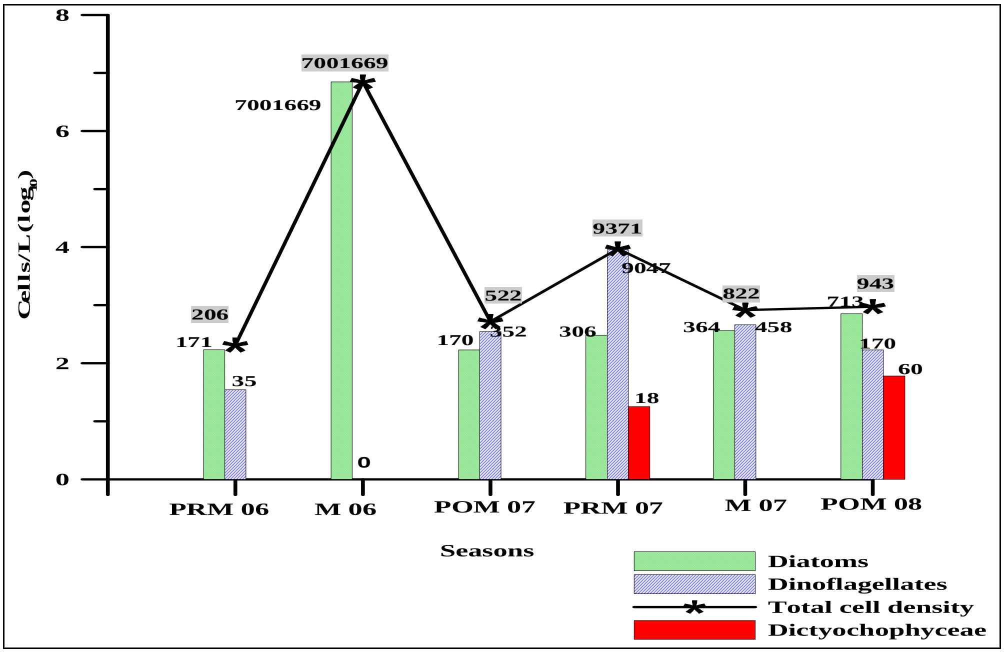
**Figure 26: Dendrogram showing Bray Curtis similarity of phytoplankton composition at station 3 during the various seasons of 2006 to 2008**



At station 4 (off Calicut), a highest cell density of 7x $10^6$ cells $L^{-1}$ was observed during the monsoon of 2006 and lowest (206 cells $L^{-1}$) during the premonsoon of 2006. The result of qualitative and quantitative analysis of phytoplankton of station 4 is represented in table 11. Figure 27 shows the seasonal variation of major phytoplankton groups. Diatoms were present at all the seasons. The monsoon of 2006 showed preponderance of diatoms in the phytoplankton population (7x $10^6$ cells $L^{-1}$). This high cell density was due to the bloom of *Coscinodiscus asteromphalus* var. *centralis*. Figure 28 shows the Scanning Electron Micrograph of *Coscinodiscus asteromphalus* var. *centralis*. Other diatoms were fewer in number and were represented by *Biddulphia mobiliensis*, *Cymbella tumida*, *Pleurosigma accuminata* and *P. falx*. Curiously enough dinoflagellates were absent in the bloom. However, during the monsoon of 2007 dinoflagellates were dominant (458 cells $L^{-1}$) in the phytoplankton population. High dinoflagellate cell density (9047 cells $L^{-1}$) was recorded during the premonsoon of 2007. Dictyochophyceae was present only during the premonsoon of 2007 and postmonsoon of 2008 with cell densities 18 cells $L^{-1}$ and 60 cells $L^{-1}$ respectively. The result of analysis of diversity indices are presented in table 12. Shannon- Wiener's diversity index (H') and Margalef species richness (d) were low during the bloom period of *Coscinodiscus asteromphalus* var. *centralis* bloom at station 4 in the monsoon season of 2006.

The dendrogram of cluster analysis of phytoplankton composition during different seasons at station 4 (off Kochi) is given in figure 29. The cluster analysis grouped the seasons mainly into three clusters. Cluster I consisted of postmonsoon of 2007 and monsoon of 2007 at 30% similarity. Cluster II consisted of premonsoon of 2007 and postmonsoon of 2008 at 20% similarity. Cluster III consisted of monsoon of 2006 only and the composition was entirely different from other seasons, due to the bloom of *Coscinodiscus asteromphalus* var. *centralis*, when the phytoplankton population was represented by only diatoms. Among the diatoms *Coscinodiscus asteromphalus* var. *centralis* formed 99.98 % of the total population and the remaining population was represented by *Pleurosigma spp.*, *Cymbella sp.* and *Biddulphia sp.*

**Figure 27: Seasonal variation of major phytoplankton groups at Station 4 during the period 2006 to 2008**



## Table 11. Qualitative and quantitative composition of phytoplankton at Station 4 during different seasons of 2006 to 2008

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 1 | *Amphora angusta* | 2 | 0 | 0 | 0 | 0 | 0 |
| 2 | *Asterionella japonica* | 0 | 0 | 31 | 0 | 72 | 100 |
| 3 | *Biddulphia mobiliensis* | 2 | 8 | 0 | 0 | 42 | 0 |
| 4 | *Biddulphia rhombus* | 0 | 0 | 0 | 0 | 0 | 15 |
| 5 | *Campylodiscus ecclesianus* | 0 | 0 | 10 | 0 | 0 | 0 |
| 6 | *Calonies madraspatensis* | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | *Chaetoceros affinis* | 42 | 0 | 28 | 0 | 0 | 0 |
| 8 | *Chaetoceros curvisetus* | 0 | 0 | 0 | 0 | 0 | 75 |
| 9 | *Chaetoceros lorenzianus* | 0 | 0 | 0 | 0 | 0 | 60 |
| 10 | *Coscinodiscus asteromphalus var. centralis* | 0 | 7000000 | 0 | 0 | 0 | 0 |
| 11 | *Coscinodiscus centralis* | 0 | 0 | 10 | 150 | 34 | 45 |
| 12 | *Coscinodiscus eccentricus* | 0 | 0 | 0 | 0 | 54 | 0 |
| 13 | *Coscinodiscus marginatus* | 9 | 0 | 0 | 0 | 0 | 0 |

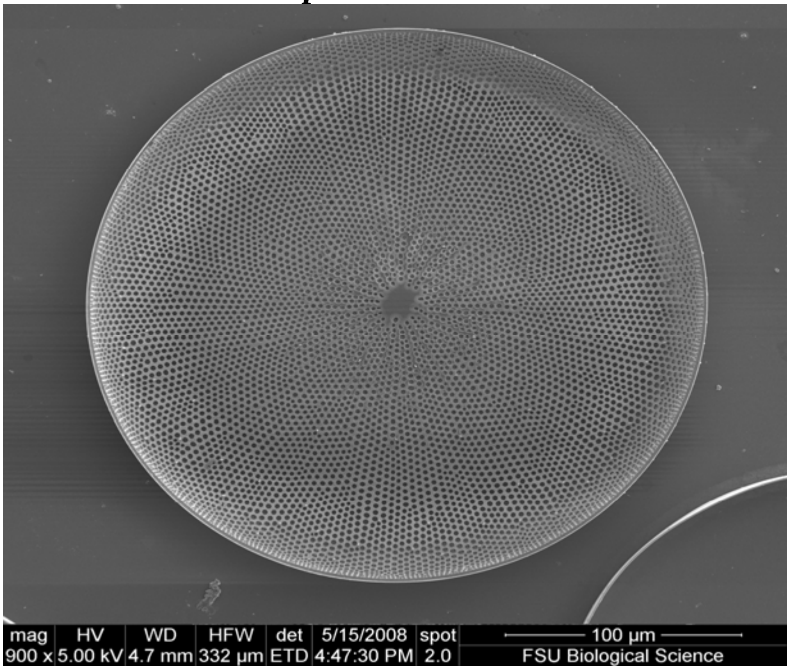
| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 14 | *Cylindrotheca gracilis* | 4 | 0 | 19 | 0 | 18 | 0 |
| 15 | *Cymbella tumida* | 0 | 10 | 0 | 0 | 0 | 0 |
| 16 | *Diploneis splendida* | 15 | 0 | 0 | 0 | 0 | 0 |
| 17 | *Ditylum sol* | 2 | 0 | 0 | 18 | 0 | 30 |
| 18 | *Gyrosigma tenuissimum* | 0 | 0 | 12 | 0 | 0 | 0 |
| 19 | *Navicula cincta* | 0 | 0 | 0 | 0 | 0 | 16 |
| 20 | *Navicula humerosa* | 0 | 0 | 0 | 0 | 0 | 32 |
| 21 | *Navicula longa* | 0 | 0 | 0 | 0 | 18 | 0 |
| 22 | *Navicula maculosa* | 0 | 0 | 0 | 0 | 0 | 40 |
| 23 | *Nitzschia closterium* | 15 | 0 | 0 | 0 | 0 | 0 |
| 24 | *Nitzschia sigma* | 2 | 0 | 0 | 0 | 0 | 0 |
| 25 | *Pleurosigma accuminatum* | 0 | 1612 | 0 | 0 | 0 | 15 |
| 26 | *Pleurosigma angulatum* | 0 | 0 | 0 | 0 | 30 | 0 |
| 27 | *Pleurosigma angulatum* var. *strigosum* | 0 | 0 | 0 | 0 | 18 | 0 |
| 28 | *Pleurosigma aestuarii* | 0 | 10 | 0 | 0 | 78 | 0 |
| 29 | *Pleurosigma falx* | 0 | 29 | 12 | 0 | 0 | 0 |
| 30 | *Pleurosigma naviculaceum* | 0 | 0 | 0 | 60 | 0 | 0 |
| 31 | *Pleurosigma strigosum* | 0 | 0 | 0 | 0 | 0 | 35 |
| 32 | *Pseudonitzschia seriata* | 0 | 0 | 0 | 0 | 0 | 125 |
| 33 | *Skeletonema costatum* | 46 | 0 | 0 | 0 | 0 | 0 |
| 34 | *Stephanopyxis turris* | 0 | 0 | 0 | 18 | 0 | 0 |
| 35 | *Surirella fastuosa* | 0 | 0 | 0 | 60 | 0 | 0 |
| 36 | *Surirella flumiensis* | 0 | 0 | 48 | 0 | 0 | 0 |
| 37 | *Thalassionema frauenfeldii* | 22 | 0 | 0 | 0 | 0 | 80 |
| 38 | *Thalassionema nitzschioides* | 0 | 0 | 0 | 0 | 0 | 45 |
| 39 | *Thalassiosira subtilis* | 4 | 0 | 0 | 0 | 0 | 0 |
| 40 | *Tropidoneis longa* | 6 | 0 | 0 | 0 | 0 | 0 |
| | Total | 171 | 7001669 | 170 | 306 | 364 | 713 |
| | Class: Dinophyceae | | | | | | |
| 1 | *Ceratium concilians* | 0 | 0 | 0 | 0 | 30 | 0 |
| 2 | *Ceratium furca* | 4 | 0 | 180 | 8160 | 150 | 80 |
| 3 | *Ceratium fusus* | 0 | 0 | 36 | 0 | 32 | 0 |
| 4 | *Ceratium horridum* | 0 | 0 | 0 | 0 | 42 | 0 |
| 5 | *Ceratium kofoidii* | 0 | 0 | 0 | 0 | 0 | 55 |

| No. | Species | Seasons | | | | | |
|---|---|---|---|---|---|---|---|
| | Class. Bacillariophyceae | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| 6 | *Ceratium symmetricum* | 0 | 0 | 0 | 0 | 96 | 0 |
| 7 | *Ceratium tripos* | 0 | 0 | 0 | 30 | 0 | 0 |
| 8 | *Dinophysis accuminata* | 0 | 0 | 0 | 0 | 72 | 0 |
| 9 | *Dinophysis caudata* var. *acutiformis* | 0 | 0 | 17 | 0 | 0 | 0 |
| 10 | *Diplopsalis lenticula* | 29 | 0 | 14 | 90 | 0 | 0 |
| 11 | *Noctiluca scintillans* | 0 | 0 | 0 | 90 | 0 | 0 |
| 12 | *Prorocentrum micans* | 2 | 0 | 0 | 69 | 0 | 0 |
| 13 | *Protoperidinium brochii* | 0 | 0 | 0 | 270 | 0 | 0 |
| 14 | *Protoperidinium cerasus* | 0 | 0 | 0 | 278 | 0 | 0 |
| 15 | *Protoperidinium compressum* | 0 | 0 | 26 | 0 | 0 | 0 |
| 16 | *Protoperidinium granii* | 0 | 0 | 0 | 0 | 0 | 35 |
| 17 | *Protoperidinium minor* | 0 | 0 | 0 | 60 | 0 | 0 |
| 18 | *Protoperidinium oceanicum* | 0 | 0 | 7 | 0 | 0 | 0 |
| 19 | *Protoperidinium pellucidum* | 0 | 0 | 24 | 0 | 0 | 0 |
| 20 | *Protoperidinium steinii* | 0 | 0 | 0 | 0 | 36 | 0 |
| 21 | *Pyrophacus steinii* | 0 | 0 | 48 | 0 | 0 | 0 |
| | Total | 35 | 0 | 352 | 9047 | 458 | 170 |
| | Class: Dictyochophyceae | | | | | | |
| 1 | *Dictyocha fibula* | 0 | 0 | 0 | 18 | 0 | 30 |
| 2 | *Dictyocha octonaria* | 0 | 0 | 0 | 0 | 0 | 30 |
| | Total | 0 | 0 | 0 | 18 | 0 | 60 |
| | Grand total | 206 | 7001669 | 522 | 9371 | 822 | 943 |

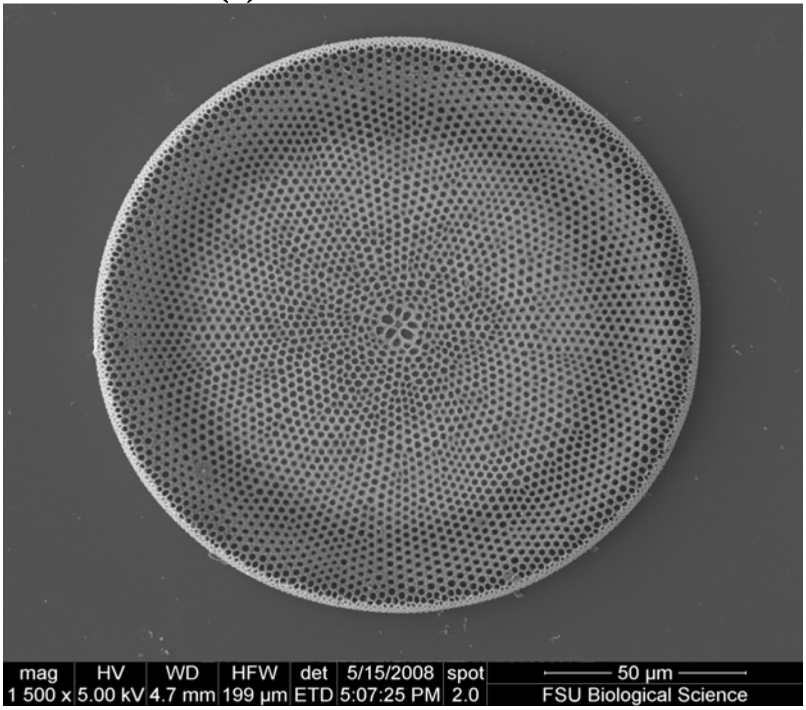
**Table 12. Phytoplankton diversity indices of Station 4 during the period 2006 to 2008**

| Diversity indices of phytoplankton at Station 4 | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | Lambda' |
| PRM 06 | 16 | 206 | 2.815 | 0.811 | 3.246 | 0.133 |
| M 06 | 6 | 7001669 | 0.317 | 0.001 | 0.003 | 0.999 |
| POM 07 | 16 | 522 | 2.397 | 0.836 | 3.344 | 0.155 |
| PRM 07 | 14 | 9371 | 1.421 | 0.254 | 0.967 | 0.761 |
| M 07 | 16 | 822 | 2.235 | 0.931 | 3.725 | 0.089 |
| POM 08 | 19 | 943 | 2.628 | 0.944 | 4.011 | 0.070 |

**Figure 28. Scanning Electron Micrographs of *Coscinodiscus asteromphalus* var. *centralis***

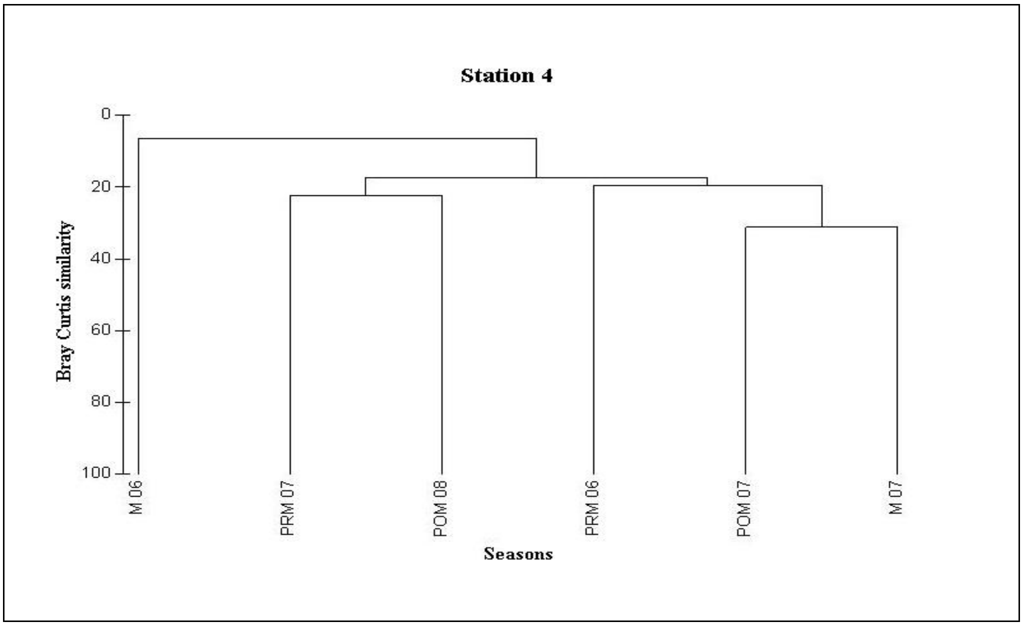


**(a) Internal view of valve**



**(b) External view of valve**

**Figure 29. Dendrogram showing the Bray Curtis similarity of phytoplankton composition at station 4 during the various seasons of 2006 to 2008.**



## 3.4 Discussion

Growth and sustenance of phytoplankton population depend on various environmental both abiotic and biotic factors which depict spatial and seasonal variations. The major factors affecting phytoplankton production are irradiance, spectral composition of light, sea surface temperature, salinity, concentration of major nutrients and grazing by herbivorous zooplankton, which in turn are dependent on several other abiotic and biotic factors (Svedrup *et al*., 1942; Raymont, 1980). Along the west coast of India, monsoon plays a critical role in controlling environmental features such as sea surface temperature, salinity, dissolved oxygen content and nutrient generation which in turn become responsible for production of phytoplankton and zooplankton (Rajagopalan *et al*., 1992). All living organisms depend on the conversion of solar energy to chemical energy by the process of photosynthesis and are greatly dependent upon chlorophyll. Among the various plant pigments (chlorophyll, carotenoides, xanthophylls and biliproteins) involved in photosynthesis, only chlorophyll *a* is common to all photosynthetic organisms. Therefore, chlorophyll *a* is recognized as the main pigment and all other pigments are treated as accessory pigments. Measurement of chlorophyll *a* is one of the most widely used techniques for the estimation of standing crop of planktonic micro algae, since this photosynthetic pigment is present in all algae. Seasonal dynamics of chlorophyll *a* accompanied by microscopic examination of live/ fixed materials were used to estimate the phytoplankton assemblages in estuarine waters (Ansotegui *et al*., 2001). The determination of phytoplankton biomass can be investigated in many ways, one of which is to measure chlorophyll *a* that is the fastest chemical measuring method (Vonshak, 1986). Chlorophyll *a* is a well accepted index for phytoplankton abundance and population of primary producers in an aquatic environment (Jeffrey, 1961 and 1968; Jeffrey *et al*., 1997; Camdevy'ren *et al*., 2005). Estimation of chlorophyll *a* is now widely accepted method for the monitoring of Harmful Algal Blooms (Sakshaug, 1989; Guzman *et al*., 2004; Wei *et al*., 2008; Anderson, 2009). Even under conditions in which the HAB species would not have a "visible discolouration", the monitoring of chlorophyll *a* is useful. During this study, estimation of chlorophyll *a* is used as the index of HABs along southwest coast of India.

In the present study five algal blooms were recorded in the study area and all were observed during southwest monsoon period. During monsoon of 2006 three algal blooms were observed. These multi species blooms were dominated by *Thalassiosira partheneia* and *Noctiluca scintillans* (off Alapuzha), *Thalassiosira mala* (off Kochi) and *Coscinodiscus asteromphalus* var. *centralis* (off Calicut). During the monsoon period of 2007 two algal blooms were observed one a multi species bloom, dominated by *Thalassiosira partheneia*, *Noctiluca scintillans* and *Ceratium* spp. (off Alapuzha) and the other *Thalassiosira partheneia* (off Kochi). Along the west coast of India, Subrahmanyan (1958) described a bimodal oscillation in standing crop, with a primary maxima occurring during southwest monsoon period in June-July and a secondary maxima during the northeast monsoon months between December-April. However, Subrahmanyan noticed slight variation in the intensity of the bloom and the time of occurrence. Devassy and Bhattathiri (1974) observed maximum density of diatoms in the postmonsoon months, dinoflagellates in premonsoon months and other algae during the monsoon months in the Cochin backwaters. They observed bloom of diatoms, *Nitzschia sigma* in May (1.4x $10^6$ cells $L^{-1}$) *S. costatum* in November and December (4x $10^5$ and 5x $10^5$ cells $L^{-1}$). Dinoflagellate *C. furca* with cell density of 1.2x $10^5$ cells $L^{-1}$ occurred in March and *Peridinium* with cell density of 5.9x $10^4$ cells $L^{-1}$ in April. Gowda *et al* (2001) recorded phytoplankton blooms along the Mangalore coast in pre and postmonsoon months. Bloom of the diatom *Cerataulina berganii* appeared in December and April, *Chaetoceros curvisetus* occurred in December. The density of dinoflagellates were comparatively less, although high density of *C. fusus* (1140 cells $m^{-3}$) occurred during January and highest density of *Ceratium furca* (3327 cells $m^{-3}$) occurred in March. Selvaraj *et al* (2003) recorded peaks of phytoplankton production in the surf zone and back waters of Cochin during August to January due to occasional blooming of certain species of diatoms. They observed blooming of *P. normanii* in August with cell density of 8.5x $10^4$ cells $L^{-1}$, *Nitzschia* sp. in September with cell density of 7170 cells $L^{-1}$, *Synedra* sp with cell density of 2.6x $10^4$ cells $L^{-1}$ in October, *Thalassionema* in October (3.1x$10^4$ cells $L^{-1}$) and *Thalassiosira* sp. with cell density of 5.7x$10^4$ cells $L^{-1}$ in December. Jugnu and Kripa (2008) recorded seventeen algal blooms along the Kerala coast during the period 2001- 2003, of these 13 blooms were by diatom species (*Coscinodiscus, Thalassiothrix, Thalassionema, Pleurosigma, Chaetoceros and Fragilaria*).

Nutrients, temperature and salinity have been identified as the major triggering factors for the seasonal blooms in coastal waters of India (Qasim *et al.,* 1972; Gopinathan, 1974; Mathew *et al.,* 1988). Diatoms require the major nutrients like nitrate, phosphate and silicate for their photosynthesis. Near shore waters of the west coast of India is generally, enriched with sufficient quantities of nutrients through out the year, which indicated that the nutrients alone never acted as limiting factors for phytoplankton productivity in these region. It is probable that intermittent rain during the premonsoon months results in reducing the salinity of surface waters along with abrupt changes in surface temperature. These factors might act as a triggering mechanism to induce blooming of certain species of phytoplankton which prefer such conditions in the presence of sufficient nutrients for their sporadic growth and blooming in coastal waters (Selvaraj *et al*., 2003). Southwest coast of India is one of the major upwelling systems of the world (Bakun *et al.,* 1998). It was established that upwelling takes place along this coast during the summer monsoon months from May to September and the ensuing productivity sustains a fishery for a number of commercially important fishes. According to Bhattathiri *et al* (1996), highest chlorophyll a was observed during summer monsoon near the coastal waters off Mangalore. This was due to the upwelling contributing to high nitrate levels in the surface layers which in turn supported high phytoplankton production.

For the better understanding of algal blooms observed during the present investigation, each bloom is discussed separately. Algal blooms were not observed at station 1 (off Kollam) during the study period. The coastal and near shore waters of the west coast of India are enriched by heavy rainfall and land runoff from June to September every year (Bhargava *et al.*, 1978). Among nitrate and phosphate, phosphate controls the quantity of plant biomass in the estuarine/ coastal waters (Lukatelich and McComb, 1986). They have noted in many occasions that no bloom resulted when there was an abundant supply of nitrate. Even if nitrate concentration was high during the monsoon period of 2007 at station 1 no bloom occurred in this region. It is likely that low phosphate content coupled with drop in salinity and heavy loads of suspended solids resulted in reduced photosynthesis during the period.

During monsoon of 2006 at station 2 (off Alapuzha) a “super bloom” with high surface chlorophyll *a* concentration (225.26 mg $m^{-3}$) was observed with a phytoplankton cell density of 4x $10^6$ cells $L^{-1}$. The bloom was dominated by small centric diatom *Thalassiosira partheneia* with a cell density of 3932710 cells $L^{-1}$ and dinoflagellate *Noctiluca scintillans* (= *N. miliaris*) with a cell density of 73583 cells $L^{-1}$. According to Sakshaug (1989) phytoplankton blooms with chlorophyll *a* concentration exceeding 100 μg $L^{-1}$ are termed as super blooms. Such blooms have been recorded in the Weddell Sea on a number of occasions. Smetacek *et al* (1992) examined a super bloom of centric diatoms (*Thalassiosira antarctica*, *Podosira pseudodenticulata* and *Stellarima microtrias*) associated with ice platelets in the pack ice. In Dabob Bay (Washington), blooms of phytoplankton dominated by diatoms, occurred in late winter-early spring period with depth integrated chlorophyll levels ranging from 20 to 230 mg $m^{-2}$. The species which formed the bloom included *Thalassiosira spp*., *Skeletonema sp*., and *Chaetoceros spp*. (Horner *et al*., 2005). The maximum chlorophyll concentration recorded in this bloom was 220 μg $L^{-1}$. The *Noctiluca* cells observed during the bloom along southwest coast was without the endosymbiont (*Pedinomonas noctilucae*) and hence are red *Noctiluca*. The *Noctiluca* blooms which occur regularly in the Northern Arabian Sea during the winter cooling are green in colour due to the presence of the endosymbiont *Pedinomonas noctilucae* (Dwivedi *et al*., 2006; Padmakumar *et al*., 2007; Gomes *et al*., 2008). *Noctiluca* cells are large (300-1000 μm diameter) with 3-6 food vacuoles and *T. partheneia* was the dominant food item found within the food vacuoles of *Noctiluca* cells. A high proportion (>80%) of *Noctiluca* cells contained food particles in their vacuoles, suggesting that the increase in abundance of *Noctiluca* was most likely stimulated by enhanced availability of food. This is an interesting trophic feature where a heterotroph becomes a mixotroph. Occurrence of small-sized *Noctiluca* cells in the bloom was indicative of high population growth. This type of *Noctiluca* aggregation during diatom bloom was reported by Dela-Cruz *et al* (2002) along the southeast coast of Australia. According to Nair *et al* (1984), bloom of *Noctiluca miliaris was* observed at the time of dissipation of the mud-bank along the west coast of India. During this bloom diatoms constitute 98.12% and dinoflagellates 1.88%. Numerous researchers have reported diatoms from Arabian Sea, Bay of Bengal, Indian Ocean, west and east coast of Indian EEZ (Subrahmanyan, 1946; Subrahmanyan and Sharma, 1960; Gopinathan, 1975a; 1975b and 1984: Desikachary *et al*., 1986; 1987; 1987a; Desikachary, 1988; Sanilkumar, 2009). Curiously enough there are no previous reports on the occurrence of *Thalassiosira partheneia* from the Indian waters. The present is the first one related to the occurrence of *T. partheneia* and its bloom formation in the Arabian Sea (Lat. 09°25.23 N, Long. 76°19.41 E).

The station 2 is located in a mud bank area near Punnapara (off Alapuzha) and the phytoplankton productivity of the area, is likely influenced by the unique physico-chemical environment of an active mud bank region. Southwest monsoon season is the period when mud-banks are formed at some places along the southwest coast of India notably the coast of Kerala. This is a unique feature observed only in this region and has not been reported so far from any other place in the world. The source of mud for the Alapuzha mud-bank is the subterranean mud and the mud received from Vembanad lake system. (Damodaran, 1973; Rao *et al.,* 1980; Mathew *et al.,* 1981; Gopinathan *et al.,* 1984). Mud-banks are maintained by the southwest monsoon with its westerly winds. These winds have more northerly components which cause the monsoon swells in the inshore region. The waves produced by this wind action provide a constant thrust preventing the mud from dispensing into the open sea. The monsoon swell also provides a continuous source of energy to keep the mud in suspension. The temperature (28°C) and salinity (33 psu) in the mud bank region were lower in comparison to other seasons. The dissolved oxygen is lower during the monsoon season, lowest during the postmonsoon and the summer in the mud-bank region. The surface nutrient concentration of the bloom area off Alapuzha was high with the nitrate concentration of 3.29 µmol $L^{-1}$, the phosphate of 0.303 µmol $L^{-1}$ and silicate 26.34 µmol $L^{-1}$. These cooler waters being rich in nutrient content seem to favour higher rates of primary production (Rao *et al.,* 1984; 1992).

During the monsoon of 2007 a high chlorophyll *a* concentration (127.61 mg $m^{-3}$) was observed at station 2 (off Alapuzha) due to a multispecies bloom dominated by the diatom *Thalassiosira partheneia* (1675490 cells $L^{-1}$). The next dominant species belonged the dinoflagellate genus *Ceratium* (42155 cells $L^{-1}$), followed by *Noctiluca scintillans* (7356 cells $L^{-1}$). The physico-chemical parameters of the area followed a pattern very similar to that recorded during the monsoon season of previous year. Among the species of *Ceratium* the harmful species *C. furca* recorded with a cell density of 8900 cells $L^{-1}$. *Ceratium* species are generally considered non-toxic and unpalatable. Although the toxicity of *Ceratium* has not been demonstrated, fish mortality was observed in association with *Ceratium* blooms in Thailand and Japan and the causative factor has been attributed to oxygen depletion (Taylor *et al*., 1995). *Ceratium* blooms caused mass death of *Ostrea lurida* (Pacific oyster) larvae in Mexico (Landsberg, 2002), along with mortality among other invertebrates (Hallegraeff *et al*., 1995). According to Franks *et al* (1989) in Gulf of Maine, *Ceratium longipes* bloom was observed during upwelling period with cell density reaching 5000 cells $L^{-1}$.

Station 3 near Azheekod (off Kochi) *Thalassiosira mala* blooms with surface chlorophyll *a* concentration of 66.18 mg $m^{-3}$ were observed during the southwest monsoon season of 2006. The cell density in the bloom area was 6.7x $10^6$ cells $L^{-1}$. The cells were connected with mucilage threads and embedded in gelatinous formless masses. *Thalassiosira mala* is one of the first or probably the first marine planktonic diatom to be reported harmful to shellfish. A bloom of this species discoloring the water of Tokyo Bay in September 1951 was considered responsible for the heavy financial loss by the death of the cultured bivalve mollusks (Takano, 1956 and 1965). Takano remarked that mechanical damage of gills caused by gelatinous substances exuding from the diatoms prevented respiration of bivalves (Takano, 1956 p. 65). This along with poor water quality was regarded responsible for the death of the bivalves. Detection of the bloom of *Thalassiosira mala* off Kochi (Lat. 10°11.02 N, Long. 76°09.22 E) was the first report from the Indian waters. The concentration of the bloom was similar to that described by Takano (1965). The cellular mass had marginal strutted processes with four satellite pores and a subcentral one with three satellite pores. Selvaraj (2003) observed *Thalassiosira* sp. bloom from the surface waters and backwaters of Cochin in December with a cell density of 57000 cells $L^{-1}$. The percentage composition of diatoms in the bloom area was 99.99% and the dinoflagellates were very few in numbers. The dinoflagellates present were *Ceratium furca*, *Dinophysis accuminata* and *Protoperidinium leonis*. The diatoms other than *T. mala* observed along with the bloom were *Amphora alata*, *A. gigantia* var. *sulcata*, *Chaetoceros affinis*, *Ditylum sol*, *Eucampia zodiacus*, *Nitzschia sigma* and *Surirella striatula*.

Primary production and standing crop of phytoplankton of the west coast of India have been studied by Subrahmanyan (1959) and Nair *et al* (1968). Radhakrishna (1969) examined these in Alleppey coastal waters. Shah (1973) has studied the chlorophyll *a* from inshore waters of Cochin. Chennubhotla (1969) and Subrahmanyan *et al* (1967) have studied the biomass and the total cells of phytoplankton of the west coast of India. Gopinathan *et al* (1974) investigated the phytoplankton standing crop in the inshore areas of Cochin. All these investigations revealed that all along the west coast of India phytoplankton production is at its highest during the southwest monsoon.

The station 3 which is situated off Kochi was influenced by coastal upwelling during the southwest monsoon and also by the estuarine discharge from Cochin estuary through Azheekode and Kochi bar mouths. The surface nutrient concentration of the bloom area was nitrate (8.3 µmol $L^{-1}$), phosphate (3.205 µmol $L^{-1}$) and silicate (55.7 µmol $L^{-1}$). The nutrient values were higher than that of other seasons. Goebel *et al* (2005) explains that high fresh water influx and storms promote diatom blooms during spring, summer and autumn in Doubtful sound, New Zealand. Diatom blooms form when mixing of the surface low salinity layer (LSL- high in silicic acid and low in nitrate and phosphate) and the underlying saline layer (SL- low in silicic acid but relatively high in nitrate and phosphate) reduce nutrient limitations in the thin photic zone of the fjord. According to Sasamal *et al* (2005) in northwestern Bay of Bengal, the diatom blooms mostly take place in shallow coastal waters during the spring season. The source of nutrient can either be terrestrial effluents or the upwelling of subsurface water along the coast. The species diversity index (Shannon- Weiner index 0.0006) and species richness (Margalef species richness 0.954) was lower in the bloom area.

High nutrient inputs to the photic zone during upwelling coincide with high diatom biomass. Flagellates dominate under low phosphate and silicate along with high ammonium concentrations during stratification (Legendre, 1990). Diatom production contributes to the transfer of nitrogen from allochthonous nitrate to pools of both ammonium and dissolved organic nitrogen (Alvarez-Salgado *et al*., 1996). Small diatoms such as *Skeletonema* and *Thalassiosira* have high standing stock, growth rates and productivity and are typically associated with turbulent upwelled water. Medium-sized diatoms such as those of the genera *Cerataulina*, *Chaetoceros, Lauderia, Coscinodiscus* and *Thalassionema* have a lower productivity and growth rate and often succeed the smaller diatoms (Margalef, 1958). *Thalassiosira* spp., *Skeletonema costatum* and *Chaetoceros* spp. are common in spring blooms in coastal upwelling regions world wide. These genera often dominate the diatom assemblage in upwelling zones, and blooms coincide with high primary production found in some estuarine ecosystems affected by upwelling (Tilstone *et al*., 1999). Physical processes have a greater influence on the *Thalassiosira* spp. biomass than biogeochemical processes during upwelling, which cause a net export of this diatom assemblage towards the shelf. The dominance of *Thalassiosira* biomass in the water column during upwelling is associated with high nutrient concentrations. These diatoms have a strong dependency on $SiO_4$ (Tilstone *et al*., 2000).

During southwest monsoon of 2007, at station 3 (off Kochi) a high chlorophyll *a* concentration was observed due to an increase in the cell density of diatoms, mainly *Thalassiosira partheneia* (182100 cells $L^{-1}$). The total cell density of the bloom was 182940 cells $L^{-1}$. Nutrient concentration was high (Nitrate 24. 746 µmol $L^{-1}$, Silicate 243.6 µmol $L^{-1}$). But the phosphate concentration was low (0.264 µmol $L^{-1}$) compared to other seasons. Temperature and salinity were low 28°C and 27 psu respectively.

A “super bloom” of *Coscinodiscus asteromphalus* var. *centralis* with a very high value of chlorophyll *a*, 206.5 mg $m^{-3}$ was observed off Calicut during monsoon of 2006 (Padmakumar *et al.*, 2007). The cell density of the bloom was 7x $10^6$ cells $L^{-1}$ and the dinoflagellates were completely absent in the bloom area. The large centric diatom *Coscinodiscus* sp. has been recorded worldwide, capable of developing blooms and damaging shellfish and macroalgae cultivations, and damaging commercial fishery areas (Nagai *et al.*, 1995; Nehring, 1998). In the west coast of India, Bhimachar and George (1950) observed an abrupt set back in the fisheries of Malabar and Kanara coast due to red water phenomenon which in turn was caused by *Noctiluca* and *Coscinodiscus*. Thangaraja *et al* (2007) reported massive fish kills associated with diatom bloom dominated by *Coscinodiscus* spp. from the Oman waters and the reason for the fish kill was found to be oxygen depletion. Mathew *et al* (1988) reported blooms of *Coscinodiscus* sp. from northern parts of southwest coast of India mainly from Karwar to Mangalore, normally during November- March. During the present investigation *Coscinodiscus* bloom was recorded during the peak summer monsoon period. Jugnu and Kripa (2006) recorded *Coscinodiscus asteromphalus* bloom from the Kerala coast during southwest monsoon 2002, when high nutrients, low temperatures and salinity and high irradiance occur. The cell densities were the highest when the temperature was lowest. Dissolved inorganic nitrogen is the most important nutrient for the development of micro algal blooms. The nitrate concentration (3.185 µmol $L^{-1}$) was high during the bloom and seems to trigger the bloom of this species when low temperatures (28°C) and salinity (34psu) prevail. Other nutrients like phosphate (2.815 µmol $L^{-1}$) and silicate (42.27 µmol $L^{-1}$) were also high during the *Coscinodiscus* bloom. Silicate, utilized for the formation of siliceous frustules of diatoms, constitutes one of the most important nutrients regulating the phytoplankton growth and proliferation leading to bloom (Kristiansen and Hoell, 2002). Larger phytoplankton species with high nutrient requirements respond faster to favourable environmental conditions and dominate the phytoplankton population and forms the bloom (Azov, 1986). Primary production in the Arabian Sea is believed to be controlled primarily by the availability of macronutrients, especially nitrate (Sen Gupta and Naqvi, 1984; Naqvi *et al.,* 2003). Extensive enrichment of the euphotic zone with macronutrients occurs seasonally, particularly during the summer or southwest monsoon, both along the western and eastern boundaries of the Arabian Sea, off Somalia (Smith and Codispoti, 1980), Arabia (Morrison *et al.,* 1998; Woodward *et al.,* 1999) and western India (Jayakumar *et al.,* 2001; Naqvi *et al.,* 2003). Gelatinous secretion during the bloom of the diatom *Coscinodiscus* sp. in North Sea negatively affected the commercial fishery of the region (Boalch, 1984).

West coast of India is known for its higher productivity, due to the frequent upwelling process, particularly in the southern region. A strong upwelling is regularly observed here during summer (Prasannakumar *et al.,* 2000) and the whole of southwest monsoon season, largely restricted to the shelf (Banse, 1959). Upwelling is an important process in the redistribution of nutrients in the oceanic regime. It causes profound increase in productivity of a region by increasing nutrient content in the euphotic zone. In the process, the cooler nutrient-rich waters from beneath are drawn upwards when strong winds push the warm surface waters away from shore. The plant life, particularly plankton, thrives here and not surprisingly such areas are associated with active fishery (Madhupratap *et al.,* 2001) and also regular occurrence of algal blooms. Many reasons have been proposed for this faster response and bloom of diatoms under the high nutrient and high light conditions which occur during this period. Diatoms divide faster and reach higher cell densities because of their inherently high growth rates (Smayda, 1997), accelerated nitrogen assimilation under nutrient rich conditions (Dugdale and Wilkerson, 1992), higher growth efficiency at low light (Goldman and Mc-Gilcuddy, 2003). According to Smetacek (1995), the silica cell wall of the diatoms resists attack by small predatory flagellates or pathogens and grazing by copepods (Hamm *et al.,* 2003).

Micro algae which are capable of producing toxic algal blooms were recorded during the present study period from the southwest coast of India. Their occurrence and percentage contribution to total phytoplankton community was different. Besides these, toxic species of micro algae like *Alexandrium sp*., *Pseudonitzschia sp*., *Prorocentrum spp*. and *Dinophysis spp*. were also recorded from the southwest coast. All these species are capable of producing toxins at very low densities (100 to 1000 cells $L^{-1}$). *Psuedonitzschia sp*. is known to produce domoic acid (DA), a potent neurotoxin that can be devastating to aquatic life via trophic transfer in the food web (Fritz *et al*., 1992; Bates *et al*., 1998; Scholin *et al*., 2000). In humans, DA exposure manifests itself as amnesic shellfish poisoning (ASP) following the consumption of contaminated filter-feeding mollusks (Bates *et al*., 1989; Trainer *et al*., 2007). Toxin production in *Pseudonitzschia* species has been found to show regional variations. Thus the same *Pseudonitzschia* species may be toxic in one part of the world but not in the other (Bates *et al., 1998*). During this study *Pseudonitzschia sp*. was observed during postmonsoon of 2008 from station 4 (off Calicut), which is a famous shellfish harvesting ground along the west coast of India. The occurrence of toxigenic *Pseudonitzschia* species along our coasts is of concern, as it is possible that *Pseudonitzschia* spp. in the diet can result in the accumulation of domoic acid in the wild and cultured population of bivalve molluscs of the Calicut coast.

Among the toxic species observed, Diarrhoeic Shellfish Poisoning (DSP) producing genera *Dinophysis spp*. was recorded in almost all seasons from the study area. High cell density (285 cells $L^{-1}$) of *Dinophysis accuminata* was observed during the monsoon of 2007 in station 2 (off Alapuzha). DSP was first identified in Japan in 1976 (Yasumoto *et al*., 1978). The DSP toxins are okadoic acid and derivatives of polyether lactones (WHO, 1984). Recurrent bloom of *Dinophysis* sp. in French coast was reported by Lassus *et al* (1991), according to him *Dinophysis* development occurs in relatively warm and low saline surface waters with high nitrate concentration.

Toxic dinoflagellate *Alexandrium* sp. was observed during the monsoon of 2007 at station 3 (off Kochi). *Alexandrium* is capable of producing Paralytic Shellfish Poisoning (PSP). PSP is caused by one or more of about 18 different toxins which include saxitoxins, neosaxitoxins and gonyautoxins (Fremy, 1991). In many parts of the world, PSP is a recurrent and serious problem associated with blooms of toxic dinoflagellates of the genus *Alexandrium*. The potent neurotoxins produced by these organisms are accumulated by filter-feeding shellfish and other grazers and are passed on to humans and other animals at higher trophic levels, leading to illness, incapacitation, and even death. *Alexandrium* causes toxicity in many different hydrographic and climatic regimes, from temperate to tropical regions (Cembella *et al.*, 1988; La Barbera-Sanchez *et al.*, 1993).

Ciguatera poisoning has been known for centuries in subtropical and tropical areas (Richardson, 1997). Ciguatera is mainly caused by benthic dinoflagellates such as *Coolia monotis* and *Prorocentrum lima* (Hallegraeff, 1993). During the present study these dinoflagellates were recorded during the postmonsoon seasons from the southwest coast. *Prorocentrum lima* with cell density 100 cells $L^{-1}$ during postmonsoon of 2007 from the station 2 (off Alapuzha) and *Coolia monotis* from station 3 (off Kochi) during monsoon of 2008 were recorded.

Algal blooms in the study area shows seasonal occurrence, especially during the southwest monsoon period. Only diatom blooms were observed during this study period. Potentially toxic micro algae have been recognized during the study period. It is necessary to accurately identify and establish the early monitoring programmes of these species in order to undertake damage control. Studies on the effects of these blooms in seafood quality, economic liabilities on fisherfolks, correct assessment of factors triggering blooms and subsequent effects in the trophodynamics are being planned as future action.

# Chapter 4

# Standing crop of Zooplankton during Algal Blooms

## 4.1 Introduction and review of literature

Zooplankton are planktonic animals, typically between 20 and 2000µm in length, that spend most of their life cycle in the water column (Dussart, 1965; Sieburth *et al.*, 1978). Ecologically and collectively, zooplankton form the largest group of animals and their total production in the sea, as we know today, is only next to phytoplankton. Zooplankton provides a range of ecological functions, being consumers of primary production and both direct and indirect sources of energy for other organisms. Zooplankton form a major link in the energy transfer at secondary level in the aquatic biosphere and their ecology is of considerable interest in assessing the production potential of the area. A congregation of organisms represented by numerous groups, mostly of invertebrates, constitutes zooplankton community. They include carnivorous forms such as chaetognaths, hydromedusae, siphonophores and ctenophores, herbivores like many of the copepods, salps, doliolids and appendicularians and still many are omnivorous or detrivorous thus constituting an efficient group in the utilization of the biotope and energy transfer from primary level to secondary level. In accordance with the pyramidal concept in any balanced community, the herbivores dominate in terms of biomass and hence it is natural that the richest areas of zooplankton production are associated with areas of upwelling or its fringes where primary production is very high.

Zooplankton are important to the pelagic ecosystems in the Arabian sea (Baars and Oosterhuis, 1997; Smith *et al.*, 1998; Roman *et al.*, 2000). The zooplankton biomass studies are important for gaining an insight into the fish production of the oceans (Lenz, 1973; Santhakumari and Saraswathy, 1981). Zooplankton communities support higher trophic levels and are an important determinant on the potential size of a fishery (Tarling *et al.*, 1995). The knowledge of their abundance and distribution in space and time is essential to understand the carbon cycling and community dynamics in the oceans. The spatial distribution of zooplankton results from a combination of physical processes and biological processes such as diel vertical migration and predation (Mackas *et al.*, 1985).

Trophodynamics as well as physical interaction between harmful/ toxic phytoplankton and their zooplankton grazers are important but are poorly understood aspects of the ecology of harmful algal blooms. The importance of grazing becomes most apparent by its failure; if community grazing controls initial stages of toxic bloom development, there are no blooms, and the importance of grazing goes unnoticed. However, reduced grazing pressure may occur if toxicity makes bloom species unpalatable to grazers. Conversely, if grazers ingest toxic phytoplankton with impunity, and sequester phycotoxins, then vectorial intoxication of consumers beyond the grazer level in food webs can occur (White, 1981).Toxicity is often defined by effects on upper trophic level vertebrate carnivores that are not direct grazers of phytoplankton, including humans, birds or marine mammals (Anderson and White, 1992). The role of zooplankton community grazing in development and persistence of natural blooms is variable, and outcomes are situation specific. Turner and Anderson (1983) found that community grazing by copepods and polychaete larvae appeared incapable of preventing initiation of blooms of *Alexandrium tamarense* during the early spring in Cape Cod embayment. This was due to a combination of low grazing rates of individual grazers and low abundance of grazers. Graneli *et al* (1993) explained mesocosm experiments which examine phytoplankton growth under different regimes of nutrient addition and zooplankton grazing. Further, zooplankton monitoring should be incorporated into phytoplankton monitoring programs focused on harmful algal blooms. In very few cases where ongoing phytoplankton and zooplankton monitoring preceded development of a harmful bloom (Falkowski *et a*l., 1980; Buskey and Stockwell, 1993), zooplankton dynamics appear to be important components of toxic phytoplankton dynamics.

The Arabian Sea zooplankton is influenced by the biannual reversal of the monsoon wind system which results in a pronounced seasonality and forms spatial patterns in primary production (Owens *et al*., 1993) and zooplankton biomass. During both, southwest and northeast monsoon, the zooplankton biomass in the epipelagic zone increases compared to the relatively calm intermonsoon periods (Koppelmann *et al*., 2003).

Zooplankton studies in the Arabian Sea started with International Indian Ocean Expedition (1960-65) leading to the publication of atlases and papers (IOBC, 1968a, b; Prasad 1968; Wyrtiki, 1971; Krey and Babenard, 1976). After that there have been a number of publications on zooplankton standing crop and related ecology from the Indian EEZ.

George (1953) studied the marine plankton of the coastal waters of Calicut with observations on the hydrological conditions. Neritic and inshore waters of west coast are highly productive zones with rich and abundant planktonic life. These regions are influenced by the seasonal variation on account of the prevailing southwest and northeast monsoons. Off the southwest coast of India, fresh water influx from the rivers and estuaries lowers the salinity during the southwest monsoon period. Arabian Sea areas are major zones of upwelling (Currie *et al*., 1973) and this area sustain maximum abundance of zooplankton in the Indian Ocean (Prasad, 1968; Rao, 1973). According to Peter (1978) the coastal region of the southwest coast of India is one of the very rich areas of zooplankton production in the Arabian Sea. The standing stock of zooplankton was relatively high in the outer neritic zone with the highest volume in the area off Cochin and Alleppey (Purushan *et al*., 1974). Srinivasan (1974) reported distribution of chaetognaths as an indicator of upwelling along the west coast of India. Some species of chaetognaths, such as *Sagitta pacifica*, *S. hispida*, *S. regularis* and *S. draco* shows a rhythmical movement from one season to another season. These species are widely distributed both in the continental shelf and adjacent oceanic waters, during the pre monsoon and post monsoon, whereas during the southwest monsoon period, they are sparsely distributed or absent, particularly in the shelf waters. This may probably due to the reason that these species move towards the deep oceanic waters, during the monsoon period and come back to the shelf waters after the monsoon.

Menon and George (1977) reported low values of zooplankton biomass (displacement volume ml/m$^3$) from the shelf waters from January to April; afterwards there was an increase which reached a peak some time during July- September period. Among the zooplanktonic organisms, copepods formed the major component and occurred through out the area and all through the year. Zooplankton abundance increased towards the northern west coast during November and December period with higher density of copepods, chaetognaths and fish larvae (Vijayalakshmi *et al*., 1978).

Along the inshore waters of Vizhinjam, copepods formed the major component of the zooplankton community for the greater part of the year. The other dominant groups were decapod larvae, cladocerans and chaetognaths. During certain months copepods were outnumbered by cladocerans, which swarmed during monsoon months only. Decapod larvae, appendicularians, fish eggs, fish larvae and *Lucifer* exhibited a sharp decline during south-west monsoon period (Jacob *et al*., 1981). Qualitative and seasonal abundance of siphonophores along the southwest coast of India and the Laccadive Sea was studied by Rengarajan (1983), according to him surface current and upwelling play an important role in the occurrence, abundance and fluctuations of siphonophores in the area.

Mathew (1986) described influence of phytoplankton on the abundance of zooplankton, and the relationship between zooplankton and euphausiids in the continental shelf waters of southwest coast of India and he confirms the positive relationship between phytoplankton and zooplankton. Seasonal distribution of cyclopoid copepods of the mud banks off Alleppey was studied by Thompson (1986). Thirty two species of cyclopoid copepods were identified and two peaks were observed for adults as well as copepodites during the study period and this coincides with the rise in temperature and salinity. Silas and Mathew (1986) explained the spatial distribution of euphausiacea in the southeastern Arabian Sea. A number of reports are available on the zooplankton ecology of Lakshadweep archipelago (Achuthankutty *et al.,* 1989; Suresh and Mathew, 1997; Nasser *et al.,* 1998).

According to Ramamurthy (1965) a remarkable uniformity in the seasonal fluctuations of zooplankton as well as its main constituents was observed in coastal waters. The zooplankton exhibited a bimodal curve with peaks during occurring during March- May and August- November. The main peak of zooplankton production occurred during the latter half of the southwest monsoon and early northeast monsoon seasons. It has been observed that the zooplankton production is closely related to diatom production. The zooplankton increase in number and attains the peak during August- November closely following the period of peak. The relationship between zooplankton and diatoms in this coast may thus be described as direct in the initial stages which reverses subsequently. The rise in zooplankton coincides with a marked depletion in the diatom population brought about obviously by the intense grazing of the herbivores. Copepods are the important grazers of phytoplankton and microzooplankton and thus they form a major trophic link to many predatory invertebrates and fish (Atkinson, 1996). They are found distributed extensively in the water medium and sometimes account for 80 to 90% of the total zooplankton population. Most fish and prawn species depend on copepods at early stages of their life cycle and some even feed exclusively on copepods.

Zooplankton are a major link in the marine food chain and their dynamics in the upwelling areas have received considerable attention. Upwelling leads to increase in nutrients and phytoplankton stocks along coastal waters of central west coast of India. In response to this, zooplankton biomass increases and peaks along the central part of the west coast of India. A few (opportunistic) species such as *Sagitta inflata*, *Centropagus tenuiremis*, *Temora* sp., *Clausocalanus arcuicornis*, *Subeucalanus* spp., *Paracalanus* spp., *Acrocalanus* spp., *Corycaeus* spp. are found to be responsible for the zooplankton abundance. This resulted in a low diversity community. Increase in abundance of both herbivores and carnivores suggested that sequential community development had occurred, subsequent to the start of upwelling (Madhupratap *et al.*, 1990).

Madhupratap *et al* (1992) studied the zooplankton standing stock during early southwest and northeast monsoon period. According to them the southwest and early northeast monsoon seasons favour high biological productivity along the west coast of India. Apart from upwelling, inputs from fresh water run-off appears to be an important mechanism leading to this in coastal waters. Nair *et al* (1999) explained the Arabian Sea paradox by way of maintaining high microzooplankton biomass in the mixed layer between productive and less productive seasons. The smaller herbivores appear to be facultative and are able to feed on either phytoplankton or microzooplankton. There is considerable evidence that the herbivorous mesozooplankton (including larger forms like tunicates) feed on very small particles including bacteria. Thus during winter as well as during southwest monsoon period the major grazing by zooplankton would be on phytoplankton. Antony *et al* (1997) described the zooplankton abundance and secondary production in the seas around Andaman-Nicobar Islands and higher zooplankton standing stock were encountered in northeastern and southern regions. Northeast monsoon (Oct-January) was the most productive season in the Andaman Sea. Zooplankton population occurred in high abundance when surface waters were characterized by low temperature and salinity. Southwest monsoon (June- September) was the least productive season. There have been many previous reports on composition and seasonal distribution of zooplankton especially copepods, euphausiids etc. from the Indian waters (Vijayalakshmi, 1980; Haridas and Rao, 1981; Raj and Ramamirtham, 1981; Goswami, 1985; Silas and Mathew, 1986; Sarkar *et al.*, 1986; Lalithambika *et al.*, 1992; Madhupratap *et al.*, 1992; Padmavathi and Goswami, 1996; Sujata Mishra and Panigrahy, 1996; Ramaiah and Nair, 1997; Madhupratap, 1999; Santhanam and Perumal, 2003; Moly Varghese and Krishnan, 2009; Robin *et al.*, 2009; Jagdeesan *et al.*, 2010).

According to Subrahmanyan (1959b) the magnitude of standing crop of phytoplankton is also affected by zooplankton and nekton organisms present in the water which graze on the plant crop and are dependent on it for their existence. During southwest monsoon season, the standing crop of phytoplankton is at its peak and though the grazers, zooplankton, also are on the increase and even attain a peak in numbers during the same season, the rate of production of phytoplankton appears to be so high as to maintain a high bulk in the water and exceed that of the animal population. During the following season, the standing crop is of a lower magnitude. During this season, herbivores in the form of copepods and other zooplankters also occur in abundance as also plankton feeding fishes so much so the crop appears to be heavily grazed down. It is also possible that the rate of production of phytoplankton also decreases for reasons indicated earlier thus leading to lower order in the magnitude of the crop as compared with the earlier period.

Toxins associated with marine phytoplankton can enter pelagic food webs through ingestion by phytoplanktivorous zooplankton or fish, with these organisms serving as vectors for toxin transfer to higher trophic levels. Such vector-mediated exposures of species that are not direct consumers of toxic phytoplankton have resulted in unusual mortality events involving fish, seabirds, and marine mammals. Herring kill in the Bay of Fundy was caused by *Gonyaulax excavate* toxins (White, 1977) the toxins were transmitted by pteropods after feeding on the dinoflagellate. Adams *et al* (1968) had suggested that planktonic herbivores acted as intermediaries in a kill of sand lace following a *G. tamarensis* bloom off the northeast coast of United Kingdom. White (1979) found that the toxins of *G. excavate* were measurable in zooplankton samples during a bloom in the Bay of Fundy. These samples contained tintinnids, cladocerans and copepods, suggesting that a variety of planktonic herbivores can act as vectors of the toxins. A dense subsurface layer of *Gymnodinium splendens*, a feature often observed in coastal waters off southern California was actively avoided by macro zooplankton (Fiedler, 1982). Grazing zooplankton are potential vectors of phyto-toxins in the pelagic food web (Turner and Tester, 1997; Turner *et al.*, 1998). Zooplankton might thus transmit toxins to their predators. Mass mortalities of pelagic fishes such as herring and mackerel (White, 1980 and 1981; Beaulieu *et al.*, 1996, Montoya *et al.*, 1996, Castonguay *et al.*, 1997) and marine mammals (Geraci *et al.*, 1991, Landsberg & Steidinger, 1998) exposed to toxic dinoflagellate or diatom blooms, and accumulation of PSP toxins in anchovies (Montoya *et al.*, 1998), have been reported. In all these cases, zooplankton presumably acted as a link between toxic phytoplankton and higher trophic levels.

Field studies have shown that some tintinnids, especially *Favella* spp., are often found associated with high *Dinophysis* spp. densities (Santhanam and Srinivasan, 1996, Maneiro *et al*., 1998). Experiments show *Favella* spp. can graze on PSP toxins producing dinoflagellates (Stoecker *et al*., 1981, Hansen, 1989). Results from this study seem to confirm that tintinnids can also ingest dinoflagellates that produce DSP. Moreover, the population density of *Favella serrata* increased considerably after the *Dinophysis* bloom, and a reduction was observed when the density of *Dinophysis* spp. declined. Using chemical defences or poisonous substances to dampen herbivorous feeding by the blooming species, lead to starvation and death of the consumer populations, with a cascading effect on the trophic pathway (Carlsson *et al*., 1990; Graneli *et al*., 1993). According to Delgado and Alcaraz (1999) in Alfacus Bay (NW Mediterranean) mortality of copepod *Acartia grani* was attributed to the dinoflagellate *Gyrodinium corsicum* bloom. Amongst other ecological consequences, the development of *G. corsicum* blooms represents a drastic reduction of grazing pressure in the system through the control of the herbivorous populations.

In the southern portion of the Gulf of Maine, the highest PSP toxin concentrations generally occurred in the larger zooplankton size fractions dominated by larger copepods such as *C. finmarchicus* and *C. typicus* (Turner *et al*., 2000). But in Casco Bay elevated toxin levels were observed in smaller zooplankton size fractions, dominated by heterotrophic dinoflagellates, tintinnids and aloricate ciliates, rotifers, copepod nauplii, and smaller copepods such as *O. similis* and, at inshore locations, *A. hudsonica*. Thus, during spring blooms of *A. fundyense* in Casco Bay, PSP toxins can be more widespread throughout the zooplankton grazing community (Turner *et al*., 2005). According to Lester *et al* (2008) in offshore areas with high concentration of monospecific bloom of *Karenia brevis* low numbers of zooplankton were observed. However, in lower concentration areas of the bloom where the phytoplankton assemblage was mixed, high abundances of certain zooplankton genera were present, including *Oithona, Temora, Acartia,* and near shore populations of *Corycaeus* and *Paracalanidae*.

Campbell *et al* (2005) studied zooplankton grazing impacts on *Alexandrium* spp. in the near shore environment of the Gulf of Maine and according to him during the initiation phase of the bloom the biomass of the dominant zooplankton grazer (*Acartia hudsonica*) was too low to have a significant impact in controlling the bloom. However, during the later stages of the bloom when the zooplankton biomass became significant, grazing may have caused or contributed to the bloom's demise. A significant level of PSP toxins accumulated in zooplankton tissues and seems to retain the toxins for some time after the *Alexandrium* spp. bloom had declined. This poses potential risks to higher trophic levels including fishes and marine mammals that feed on zooplankton.

Leising *et al* (2005) studied copepod grazing during spring diatom bloom in Dabob Bay, USA to examine the grazing, egg production and hatching success rates of adult female *Calanus pacificus* and *Pseudocalanus newmani*. *C. pacificus* seemed most averse to diatoms of the genus *Thalassiosira*, often avoiding them when they are the most dominant unicells. These toxic diatoms may be indirectly influencing the entire food web and also causes increased occurrences of deep water anoxia when these blooms sink to the bottom and decay, resulting in an additional stressor for local fish populations. Jensen *et al* (2006) evaluated the importance of mesozooplankton grazing as a biological loss factor of harmful algal blooms in North Sea and he found that some copepod species feed efficiently on *Dinophysis* sp. and *Ceratium* sp. under natural conditions, which may affect the bloom development of these dinoflagellates. *Ceratium* spp. are generally believed to be a poor food source for copepods due to their size and shape. The development of dense *Ceratium* blooms usually takes place in autumn and has been associated with a decline in mesozooplankton (Smetacek, 1981).

Domoic acid (DA) is a potent neurotoxin and glutamate agonist produced by several species of the diatom genus *Pseudo-nitzschia*. DA has been demonstrated to elicit neuronal excitotoxicity and degeneration in mammals (Ramsdell, 2007). Human exposure to sufficient quantities of this toxin through the ingestion of contaminated seafood causes amnesic shellfish poisoning (ASP) syndrome (Jeffery *et al*., 2004). According to Leandro *et al* (2010) the marine copepod *C. finmarchicus* has the ability to ingest toxic diatom *P. multiseries* cells and assimilate DA into its tissues. *C. finmarchicus* did not discriminate between toxic vs. non-toxic *Pseudo-nitzschia* spp. when exposed simultaneously to both; however, since blooms of DA-producing diatoms are generally not monospecific events. *C. finmarchicus* accumulated DA when exposed to toxic *P. multiseries*, the amount of toxin retained was generally less than 30% of that ingested- still sufficient to facilitate trophic transfer of this toxin in natural systems.

Filamentous cyanobacteria commonly produce nuisance blooms in freshwater and brackish environments (Paerl, 1988) and some produce toxins. Filamentous cyanobacteria of the genus *Trichodesmium* are a major component of the marine phytoplankton in tropical and subtropical oceans (Carpenter 1983). Although some marine harpacticoid copepods feed on *Trichodesmium thiebautii* (O'Neil and Roman, 1992; Sellner, 1992), it is toxic to some calanoid and cyclopoid copepods, brine shrimp, and mice (Hawser *et al*., 1992). Guo and Tester (1994) investigated toxicity of *Trichodesmium* to the copepod *Acartia tonsa* during a natural bloom off North Carolina in 1992. They found that healthy intact cells were not toxic to the copepods and were ingested when no other food was available. Conversely, homogenized cells were lethal to the copepods, suggesting the presence of intracellular or cell-wall-bound toxins (Falconer, 1993). There are also some good evidences that herbivore zooplankton (Odum, 1971) grazing plays a crucial role in the initial stages of a red tide outbreak (Uye, 1986).

It is well known that zooplankters depend on phytoplankton for food, and naturally, some relationship is to be expected between them and their respective distribution. This relationship has been dealt with and reviewed by many workers in the past, mostly based on work in the temperate and polar waters (Harvey, 1934b; Harvey *et al*., 1935; Hardy 1935; Lucas, 1936a; Steeman Nielsen, 1937; Marshall and Orr, 1948; 1952). Studies on phytoplankton and zooplankton relationships in Indian waters were very few and are restricted to estuarine and inshore waters of central west coast (Pant *et al*., 1984; Goes *et al*., 1999). In Indian waters Prasad (1956) found that in the Gulf of Mannar, the relation between phytoplankton and zooplankton was inverse, whereas in Palk Bay, the relationship was direct. According to Prakash and Sarma (1964) during a monospecific bloom of *Gonyaulax polygramma* along the west coast of India there was a complete exclusion of zooplankton.

Noxious or toxic blooms of marine phytoplankton appear to be increasing in frequency in the World Ocean. Blooms are ungrazed by larger zooplankters such as copepods and cladocerans. Although, factors such as increased incidence of light, major nutrients and other physical processes are the main reason for triggering the harmful algal blooms, a large phytoplankton bloom implies that the grazing system is insufficient to check phytoplankton growth. Thus, information of the role of zooplankton is required for understanding phytoplankton bloom dynamics.

## 4.2 Materials and methods

Zooplankton samples were collected from the local sampling stations on the seasonal basis and also from the bloom stations identified during FORV Sagar Sampada cruises, and analysed as described in chapter I.

## 4.3 Results

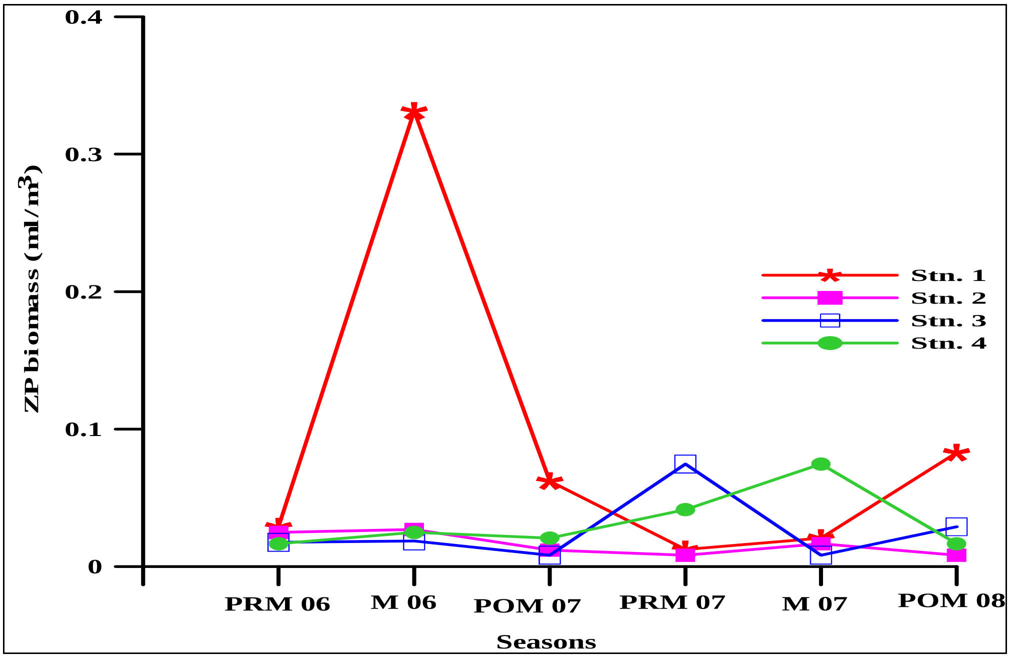
Seasonal and spatial variation of zooplankton biomass by volume (Figure 30), by wet weight (Figure 31) and by dry weight (Figure 32) was studied for six seasons (from Premonsoon 2006 to Post monsoon 2008) from four coastal stations along the southwest coast of India.

### 4.3.1 Zooplankton biomass by volume

In station 1 (off Kollam) highest zooplankton biovolume (0.331 ml $m^{-3}$) was observed during monsoon of 2006 and lowest (0.012 ml $m^{-3}$) during the premonsoon of 2007. During postmonsoon of 2007 and 2008 zooplankton biovolume was moderately high, 0.062 ml $m^{-3}$ and 0.083 ml

$m^{-3}$ respectively. In station 2 (off Alleppey) zooplankton biovolume was very low during all the seasons. Among these highest biovolume was recorded during premonsoon of 2006 (0.025 ml $m^{-3}$) and monsoon of 2006 (0.027ml $m^{-3}$). Lowest biovolume 0.008 ml $m^{-3}$ was observed during premonsoon of 2007 and postmonsoon of 2008. In station 3 (off Kochi) highest zooplankton biovolume was observed during premonsoon of 2007 (0.075 ml $m^{-3}$) and lowest during postmonsoon of 2007 and monsoon of 2007 with 0.008 ml $m^{-3}$ in both the seasons. During monsoon of 2006 and postmonsoon of 2008 moderately high biovolume was observed with values of 0.019 ml $m^{-3}$ and 0.029 ml $m^{-3}$ respectively. In station 4 (off Calicut) highest zooplankton biovolume was observed during monsoon of 2007 (0.075 ml $m^{-3}$) and lowest during premonsoon of 2006 and postmonsoon of 2008 (0.017 ml $m^{-3}$). Moderately high biovolume of 0.025 ml $m^{-3}$ and 0.041 ml $m^{-3}$ was also observed during monsoon of 2006 and premonsoon of 2007 respectively.

**Figure 30. Seasonal and spatial variation of Zooplankton Biomass (Volume) at the four stations during the study period 2006 to 2008**

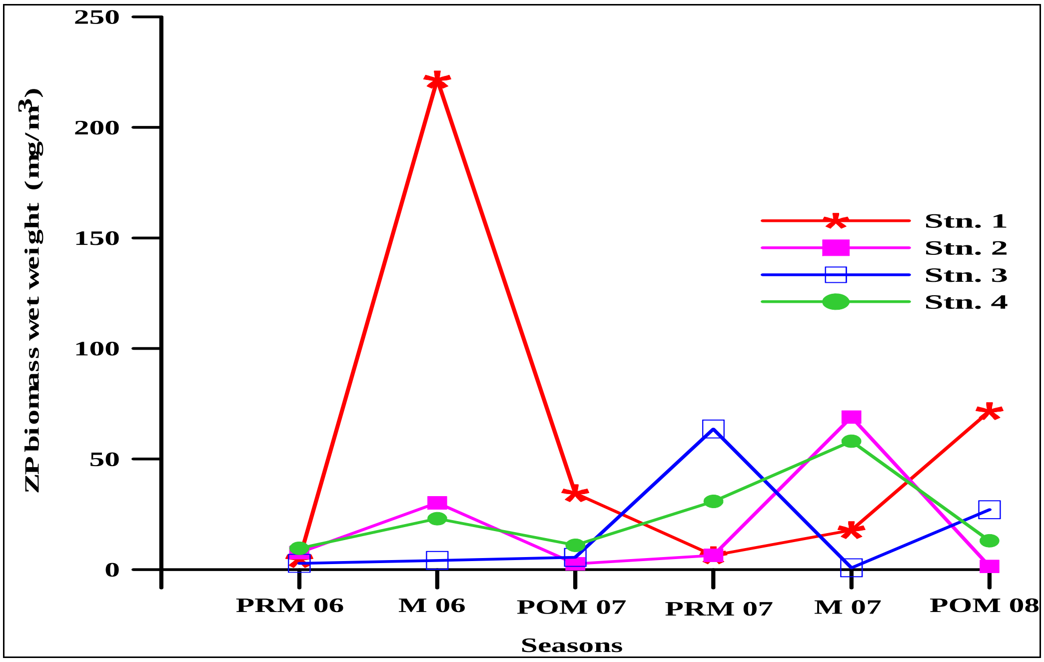


### 4.3.2 Zooplankton biomass by wet weight

Seasonal and spatial variation of zooplankton biomass in terms of wet weight was as follows. In station 1 (off Kollam) highest zooplankton biomass in terms of wet weight was observed in during the monsoon season of 2006 (221.61 mg m$^{-3}$) and the lowest during premonsoon of 2006 (4.79 mg m$^{-3}$). Moderately high values of 34.51 mg m$^{-3}$ and 71.66 mg m$^{-3}$ were observed during postmonsoon of 2007 and 2008 respectively. In station 2 (off Alleppey) highest zooplankton biomass in wet weight was observed during the monsoon of 2007 (69 mg m$^{-3}$) and monsoon of 2006 (30.22 mg m$^{-3}$). Lowest value was observed during postmonsoon of 2008 (1.42 mg m$^{-3}$). In station 3 (off Kochi) high zooplankton biomass in wet weight was observed during premonsoon of 2007 (63.58 mg m$^{-3}$), postmonsoon of 2008 (27.04 mg m$^{-3}$) and lowest during monsoon of 2007 (0.78 mg m$^{-3}$). During the monsoon season of

2006 also zooplankton biomass was very low (4.18 mg m$^{-3}$). In station 4 (off Calicut) highest zooplankton biomass in wet weight was observed during monsoon of 2007 (58.06 mg m$^{-3}$) and during premonsoon of 2007 (30.84 mg m$^{-3}$). In monsoon of 2006 also highest value was observed 23.03 mg m$^{-3}$. Lowest value was observed during premonsoon of 2006 (9.63 mg m$^{-3}$).

**Figure 31. Seasonal and spatial variation of Zooplankton Biomass (Wet weight) at the four stations during the study period 2006 to 2008**

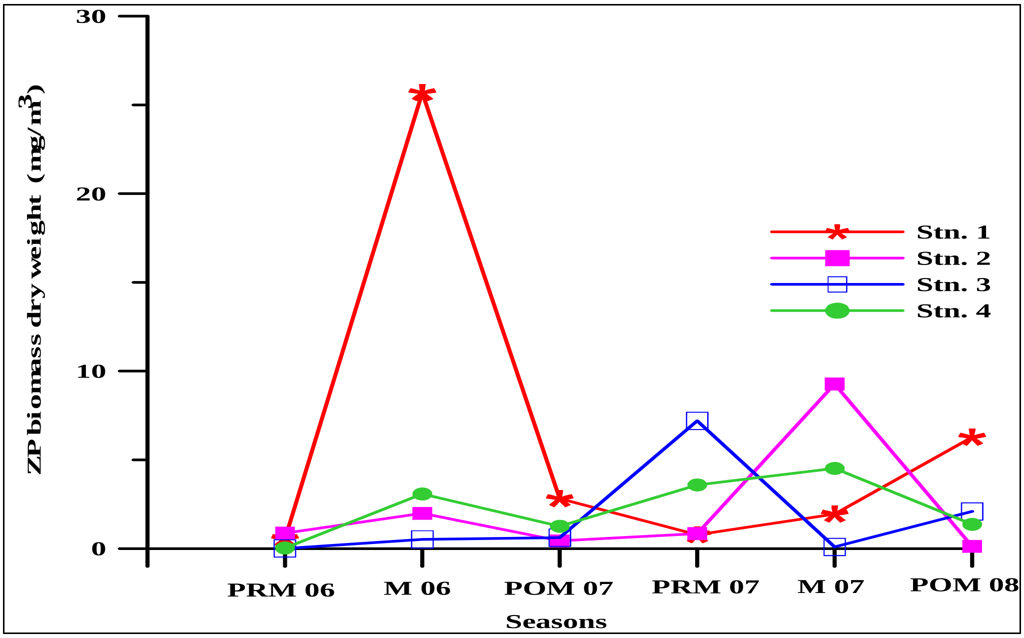


## 4.3.3 Zooplankton biomass by dry weight

In station 1 (off Kollam) highest zooplankton biomass in terms of dry weight was observed during monsoon of 2006 (25.69 mg m$^{-3}$) and lowest during the premonsoon of 2006 and premonsoon of 2007 (0.57 mg m$^{-3}$ and 0.78 mg m$^{-3}$ respectively). In station 2 (off Alleppey) highest zooplankton biomass by dry weight was observed during monsoon of

2007 (9.28 mg m$^{-3}$) and also during monsoon of 2006 (1.99 mg m$^{-3}$) and lowest during postmonsoon of 2008 (0.13 mg m$^{-3}$). Postmonsoon is the season with least zooplankton biomass by dry weight observed during this study period in station 2. In station 3 (off Kochi) highest zooplankton biomass in terms of dry weight was observed during premonsoon of 2007 (7.2 mg m$^{-3}$) and lowest during the premonsoon of 2006 (0.01 mg m$^{-3}$). During postmonsoon of 2008 a moderate value of 2.1 mg m$^{-3}$ was observed. In station 4 (off Calicut) highest zooplankton biomass in terms of dry weight was observed during monsoon of 2007 (4.52 mg m$^{-3}$). Also during monsoon of 2006 and premonsoon of 2007 highest zooplankton biomass was observed, 3.08 mg m$^{-3}$ and 3.59 mg m$^{-3}$ respectively. Lowest zooplankton biomass was observed during premonsoon of 2006 (0.04 mg m$^{-3}$).

**Figure 32. Seasonal and spatial variation of Zooplankton Biomass (Dry weight) at the four stations during the study period 2006 to 2008**



## Seasonal and spatial variation of different groups of zooplankton

### 4.3.4 Zooplankton abundance and percentage composition

Zooplankton abundance and percentage composition at station 1 (off Kollam) is presented in table 13 and figure 33. Abundance is represented by number/ 1000m$^3$. At station 1, highest zooplankton abundance was observed in the monsoon of 2006 (2931422/ 1000m$^3$) and monsoon of 2007 (493193/ 1000m$^3$) and lowest during premonsoon of 2006 (72513/ 1000m$^3$). In monsoon of 2006 copepods formed the 99.67% of the total zooplankton community. Copepods dominated the zooplankton in abundance throughout the study period, constituting 58.12 to 99.67% of total community composition. Other dominant zooplankton groups, in order of abundance were Cladocera, Lucifer, Mysids, Oikopleura, Siphonophores and Brachyuran zoea. Amphipods were observed only during the postmonsoon of 2008 constituting 3.73% of the total biomass. The result of analysis of zooplankton diversity indices of station 1 is presented in table 14. Zooplankton richness (d 0.724) and diversity index (H’ 1.47) were low during the monsoon of 2006 and highest during the postmonsoon of 2008 (d 2.849, H’ 3.73).

The dendrogram of cluster analysis of zooplankton abundance during different seasons at station 1 is given in figure 34. Cluster analysis grouped two clusters. Cluster I happened in the premonsoon of 2006 and premonsoon of 2007 registering 70% similarity in group composition. Cluster II with 65% similarity occurred in the monsoon of 2007 and postmonsoon of 2008.

## Table 13. Zooplankton abundance (Number/ 1000m$^3$) at station 1 during the different season of 2006 to 2008

| Groups | Seasons | | | | | |
|---|---|---|---|---|---|---|
| | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| Alima larvae | 0 | 0 | 0 | 584.12 | 0 | 0 |
| Amphipods | 0 | 0 | 0 | 0 | 0 | 13049.42 |
| Chaetognaths | 3247.86 | 0 | 0 | 2179.05 | 2684.45 | 33406.52 |
| Cladocerans | 2518.75 | 6164.3 | 778.82 | 7394.67 | 0 | 695.97 |
| Copepods | 53225.1 | 2921877.5 | 110592.8 | 143978.62 | 425336.59 | 203396.99 |
| Crustacean larvae | 0 | 0 | 0 | 0 | 29528.98 | 20879.08 |
| Ctenophores | 0 | 0 | 0 | 0 | 0 | 33.14 |
| Doliolids | 0 | 0 | 42251.13 | 0 | 0 | 0 |
| Euphausids | 1126.81 | 0 | 0 | 0 | 0 | 0 |
| Fish eggs | 0 | 0 | 1362.94 | 439.12 | 2684.45 | 1913.92 |
| Fish larvae | 66.28 | 0 | 592.4 | 0 | 447.41 | 0 |
| Gastropods | 0 | 0 | 10319.4 | 0 | 0 | 2435.89 |
| Jelly fish | 0 | 0 | 190.56 | 0 | 0 | 0 |
| Lamellibranch larvae | 0 | 0 | 0 | 0 | 0 | 1043.95 |
| Lucifer | 331.41 | 1590.79 | 588.26 | 588.26 | 3877.54 | 51837.28 |
| Mysids | 530.26 | 0 | 584.12 | 434.98 | 0 | 869.96 |
| Oikopleura | 5634.04 | 0 | 778.82 | 1304.94 | 16554.12 | 869.96 |
| Polychaete larvae | 0 | 0 | 194.71 | 0 | 0 | 1739.92 |
| Prawn larvae | 0 | 0 | 194.71 | 289.99 | 0 | 0 |
| Pteropods | 0 | 0 | | 2174.9 | 0 | 0 |
| Siphonophores | 3844.4 | 0 | 6425.29 | 575.83 | 11036.08 | 6263.72 |
| Zoea larvae | 1988.48 | 1789.64 | 1557.65 | 3044.87 | 1043.95 | 11483.49 |
| Total | 72513.36 | 2931422.23 | 176411.63 | 162989.35 | 493193.57 | 349919.21 |

**Figure 33. Percentage composition of major zooplankton groups at station 1 during the different seasons of 2006 to 2008**

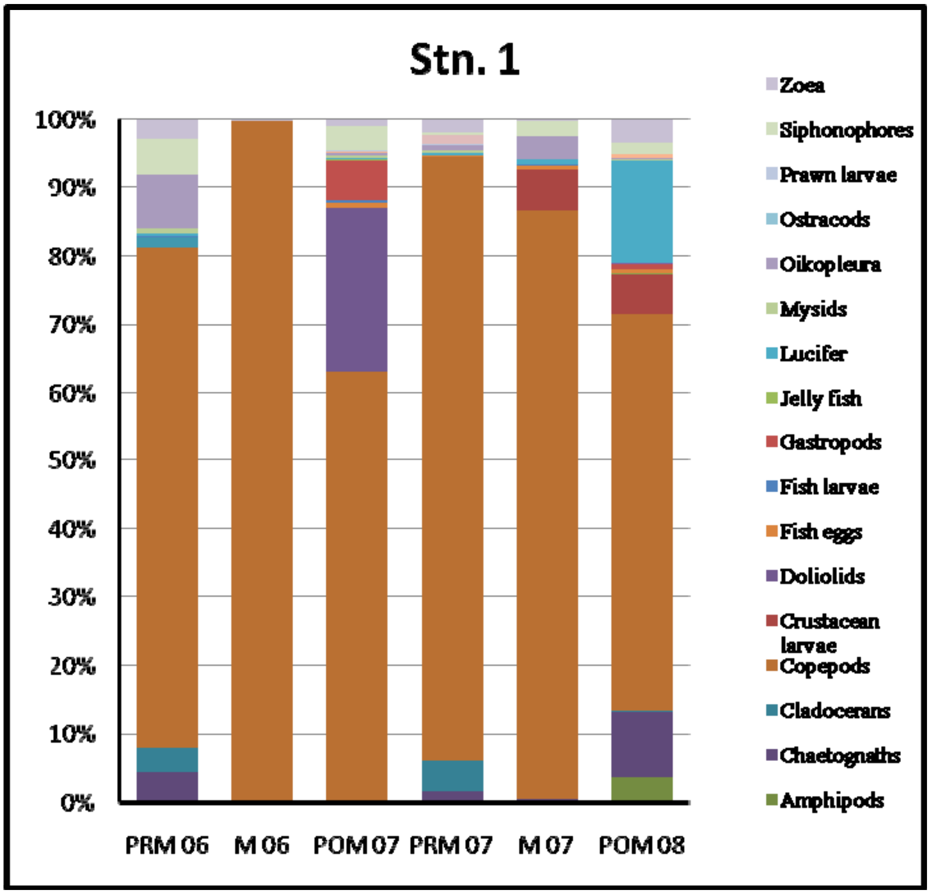


**Table 14. Zooplankton diversity indices of station 1 during the period 2006 to 2008**

| Station 1: Zooplankton diversity indices | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | 1-Lambda |
| PRM 06 | 10 | 70.7506 | 2.113 | 0.959 | 3.19 | 0.879 |
| M 06 | 4 | 63.0246 | 0.724 | 0.734 | 1.47 | 0.529 |
| POM 07 | 14 | 100.49 | 2.819 | 0.945 | 3.6 | 0.904 |
| PRM 07 | 12 | 83.8633 | 2.484 | 0.949 | 3.4 | 0.889 |
| M 07 | 9 | 92.8096 | 1.766 | 0.937 | 2.97 | 0.852 |
| POM 08 | 15 | 135.982 | 2.849 | 0.953 | 3.73 | 0.915 |

**Figure 34. Dendrogram showing the Bray Curtis similarity in the abundance of zooplankton at station 1 during the various seasons of 2006 to 2008**

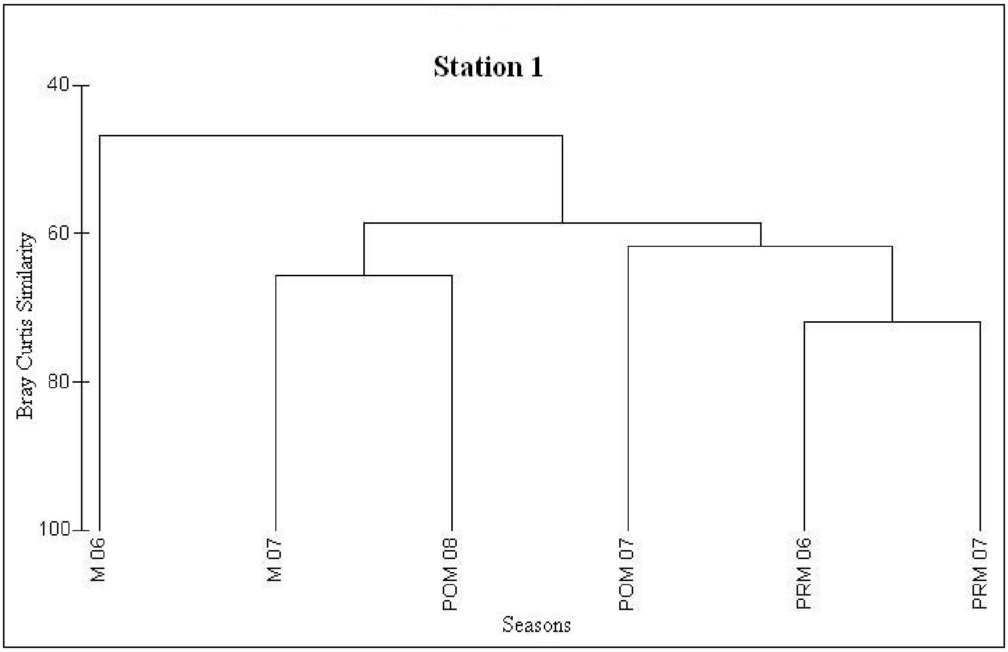


Table 15 and figure 35 show the abundance and percentage composition of various groups of zooplankton at station 2 (off Alleppey). Highest zooplankton abundance with reference to number was observed during the premonsoon of 2006 (819826/ 1000m$^3$) and monsoon of 2006 (832869/ 1000m$^3$) and lowest during the postmonsoon of 2008 (7344/ 1000m$^3$). Copepods dominated the zooplankton in abundance throughout the study period forming 30.35 to 100% of total zooplankton composition. During monsoon of 2007 zooplankton was represented by copepods only (100%). Similarly during premonsoon of 2006, copepods dominated (99.97%) the total zooplankton composition and the remaining was formed *Lucifer* spp. (0.01%) and mysids spp. (0.01%). The result of analysis of zooplankton diversity indices of station 2 is presented in table 16. Margalef species richness (d) and Shannon

Wieners diversity index (H') were zero during monsoon of 2007. Richness (d= 2.89) and diversity (H'= 3.395) was high during postmonsoon 2008.

The dendrogram of cluster analysis of the various groups of zooplankton abundance during different seasons at station 2 is given in figure 36. Cluster analysis grouped the seasons into two clusters. The zooplankton fauna of premonsoon of 2006 and monsoon of 2007 showed a similarity at 90%, whereas it was 70% during the postmonsoon of 2007 and premonsoon of 2007.

**Table 15. Zooplankton abundance (Number/ 1000m$^3$) at station 2 during the different season of 2006 to 2008**

| | Seasons | | | | | |
|---|---|---|---|---|---|---|
| Groups | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| Amphipods | 0 | 0 | 124.28 | 0 | 0 | 0 |
| Chaetognaths | 0 | 178.13 | 248.56 | 360.41 | 0 | 782.97 |
| Cladocerans | 0 | 211748.62 | 128.42 | 14416.5 | 0 | 0 |
| Copepods | 819818.55 | 603231.29 | 67608.43 | 169514.06 | 633000.54 | 2245.33 |
| Crustacean larvae | 0 | 0 | 0 | 0 | 0 | 389.41 |
| Ctenophores | 0 | 0 | 0 | 0 | 0 | 4.14 |
| Fish eggs | 0 | 0 | 0 | 0 | 0 | 20.17 |
| Fish larvae | 0 | 17537.22 | 0 | 0 | 0 | 24.86 |
| Lucifer | 4.1427 | 173.99 | 124.28 | 4204.81 | 0 | 994.24 |
| Molluscan larvae | 0 | 0 | 0 | 0 | 0 | 37.28 |
| Mysids | 4.1427 | 0 | 0 | 0 | 0 | 0 |
| Oikopleura | 0 | 0 | 745.68 | 720.83 | 0 | 41.42 |
| Ostracods | 0 | 0 | 0 | 600.69 | 0 | 0 |
| Prawn larvae | 0 | 0 | 0 | 0 | 0 | 53.85 |
| Pteropods | 0 | 0 | 0 | 1441.65 | 0 | 0 |
| Siphonophores | 0 | 0 | 0 | 0 | 0 | 16.57 |
| Zoea | 0 | 0 | 132.57 | 840.96 | 0 | 2734.16 |
| Total | 819826.8 | 832869.3 | 69112.2 | 192099.91 | 633000.5 | 7344.4 |

**Figure 35. Percentage composition of major zooplankton groups at station 2 during the different seasons of 2006 to 2008**

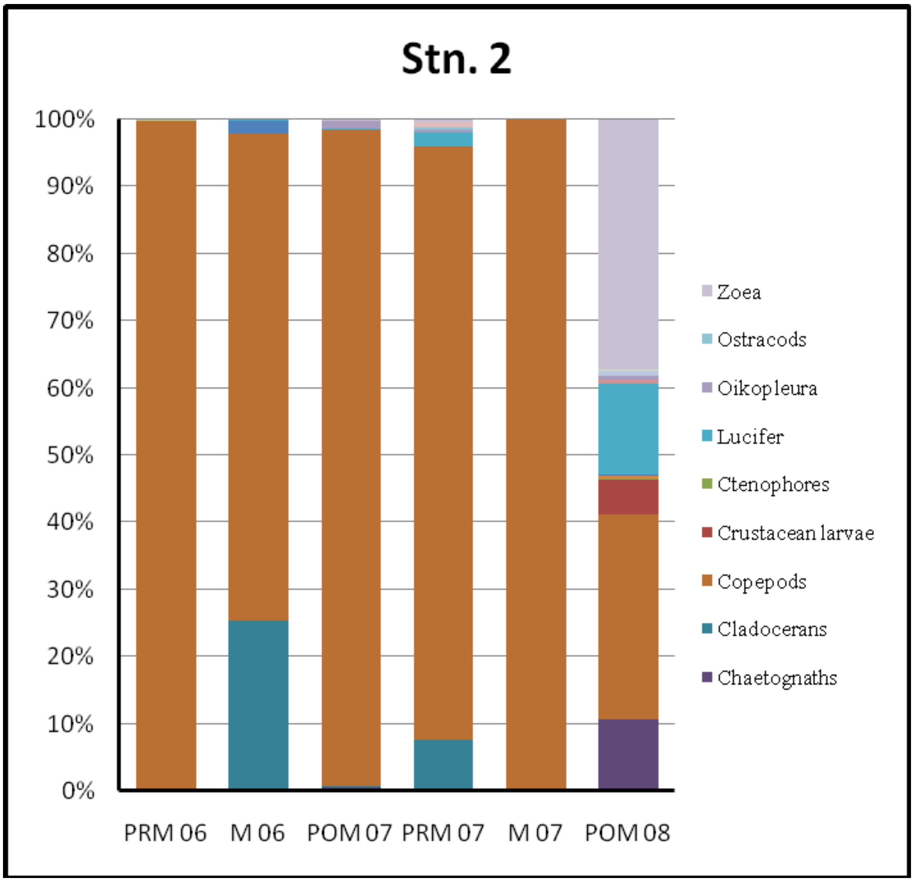
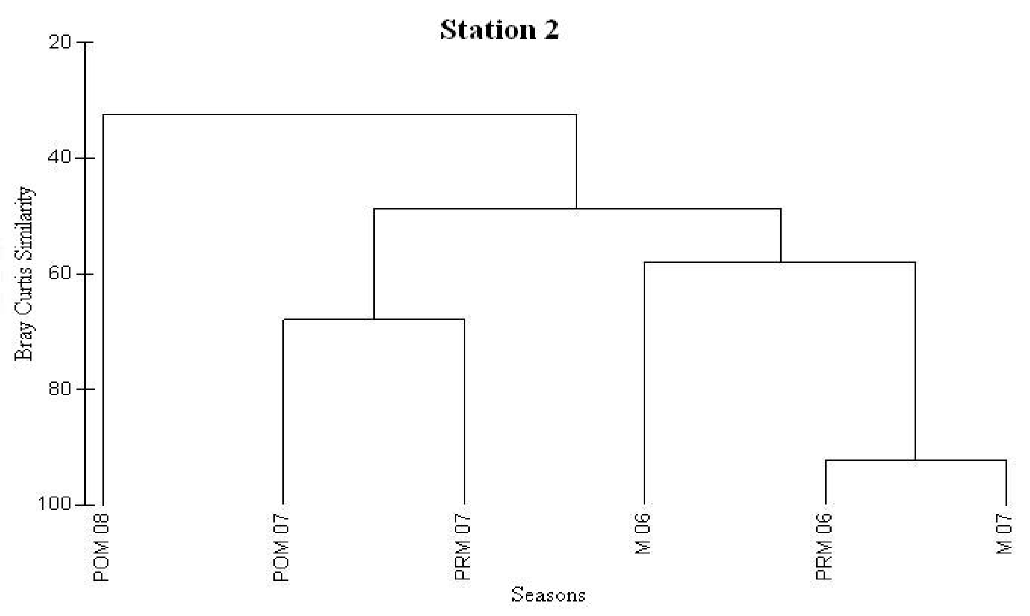


**Table 16. Zooplankton diversity indices of station 2 during the period 2006 to 2008**

| Station 2: Zooplankton diversity indices | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | 1-Lambda' |
| PRM 06 | 3 | 32.944 | 0.572 | 0.323 | 0.512 | 0.167 |
| M 06 | 5 | 68.113 | 0.948 | 0.835 | 1.938 | 0.709 |
| POM 07 | 7 | 38.759 | 1.641 | 0.882 | 2.476 | 0.789 |
| PRM 07 | 8 | 65.337 | 1.675 | 0.926 | 2.779 | 0.841 |
| M 07 | 1 | 28.207 | 0 | 0 | 0 | 0 |
| POM 08 | 12 | 44.975 | 2.890 | 0.947 | 3.396 | 0.914 |

**Figure 36. Dendrogram showing the Bray Curtis similarity in the abundance of zooplankton at station 2 during the various seasons of 2006 to 2008**



Zooplankton abundance and percentage compositions at station 3 (off Kochi) during the study period are presented in table 17 and figure 37. Highest zooplankton abundance in number was observed during premonsoon of 2007 (1910497/ 1000m$^3$) and lowest during monsoon of 2007 (2299/ 1000m$^3$). Copepod forms the dominant group throughout the study period occupying 21.98 to 99.12% of the total zooplankton community. During the monsoon of 2006 zooplankton was represented by copepoda (89.36%), cladocera (9.57%) and fish larvae (1.06%). The result of analysis of zooplankton diversity indices (Margalef dominance d and Shannon Wiener's diversity index H') of station 3 are presented in table 18. Zooplankton richness (d= 3.19) and diversity index (H'= 3.64) were highest during the monsoon of 2007, whereas in the monsoon of

2006 zooplankton richness (d= 0.65) and diversity index (H'= 0.675) were very low.

The dendrogram of cluster analysis of zooplankton abundance during the various seasons at station 3 is given in figure 38. Cluster analysis grouped the seasons into two main clusters. Cluster analysis based Bray Curtis similarity showed that similar cluster with around 60% similarity in faunistic composition is occurred during the postmonsoon and premonsoon of 2007 and with 50% similarity during premonsoon and monsoon of 2006.

**Table 17. Zooplankton abundance (Number/ 1000m$^3$) at station 3 during the different season of 2006 to 2008**

| Groups | Seasons | | | | | |
|---|---|---|---|---|---|---|
| | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| Actinotroch larvae | 0 | 0 | 0 | 0 | 372.84 | 0 |
| Amphipods | 0 | 0 | 0 | 0 | 169.85 | 0 |
| Chaetognaths | 0 | 0 | 0 | 932.1 | 16.57 | 4751.65 |
| Cladocerans | 0 | 1155.81 | 0 | 103.57 | 66.28 | 0 |
| Copepods | 7436.1 | 10787.52 | 34040.35 | 1893616.1 | 505.41 | 43021.67 |
| Crustacean larvae | 0 | 0 | 4648.08 | 7353.25 | 0 | 35701.56 |
| Fish eggs | 0 | 0 | 43746.63 | 5178.34 | 385.27 | 6292.72 |
| Fish larvae | 430.84 | 128.42 | 273.42 | 0 | 302.42 | 0 |
| Jelly fish | 0 | 0 | 0 | 0 | 0 | 3724.26 |
| Lucifer | 416.57 | 0 | 136.71 | 517.83 | 194.71 | 0 |
| Megalopa larvae | 0 | 0 | 0 | 0 | 8.29 | 0 |
| Molluscan larvae | 0 | 0 | 0 | 0 | 0 | 385.27 |
| Mysids | 231.99 | 0 | 0 | 310.7 | 53.85 | 57918.72 |
| Oikopleura | 0 | 0 | 149.14 | 1449.94 | 0 | 0 |
| Polychaete larvae | 0 | 0 | 0 | 0 | 0 | 2440.03 |
| Prawn larvae | 0 | 0 | 140.85 | 414.27 | 33.14 | 0 |
| Siphonophores | 0 | 0 | 0 | 0 | 149.14 | 0 |
| Zoea | 7738.51 | 0 | 6562 | 621.4 | 41.43 | 7320.1 |
| Total | 16254 | 12071.75 | 89697.18 | 1910497.5 | 2299.2 | 161556 |

**Figure 37. Percentage composition of major zooplankton groups at station 3 during the different seasons of 2006 to 2008**

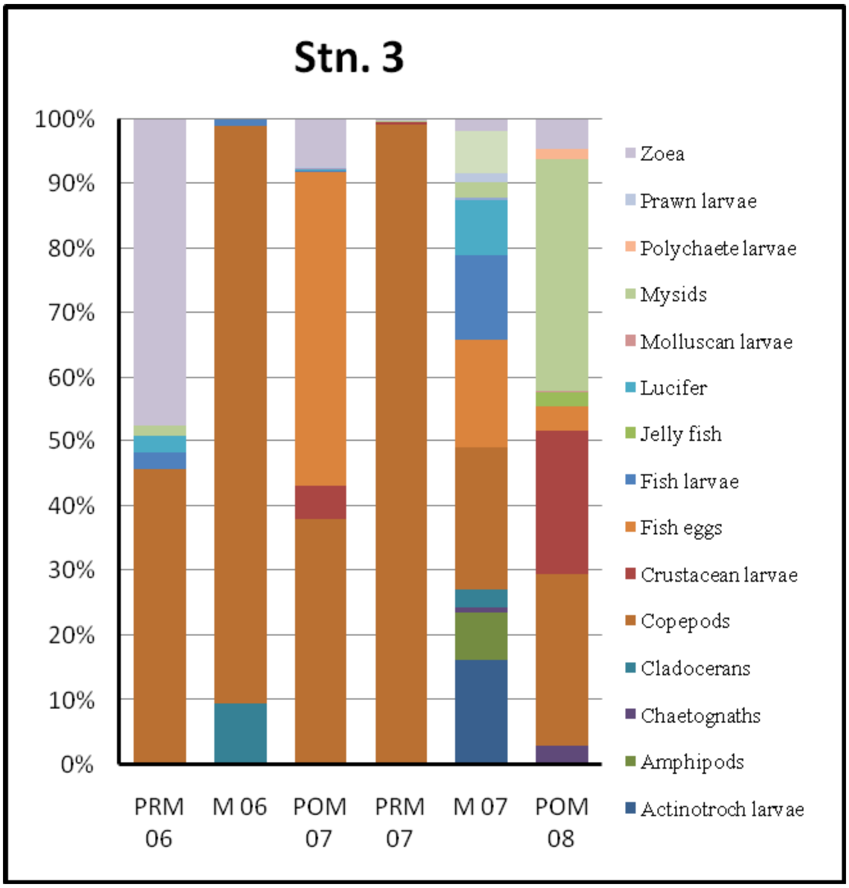
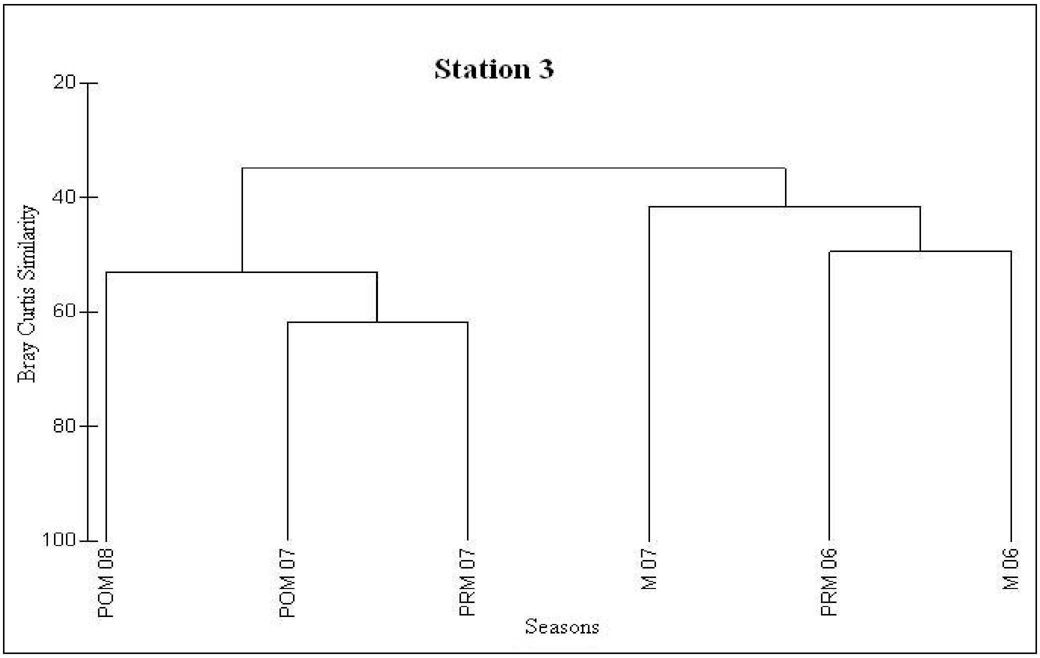


**Table 18. Zooplankton diversity indices of station 3 during the period 2006 to 2008**

| Station 3: Zooplankton diversity indices | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | 1-Lambda |
| PRM 06 | 5 | 31.642 | 1.158 | 0.954 | 2.215 | 0.769 |
| M 06 | 3 | 19.388 | 0.675 | 0.913 | 1.448 | 0.603 |
| POM 07 | 8 | 59.728 | 1.712 | 0.923 | 2.765 | 0.833 |
| PRM 07 | 10 | 88.198 | 2.009 | 0.835 | 2.775 | 0.782 |
| M 07 | 13 | 42.789 | 3.195 | 0.983 | 3.638 | 0.917 |
| POM 08 | 9 | 89.391 | 1.781 | 0.971 | 3.077 | 0.875 |

**Figure 38. Dendrogram showing the Bray Curtis similarity in the abundance of zooplankton at station 3 during the various seasons of 2006 to 2008**



Zooplankton abundance and percentage compositions of station 4 (off Calicut) during the study period are presented in table 19 and figure 39. Highest zooplankton abundance in number was observed during the postmonsoon of 2007 (944529/ 1000m$^3$) and premonsoon of 2007 (742797/ 1000m$^3$) and lowest during the monsoon of 2006 (162227/ 1000m$^3$). Copepod formed the dominant group at station 4, the percentage abundance varying between 49.55 to 96.82% of the total zooplankton composition. During monsoon of 2006, zooplankton was represented by copepods (82.13%), copepodites (13.26%), fish eggs (1.69%), ostracoda (1.35%) and zoea larvae (1.57%). But during monsoon of 2007 percentage composition of copepod was 49.55% and copepodites were totally absent. Brachyuran zoea was present in all the seasons. The result of analysis of zooplankton diversity indices

(Margalef species richness d and Shannon Wiener's diversity index H') of station 4 is presented in table 20. Zooplankton richness (d= 2.173) and diversity index (H'= 3.24) was highest during monsoon 2007, whereas during monsoon of 2006 richness (d= 1.01) and diversity index (H'= 2.19) were low.

The dendrogram of Bray Curtis similarity index of zooplankton abundance during the various seasons at station 4 is given in figure 40. Cluster analysis grouped the seasons into one main cluster with 80% similarity in zooplankton community during premonsoon of 2006 and 2007. Postmonsoon of 2007 join to main cluster with 70% similarity in faunistic composition. Zooplankton community of monsoon of 2006 formed a single group with 55% dissimilarity with other seasons.

**Table 19. Zooplankton abundance (Number/ 1000m$^3$) at station 4 during the different season of 2006 to 2008**

| | Seasons | | | | | |
|---|---|---|---|---|---|---|
| Groups | PRM 06 | M 06 | POM 07 | PRM 07 | M 07 | POM 08 |
| Alima larvae | 0 | 0 | 132.57 | 0 | 0 | 571.69 |
| Amphipods | 0 | 0 | 0 | 0 | 289.99 | 0 |
| Chaetognaths | 956.96 | 0 | 0 | 0 | 0 | 0 |
| Cladocerans | 0 | 0 | 12991.43 | 0 | 9424.58 | 13148.85 |
| Copepods | 623389.54 | 133244.96 | 854782.72 | 719168.15 | 129044.29 | 212477.7 |
| Copepodites | 0 | 21508.76 | 0 | 0 | 0 | 0 |
| Crustacean larvae | 0 | 0 | 22403.58 | 385.27 | 0 | 25344.88 |
| Euphausiids | 0 | 0 | 0 | 0 | 0 | 18865.74 |
| Fish eggs | 0 | 2734.16 | 16570.69 | 1541.07 | 13629.4 | 381.13 |
| Fish larvae | 410.12 | 0 | 2121.05 | 0 | 579.97 | 0 |
| Jelly fish | 0 | 0 | 0 | 0 | 37.28 | 20580.8 |
| Lucifer | 20779.65 | 0 | 4374.66 | 16951.82 | 74671.69 | 0 |
| Medusa | 0 | 0 | 0 | 256.85 | 0 | 0 |
| Molluscan larvae | 0 | 0 | 0 | 0 | 3479.85 | 952.81 |
| Mysids | 4921.5 | 0 | 1855.92 | 770.54 | 0 | 0 |
| Oikopleura | 0 | 0 | 3049.01 | 0 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Ostracods | 0 | 2187.33 | 0 | 0 | 0 | 0 |
| Polychaete larvae | 0 | 0 | 0 | 0 | 0 | 190.56 |
| Prawn larvae | 0 | 0 | 0 | 0 | 1159.95 | 0 |
| Siphonophores | 0 | 0 | 0 | 0 | 27113.8 | 0 |
| Zoea | 21873.32 | 2551.89 | 26247.98 | 3724.26 | 1014.96 | 8384.77 |
| Total | 672331.09 | 162227.1 | 944529.61 | 742797.96 | 260445.76 | 300899 |

**Figure 39. Percentage composition of major zooplankton groups at station 4 during the different seasons of 2006 to 2008**

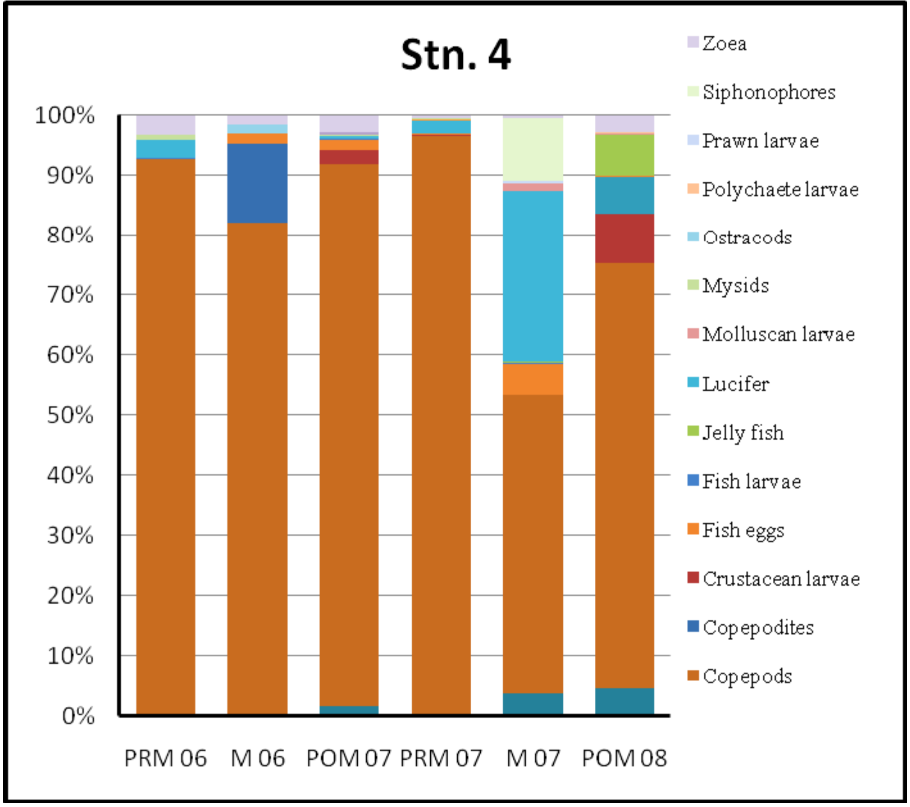
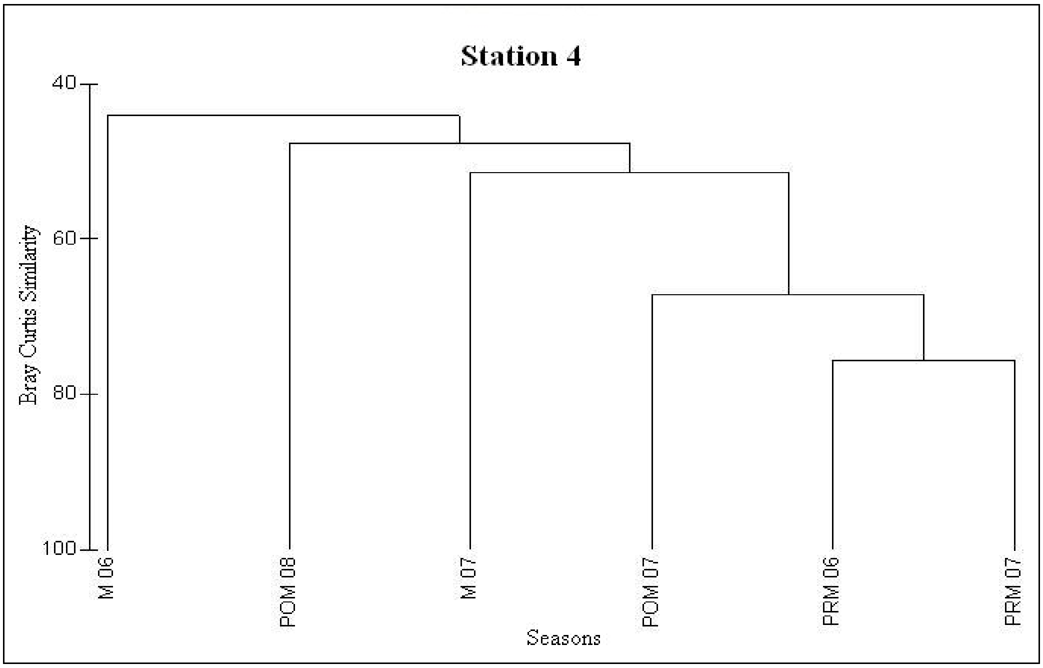


**Table 20. Zooplankton diversity indices of station 4 during the period 2006 to 2008**

| Station 4: Zooplankton diversity indices | | | | | | |
|---|---|---|---|---|---|---|
| Seasons | S | N | d | J' | H'(log2) | 1-Lambda |
| PRM 06 | 6 | 70.70 | 1.174 | 0.892 | 2.306 | 0.759 |
| M 06 | 5 | 52.39 | 1.010 | 0.942 | 2.188 | 0.759 |
| POM 07 | 10 | 109.7 | 1.916 | 0.927 | 3.08 | 0.859 |
| PRM 07 | 7 | 68.31 | 1.420 | 0.859 | 2.41 | 0.755 |
| M 07 | 11 | 99.64 | 2.173 | 0.936 | 3.24 | 0.881 |
| POM 08 | 10 | 96.64 | 1.969 | 0.942 | 3.129 | 0.872 |

**Figure 40. Dendrogram showing the Bray Curtis similarity in the abundance of zooplankton at station 4 during the various seasons of 2006 to 2008**



Two way ANOVA between zooplankton biomass in volume, dry weight, stations and seasons are shown in table 21. No significant relation was apparent in the data obtained.

**Table 21 (a) to (c). ANOVA of Zooplankton biomass between the various stations during the period premonsoon of 2006 to postmonsoon of 2008.**

| (a) | Zooplankton Biomass by Volume | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 0.0197 | 0.00658 | 1.585 | 0.235 |
| Seasons | 5 | 0.0174 | 0.00347 | 0.836 | 0.544 |
| Residual | 15 | 0.0623 | 0.00415 | | |
| Total | 23 | 0.0994 | 0.00432 | | |

| (b) | Zooplankton Biomass by Wet weight | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Station | 3 | 7029.24 | 2343.08 | 1.068 | 0.392 |
| Seasons | 5 | 9900.72 | 1980.15 | 0.902 | 0.505 |
| Residual | 15 | 32915.8 | 2194.39 | | |
| Total | 23 | 49845.8 | 2167.21 | | |

| (c) | Zooplankton Biomass by Dry weight | | | | |
|---|---|---|---|---|---|
| Source of Variation | DF | SS | MS | F | P |
| Stations | 3 | 81.974 | 27.325 | 0.916 | 0.457 |
| Seasons | 5 | 136.496 | 27.299 | 0.915 | 0.498 |
| Residual | 15 | 447.54 | 29.836 | | |
| Total | 23 | 666.01 | 28.957 | | |

### 4.3.5 Standing crop of Zooplankton during Algal Blooms

Concentration of chlorophyll *a* is taken as the index of algal blooms and phytoplankton standing crop during study period along the southwest coast of India. Area with highest chlorophyll *a* concentration was identified and the phytoplankton samples were analysed for finding out the species which bloomed. Zooplankton standing crop of the bloom area in terms of dry weight, abundance and percentage composition was used for the study of zooplankton standing crop during the algal blooms. Figure 41 shows seasonal variation of surface chlorophyll *a* concentration and zooplankton in dry weight at station 1 (off Kollam) during the study period. Chlorophyll *a* and zooplankton in dry weight shows an inverse relationship in all the seasons except monsoon 2006. In station 1 during this study period no algal blooms were observed, eventhough high concentration of surface chlorophyll *a* was recorded during monsoon 2006 (38.15 mg $m^{-3}$) and postmonsoon 2007 (52.42 mg

$m^{-3}$). But the total phytoplankton cell density was very low during monsoon 2006 (153 cells $L^{-1}$) and postmonsoon 2007 (157 cells $L^{-1}$) when compared to this high value of chlorophyll *a*. Large and chain forming diatoms seemed to play a role in the inconsistency between lower cell counts and higher biomass levels.

Figure 42 shows seasonal variation of surface chlorophyll *a* and zooplankton dry weight at station 2 (off Alleppey) during the study period. Chlorophyll *a* and zooplankton dry weight showed an inverse relationship in all the seasons except monsoon of 2007. During monsoon of 2007, surface chlorophyll *a* concentration and zooplankton biomass in dry weight were high. High chlorophyll *a* (127.61 mg $m^{-3}$) concentration was due to a multi species bloom dominated by diatom *Thalassiosira partheneia* (1675490 cells $L^{-1}$) and dinoflagellates like *Ceratium* spp. (42155 cells $L^{-1}$) and *Noctiluca scintillans* (7356 cells $L^{-1}$). Zooplankton was dominated by copepods during this bloom period. During the monsoon season of 2006, surface chlorophyll *a* concentration was very high (225.26 mg $m^{-3}$) due to the bloom of diatom *Thalassiosira partheneia* (3932710 cells $L^{-1}$ and heterotrophic dinoflagellate *Noctiluca scintillans* (73583 cells $L^{-1}$). During this bloom period zooplankton dry weight was 1.99 mg $m^{-3}$. Copepods (72.42%), cladocerans (25.42%), fish larvae (2.11%), chaetognaths (0.02%) and Lucifer (0.02%) were the major zooplankton group during the bloom.

Figure 41. Figure showing the distribution of chlorophyll *a* during the various seasons at station 1 along with zooplankton biomass by dry weight

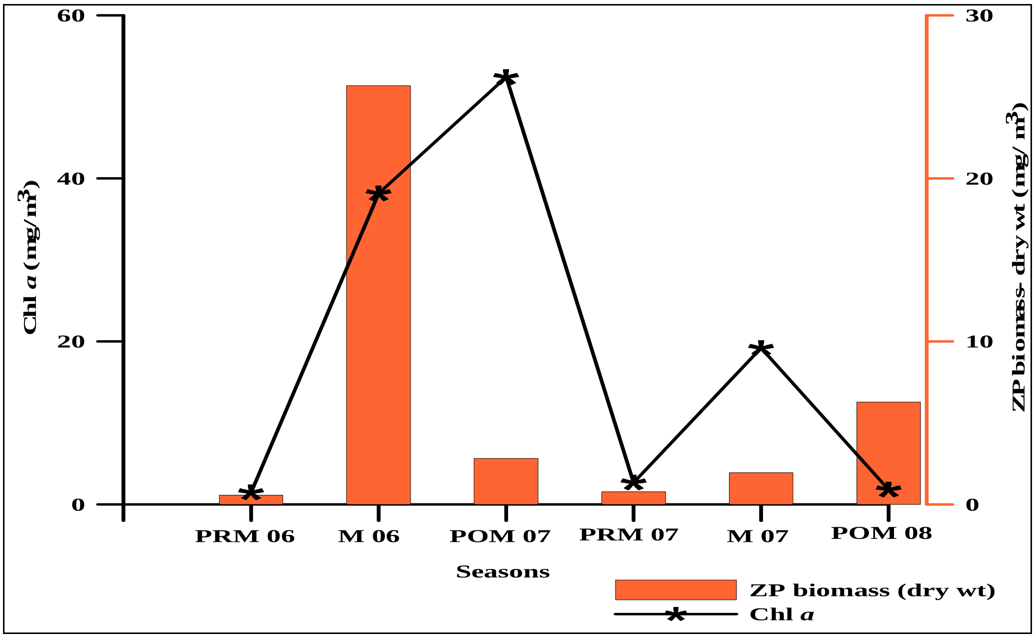
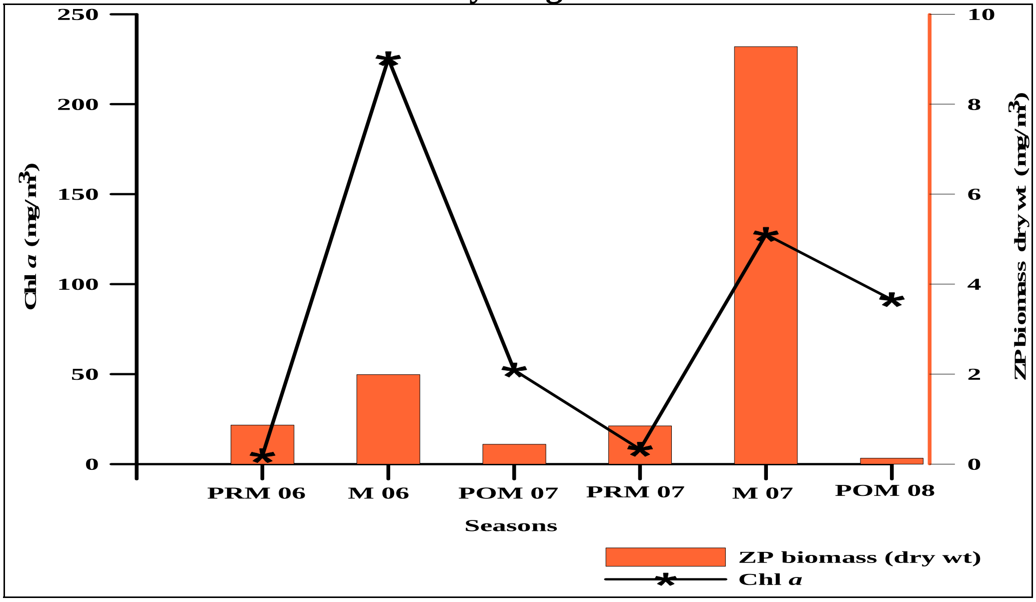


Figure 42. Figure showing the distribution of chlorophyll *a* during the various seasons at station 2 along with zooplankton biomass by dry weight



Seasonal variations of surface chlorophyll *a* and zooplankton dry weight at station 3 (off Kochi) during the study period are presented in figure 43. Chlorophyll *a* and zooplankton dry weight showed an inverse relationship in all the seasons. At station 3, two algal blooms occurred during the study period, one during the monsoon of 2006 and the other during the monsoon of 2007. During monsoon of 2006, a toxic diatom bloom of *Thalassiosira mala* was observed off Kochi with high chlorophyll *a* concentration (66.18 mg $m^{-3}$) and cell density of 6741230 cells $L^{-1}$. In this bloom area the zooplankton biomass was very low (0.52 mg $m^{-3}$) and was represented by copepods (89.36%), cladocerans (9.57%) and fish larvae (1.06%). During monsoon of 2007, *Thalassiosira partheneia* bloom was observed with cell density of 182100 cells $L^{-1}$ along with surface chlorophyll *a* concentration of 30.82 mg $m^{-3}$. Zooplankton biomass in dry weight (0.1 mg $m^{-3}$) and abundance in number (2299/ 1000$m^3$) in the bloom area was very low although zooplankton diversity was very high (diversity index H'= 3.638) during this bloom, probably indicating that species belonging to carnivorous species dominated the area.

**Figure 43. Figure showing the distribution of chlorophyll *a* during the various seasons at station 3 along with zooplankton biomass by dry weight**

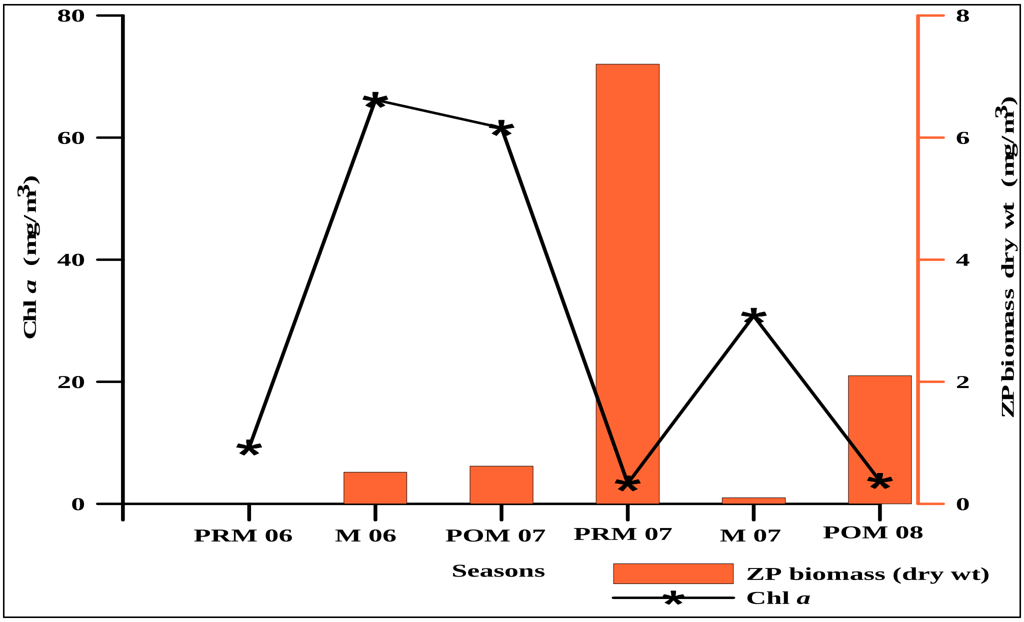
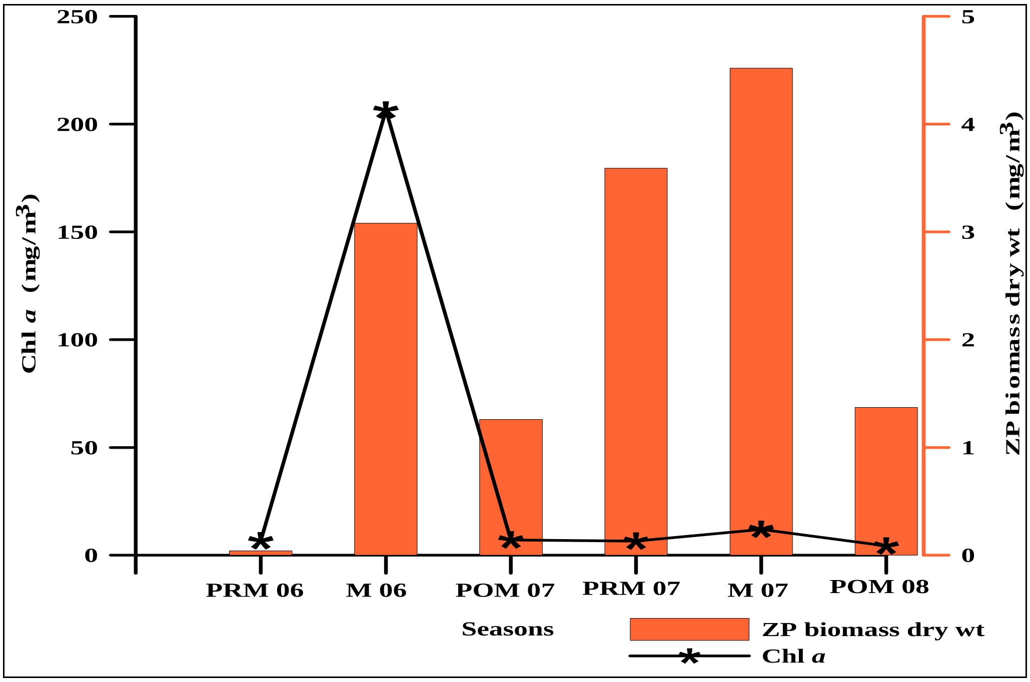


Figure 44 shows seasonal variation of surface chlorophyll *a* and zooplankton dry weight at station 4 (off Calicut) during the study period. In station 4 during monsoon of 2006 a monospecific bloom of *Coscinodiscus asteromphalus* var. *centralis* was observed with high chlorophyll *a* concentration of 206.5 mg $m^{-3}$. Phytoplankton standing crop of the bloom area was represented by diatoms only with a cell density of $7x10^6$ cells $L^{-1}$. *Coscinodiscus asteromphalus* var. *centralis* formed 99.97% of the total phytoplankton composition and the rest was represented by species of the genera *Biddulphia*, *Cymbella* and *Pleurosigma*. During this bloom period zooplankton biomass was 3.08 mg $m^{-3}$. Zooplankton diversity was very low and comprised of copepods (82.13%), copepodites (13.26%), fish eggs (1.69%), ostracods (1.35%) and zoea (1.57%). During this study copepodites (13.26%) were observed only from station 4 along with *Coscinodiscus asteromphalus* var. *centralis* bloom.

**Figure 44. Figure showing the distribution of chlorophyll *a* during the various seasons at station 4 along with zooplankton biomass by dry weight**



## 4.4 Discussion

The dynamics of rapid and/ or massive increase or decrease of plankton populations is an important subject in marine plankton ecology. Generally, nutrient levels and environmental conditions are the key factors affecting algae growth. The water must contain high levels of inorganic nutrients (nitrogen and phosphorous) for the algae to utilize. Water temperature and salinity levels must be within a certain range to enhance plankton growth. A frequent outcome of plankton blooms is massive cell lysis and rapid disintegration of large algae populations. This is closely followed by an equally rapid increase in the concentration of bacteria and by a fast de-oxygenation of water, which could be detrimental to aquatic plants and animals. Several researchers have tried to explain the dynamics of algal blooms by focusing on different factors such as nutrients upwelling ((Edwards and Brindley, 1996), spatial patchiness (Mathews and Brindley, 1996). Steele and Henderson (1993) and Edwards and Brindley (1999) observed that the choice of the functional form for zooplankton mortality has a major influence on the bloom dynamics. Probably, one of the main factors behind plankton bloom and species succession is the toxin produced by the harmful phytoplankton. During a HAB, the cumulative effect of all the released toxins may affect other aquatic organisms causing their massive mortality. Reduction of grazing pressure of zooplankton due to toxin producing phytoplankton can be one of the key parameters in this context (Kirk and Gilbert, 1992). There is also good evidence that herbivorous grazing plays a crucial role in the initial stages of red tide outbreak (Uye, 1986). Turner *et al* (1998) reviewed earlier studies of zooplankton community grazing impact on natural harmful algal blooms. The grazing pressure from the copepod community is important at the initial stage of the bloom and is almost insignificant at the peak of the bloom. In some cases, grazing is incapable of preventing development of algal blooms, but may contribute to their termination (Nakmura *et al*., 1996; Buskey *et al*., 2001). Conversely, grazing may retard initial development of algal bloom, but once developed, the bloom becomes immune to grazing pressure. Recent studies indicate that copepod grazing impact on algal blooms is variable, but usually quite low (Campbell *et al*., 2005; Jansen *et al*., 2006).

During the study period five algal blooms were recorded from the study area. Standing crops of zooplankton groups during these algal blooms are discussed here. Among the five algal blooms, three were by *Thalassiosira partheneia* observed during monsoon of 2006 and 2007 at station 2 and monsoon of 2007 in station 3. During 2006 monsoon period, the bloom was dominated by diatom *T. partheneia* (3.93x $10^6$ cells $L^{-1}$) and dinoflagellate *Noctiluca scintillans* (7.3x $10^4$ cells $L^{-1}$). *T. partheneia* cells were found in mucilaginous assemblages. *Thalassiosira partheneia* forms colonies of sizes up to 5 cm in length and up to 1 cm in diameter, each with several hundred up to 25,000 cells (Elbrachter and Boje, 1978). *T. partheneia* also seems to be a food source for filter feeders but only after disintegration into short chains and single cells. It was observed that during this bloom the zooplankton standing crop was very low (Zooplankton biomass in volume 0.027 ml $m^{-3}$ and in dry weight 1.99 mg $m^{-3}$) and was represented by copepods, cladocerans, fish larvae, chaetognaths and lucifer. Copepods were represented by the genera *Eucalanus*, *Paracalanus*, *Acrocalanus*, *Canthocalanus* and *Temora*. Abundance of copepods (72.42%) was low when compared to other seasons during the study period. This might be due to the avoidance of copepods from the *Thalassiosira* abundant area. There are several factors that might account for this avoidance. Diatoms might be of lower nutritional quality; some experiments have suggested that copepods may prefer food of higher nutritional quality when given a choice (Cowles *et al*., 1988; Kleppel, 1993). The copepods might have been avoiding or rejecting certain diatoms to some sort of physical or mechanical hindrance (spinous nature of cells or do presence of thick frustules). The gelatinous colonies of *Thalassiosira* act as a chelator to complex toxic substances or trap required trace metals. Grazers fed more readily on single cells of *T. partheneia* than on colonies, so there may be some protection against filter feeding predation (Schnack, 1983).

Along the coasts of India *Noctiluca scintillans* is extremely common and some of the effects of swarming of *N. scintillans* on fisheries and ecosystem have been reported by Bhimachar and George (1950), Prasad (1953), Venugopal *et al* (1979), Katti *et al* (1998), Nayak *et al* (2000), Sahayak *et al* (2005). The regions where there is rapid nutrient enrichment and subsequent phytoplankton production are the obvious places of great outbreaks of *Noctiluca* since these organisms are holozoic and feed on phytoplankton. Among these, regions of upwelling near the coast are the most important. During the present study *Noctiluca* abundance of up to $7.3\times 10^4$ cells $L^{-1}$ were observed at the same time of diatom bloom, caused by the summer monsoon upwelling and also by the mud bank formations. The diatom bloom was dominated by small centric diatom *T. partheneia*, which was also the dominant food item found within the *Noctiluca* cells. The same observation on *Noctiluca* abundance during *Thalassiosira partheneia* bloom was reported from southeast coast of Australia by Dela-Cruz *et al* (2002). According to Sahayak *et al* (2005) the zooplankton biomass was high during the *Noctiluca* bloom in southern Kerala coast. Planktonic copepods are considered to play a key role in the transfer of phytoplankton carbon to higher trophic levels during the spring bloom in coastal, shelf and oceanic waters. Copepod abundance increase in response to a diatom dominated spring phytoplankton bloom and provides an important food for larvae and juvenile fish (Cushing, 1989).

During 2007 monsoon in station 2 a multi species bloom dominated by the diatom *Thalassiosira partheneia* (1675490 cells $L^{-1}$)

and dinoflagellate *Ceratium* spp. (42155 cells $L^{-1}$) and *Noctiluca scintillans* (7356 cells $L^{-1}$) was observed. The genus *Ceratium* was represented by eight species, *C. furca, C. gibberum, C. horridum, C. kofoidii, C. pentagonum, C. symmetricum, C. trichoceros* and *C. vulture*. The zooplankton biomass of the bloom area was low (0.016 ml $m^{-3}$) and was represented by copepods only. Very few reports of zooplankton grazing on *Ceratium* dominated blooms are available. Smetacek (1981) reported a decline in the mesozooplankton population in Kiel Bight associated with the development of *Ceratium* populations. *Ceratium* spp. are generally believed to constitute poor food for copepods due to their size (Graneli *et al*., 1989) or shape (Hargrave and Geen, 1970). Traditionally copepods are considered the most important grazers on larger phytoplankton species, and previous studies have proved that *Ceratium* is poor food for copepods (Marshall and Orr, 1955). According to Hansen (1991) the most important *Ceratium* predators among the protozoa are probably the thecate heterotrophic dinoflagellates like *Protoperidinium* spp. which are known to feed on large algae. During the present bloom *Protoperidinium* sp. was observed with a cell density of 305 cells $L^{-1}$. Copepods are usually the dominant mesozooplankton along the southwest coast both in terms of numbers and biomass. During the present observation of the diatom bloom suspension feeding copepod genera, *Paracalanus*, *Calanus*, *Oithona*, *Acartia* and *Centropages* were dominated in the zooplankton biomass.

Reduced number of copepods might be indicative of the fact that they avoided the diatoms due to presence of extra cellular harmful chemical. Diatom genus *Thalassiosira* is the strongest producers of the toxic aldehydes (Wichard *et al*., 2005).During high phytoplankton concentration, the copepods generally ate phytoplankton. However, they often rejected the most abundant phytoplankton species, particularly certain *Thalassiosira* spp. It is postulated that this avoidance may be related to the retardation of reproductive processes of copepods in the presence of these diatoms (Leising *et al*., 2005). Zooplankton community structure is an important factor influencing seasonal variation of *Nitzschia* population density in the Bay of Eastern Guangdong (Shinji and Akihiro, 2002; Wang *et al*., 2008).

According to Mathew *et al* (1984) zooplankton was more abundant during the period when mud banks formed. Environmental factors such as nitrate, phosphate and silicate showed definite increase in the area. The standing crop of phytoplankton which is directly linked up with these chemical properties also showed a general increase during the period. The same trend was reflected in the case of zooplankton also. Menon and George (1977) have stated that there is a recurring pattern in the zooplankton abundance and distribution in the shelf waters of the southwest coast of India and in general the period from July to September is the time of peak plankton production. Qasim (1973) has stated that spawning of fishes largely occurs along the west coast during the monsoon and post-monsoon months. In the present observations the peak in zooplankton biomass is also observed during monsoon and postmonsoon months.

During 2006 monsoon in station 3 (off Kochi) *Thalassiosira mala* bloom was observed with a cell density of 6.7x $10^6$ cells $L^{-1}$. Zooplankton biomass was very low in the bloom area [zooplankton biomass in volume (0.019 ml $m^{-3}$) and dry weight (0.52 mg $m^{-3}$)]. Zooplankton was represented by three groups, cladocera (9.57%), copepoda (89.36%) and fish larvae (1.06%). *T. mala* was one of the causative species for fish mortality in the coast of Jakarta Bay (Thoha *et al.*, 2007). Poulet *et al* (1994) have generalized from experimental evidence that diatoms have evolved an allelopathic, antipredation strategy to reduce copepod population levels by inhibiting their reproductive success. Shifts from picoplankton to diatom dominated phytoplankton communities are characteristic events that follow an influx of nutrients and are caused by diatoms capable of 2-4 doublings a day (Furnas *et al.*, 2005). Copepods are the main grazers of diatoms and it has been suggested that the predator's doubling time of one week enable diatoms to bloom before grazing pressures can regulate their growth (Coale *et al.*, 1996; Furnas *et al.*, 2005). During 2007 monsoon, *Thalassiosira partheneia* bloom was observed with a cell density of 1.8x $10^5$ cells $L^{-1}$. Other diatoms were represented by *Achnanthes brevipes, Biddulphia* spp., *Coscinodiscus* spp., *Navicula* spp., *Podosira montagnei* and *Thalassiosira subtilis*. Zooplankton biomass was very low during this bloom (Biomass in volume 0.00829 ml $m^{-3}$ and dry weight 0.1 mg $m^{-3}$) compared to the non-bloom periods.

Chan and Carpenter (1985) thought that the high growth rate, low grazing pressure, and stratified water column were the conditions that caused the dinoflagellate red tide which occurred in the east coast of North America. Diatoms like *S. costatum* can proliferate in response to nutrient pulses and lowered salinity in the post-monsoon periods before its grazers have a chance to grow to levels high enough to be able to control it. *S. costatum* blooms have been reported earlier from the west coast during the post-monsoon period (Tiwari and Nair, 1998).

As the population density grows to a red tide density, an interspecific relation in and around the community become active. The growth of algae is promoted or inhibited by the metabolic product (extra cellular secretion) from the algae themselves or by coexisting algae. The red tide population may induce animal exclusion (decrease in grazing pressure), or contrarily, being the dominant population, may become the target of grazing.

During 2006 monsoon in station 4 (off Calicut), *Coscinodiscus asteromphalus* var. *centralis* bloom was observed with very high chlorophyll *a* concentration of 206.5 mg $m^{-3}$. The biovolume of zooplankton in the bloom area was 0.025 ml $m^{-3}$ and zooplankton biomass in dry weight was 3.08 mg $m^{-3}$. Zooplankton was represented by copepods (82.13%), copepodites (13.26%), fish eggs (1.69%), ostracods (1.35%) and zoea (1.57%). The dry weight of zooplankton was found to be high when compared to the abundance of zooplankton group. It might be due to the large number of *Coscinodiscus* cells which could not be separated from the zooplankton samples. In station 4 copepods were the dominant zooplankton group during all the seasons. Copepodites and ostracods were observed in the zooplankton samples only during the *Coscinodiscus* bloom period. Along the southwest coast of India, red water is reported to occur between August and November, which marks the end of the upwelling period along this coast. Blooms of large *Coscinodiscus* sp. have been reported in the Seto Inland Sea of Japan (Manabe and Ishio, 1991) and the German Bight (Rick and Durselen, 1995), where this species account for 90% of phytoplankton biomass. Earlier workers have also observed that dinoflagellate blooms are preceded by rains and diatom maxima. Observations reviewed by

Brongersma- Sanders (1957) shows that red tides occur in upwelling areas towards the end of upwelling period and that the diatom blooms precede dinoflagellate blooms in these regions. The period when red tides are generally reported coincides with the end of the upwelling season, when the weather is warmer with longer hours of sunshine than during the monsoon months. *Coscinodiscus* bloom affecting the phytoplankton community structure was reported by Fernandes and Brandini (2004) from Southern Brazil. During the bloom, densities of diatoms and other phytoplankton were very low and even zooplankton was almost absent. Due to large cell volume and rapidity in growth this alga is a highly competitive species for nutrients. The large size leads to inefficient grazing or even avoidance by copepods (Rick and Durselen, 1995; Roy *et al*., 1989). Diatoms are generally considered to be one of the main sources of nutrition for marine grazers, forming the foundation of ecologically and economically important food webs (Legendre, 1990). Diatoms have evolved a suite of antigrazing defences, most notably the tough silica frustules that surrounds the cell (Hamm *et al*., 2003). In addition to structural defences, certain diatoms also have the capacity to produce chemical defences such as apo- fucaxanthinoids (Shaw *et al*., 1995), polyunsaturated aldehydes (PUAs) and ω-oxo acids which may deter grazing or act to limit grazer population size. Chemical defences have been reported in a wide variety of microalgae and the toxins produced can be detrimental to grazing organisms, secondary consumer groups and even the microalgae themselves (Casotti *et al*., 2005). Present observation of numerous copepodites stages in zooplankton, revealed that there is no significant deleterious effect of high diatom concentration on the hatching of copepod eggs and subsequent larval development.

Uye and Takamatsu (1990) studied the grazing response using common copepods (*Acartia* and *Psuedodiaptoms*) in Seto Inland Sea and he found that zooplankton are rejected *Chattonella* spp., *Gymnodinium* spp., *Heterocapsa* spp. and *Fibrocapsa* spp. Since these flagellates are of unfavourable size and with hard dyspeptic cell walls, a chemical substance that induced rejection was suspected, and it was confirmed that deterrent chemical compounds were present in the cells. Such grazing rejection can lead to decreased feeding pressure and avoidance of a bloom area by zooplankton. Consequently, the growth of a possible red tide population would advance satisfactorily. According to Banse (1995) the absence of spring blooms in Eastern Subarctic Pacific might be due to the persistence of sufficiently large zooplankton population through out the winter.

Mesozooplankton, particularly copepods, have traditionally been thought to be the major grazers of phytoplankton in the sea. However, there is now increasing evidence that microzooplankton, particularly ciliate protozoans, play a more important role as consumers of phytoplankton than previously thought. Several studies have reported diatom blooms after anomalous rainfall and run-off events after southwest monsoon along the west coast of India, and this has been attributed mainly by two factors, eutrophication and reduced zooplankton standing crop in these waters.

It is commonly accepted that zooplankton play an important role as phytoplankton grazers. However, the importance of grazers in the development and decay of algal bloom has been little understood. The interaction between red tide phytoplankton and zooplankton are complex and variable, mainly due to the involvement of chemical compounds.

More studies are needed, not only to investigate the feeding interactions between potential grazers and red tide phytoplankton species under controlled laboratory conditions, but also to monitor the populations of all plankton components from the start to the end of red tides in the field. Accumulation of such data and overall synthesis of information will improve the understanding of interaction between red tide algae and their grazers, and the marine food webs.

# Chapter 5

# *In situ* observations on the harmful algal blooms in the Arabian Sea (2006 to 2009)

## 5.1 Introduction

Algal blooms occurring in the Arabian Sea is of very trophic and ecological significance. The Arabian sea is considered to be one of the most productive seas in the world. The pelagic fishery of this sea sustains the livelihood of a large number of fisher folks (~ 3.4 lakhs). The west coast of India is the most important fishing zone in Indian waters where a variety of vessels and gears are used for the capture of pelagic, mid water, demersal and benthic species of commercially important fish and shellfish species. Therefore any perturbation caused in the trophic chain would ultimately be reflected in the fishery and ensuring results would have clear cut economic consequences among the fishermen community.

Harmful algal blooms have been recorded from the fossil records. Noe- Nygaard *et al* (1987) have suggested on the basis of the distribution of dinoflagellate cysts and bivalve shells in fossil sediments taken from the island of Bornholm in the Baltic Sea, that toxic dinoflagellate caused mass mortalities of bivalves on several occasions dating back to about 130 million years ago. Dale *et al* (1993) have also studied the distribution of fossil dinoflagellate cysts and present evidences suggesting bloom formation by the toxic dinoflagellate *Gymnodinium* *catenatum* in the Kattegat- Skagerrak long before anthropogenic activities can have influenced these waters. The species appeared in the region about 6000 years ago and achieved a bloom about 4500 years ago. These observations emphasize two important points with respect to exceptional algal blooms. The occurrence of such blooms is not a recent phenomenon and that phytoplankton species which bloom need not be a permanent resident of the water body where they bloom. The fact that harmful blooms can occur in pristine waters is further illustrated by the chronicles of a number of European explorers who report encounters with poisoned shellfish upon arriving in the shores of North America, New Zealand waters, South West Africa etc. In recent years (1980 onwards) increased chlorophyll *a* has been recorded in the shelf region due to intensifying coastal eutrophication and land run off (Gregg *et al*., 2005).

Not with standing the increased production of algae on regional scale in the recent past, Boyce *et al* (2010) opine that global phytoplankton concentration has declined over the past century; their decline will need to be considered in future studies of marine ecosystems, geochemical cycling, ocean circulation and fisheries. With this back drop, five instances of harmful algal blooms in the Arabian Sea, have been studied spanning a period of 4 years and the data and related information are presented case by case in this chapter.

## 5.2 Results and Discussion

### 5.2.1 Green *Noctiluca scintillans* bloom-Northern Eastern Arabian Sea (March 2007)

The phenomenon of discoloured sea water, due to sporadic intensive and localized concentration of marine phytoplankton, has been observed in various parts of the world. The discolorations may be of any shade between red, brown, yellow and green, depending on the blooming organism. The study of red water phenomenon is of considerable interest from biological and economic point of view. The blooms could leave large quantities of dead pelagic species of fish or water bodies with extreme anoxic conditions.

On the west coast of India, discoloured water caused by a variety of organisms and some times associated with mass mortality of local marine fauna, have been reported (Katti *et al.*, 1988; Naqvi *et al.*, 1998; Eashwar *et al.*, 2001; Dharani *et al.*, 2004; Sahayak *et al.*, 2005; Mohanty *et al.*, 2007).

During an oceanographic cruise onboard *FORV Sagar Sampada* in the second week of March 2007 an intense green colouration accompanied with soup like consistency was observed in the upper layers of Northern Arabian Sea (Figure 45 and 46). The phenomenon in its full intensity with intermittent patches was found to be spread over an area of around 30 km$^2$. The physical and chemical characteristics of two stations were sampled along with a non-blooming region. The location of the blooming area was Lat. 21$^o$50 32 N & Long. 66$^o$09 38 E and Lat. 21$^o$50 63 N & Long. 67$^o$03 55 E and that of non-blooming region was Lat. 21$^o$00 33 N & Long. 65$^o$01 206 E. The organism involved in the blooming process was *Noctiluca miliaris* Suriray nonphotosynthetic, heterotrophic and phagotrophic dinoflagellate. Innumerable motile prasinophyte endosymbiont (*Pedinomonas noctilucae* (Subr.) Sweeney) were found harboured in the *Noctiluca* cells giving the deep green hue to the surface waters (Figure 47 and 48).

The water samples collected from the bloom station and non-bloom station were analysed for pH, Dissolved oxygen (DO), Chlorophyll *a* and nutrients according to Parsons *et al* (1984) The CTD profiler recorded the temperature and salinity. Phytoplankton samples collected and preserved in 1-3% neutralised formalin were used for qualitative and quantitative analysis.

**Figure 45: *Noctiluca* bloom location in Northern Arabian Sea**

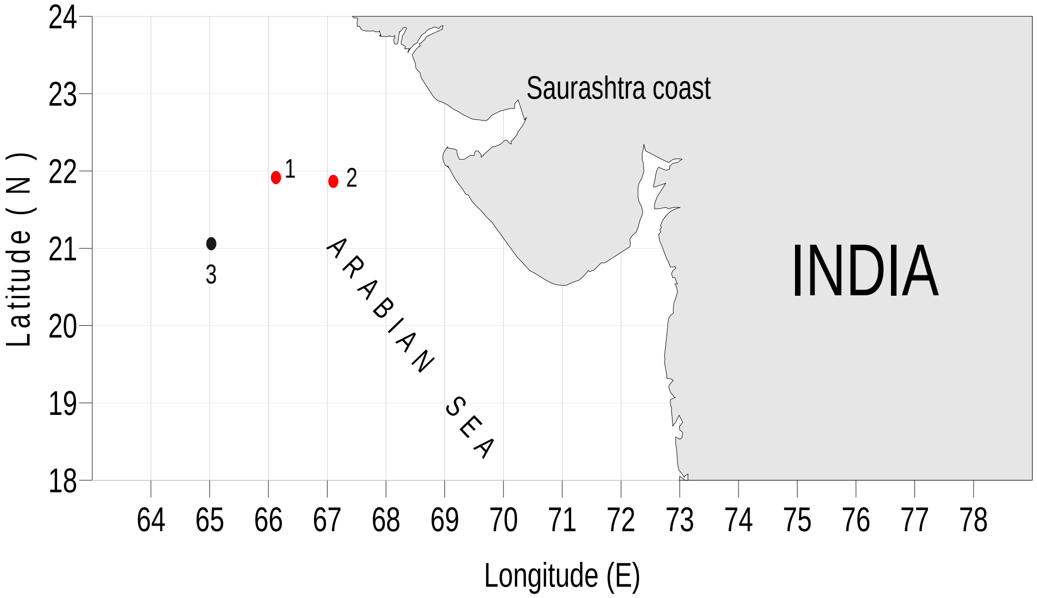


**Figure 46: Green *Noctiluca* bloom in the Northern Arabian Sea in March 2007**

**Figure 47: *Noctiluca scintillans* cells x 40**

**Figure 48: *Pedinomonas noctilucae* x 400**

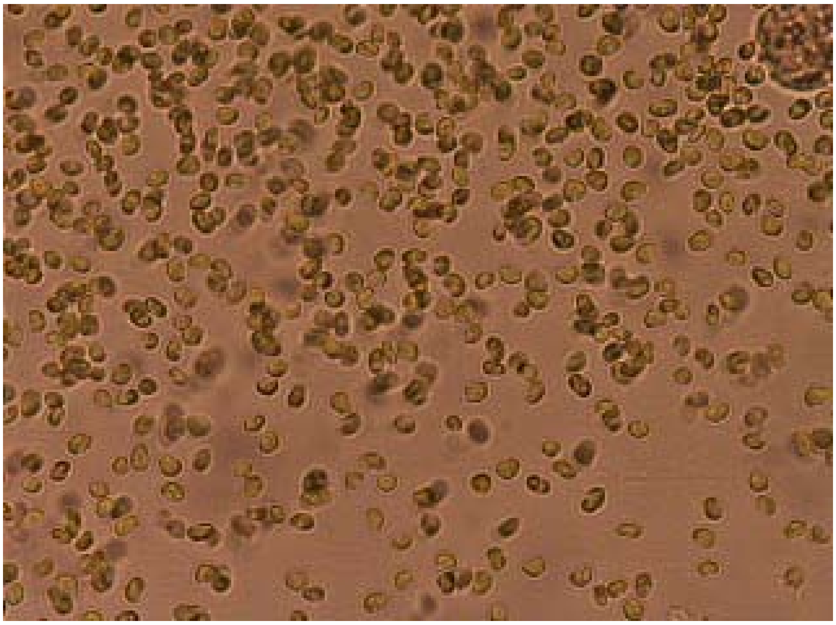


Table. 22 gives the physico chemical parameters of the area where bloom occurred and no bloom was registered. Cells have a size range from 200- 600 µm in diameter. The cells are more or less spherical, unarmored and have a well-defined oral pouch. Qualitative and quantitative analyses of phytoplankton revealed that the *Noctiluca* density was 4x $10^6$ cells $L^{-1}$ in bloom stations, while these were absent in the non-bloom station. *Noctiluca miliaris* was found along with 19 other species of phytoplankton, which included nine species of diatoms (*Chaetoceros brevis, C. didymus, Navicula digito-radiata, N. elegens, N. lyra, Rhizosolenia alata, R. hebetata, R. imbricata, Thalassionema nitzschioides*) and ten species of dinoflagellates (*Ceratium furca, C. trichoceros, C. vultur, Diplopeltopsis minor, Diplopsalis lenticula, Prorocentrum micans, Protoperidinium obovatum, P. oceanicum, P. pyriforme, P. steneii*). Among the diatoms, species of the genus

*Rhizosolenia* formed the major constituent. *Noctiluca miliaris* and *Rhizosolenia spp.* cohabitation has been reported previously also (Devassy and Sreekumaran Nair, 1987).

The surface water of the blooming area was well aerated and the dissolved oxygen values ranged between 4.96 and 5.09 ml $L^{-1}$. Among the nutrients, reduced inorganic phosphate to non-detectable levels was mainly due to consumption by the bloom sps. Nitrate values obtained were higher and could be attributed to the presence of *Noctiluca* bloom. Prasad and Jayaraman (1954) reported a similar trend in the nitrate concentration during the swarming of *Noctiluca*. Reduction in silicate concentration in bloom station might be due to the co occurrence of diatom spp. along with the *Noctiluca* bloom. Relatively high value of chlorophyll *a* in the bloom stations (21.9 and 21.3 mg $m^{-3}$) when compared to non-bloom station (0.97 mg $m^{-3}$) is due to the flagellates associated with *Noctiluca*. Relatively stable low temperature, high salinity, calm sea and muggy weather are known to favour proliferation and blooming of *Noctiluca.*

Zooplankton biomass was very high in the bloom stations (6089.74 ml $1000^{-3}$ and 7788.16 ml $1000^{-3}$) when compared with that of non-bloom station (984.68 ml $1000^{-3}$). Copepoda, Chaetognatha, Cladocera, Fish eggs, Amphipoda, Heteropoda, Jellyfish, Lucifer, Oikopleura, Salps, Doliolids, Siphonophores were abundants present in the zooplankton.

The survey conducted in this geographical area during the last seven years has shown that every year during this period the *Noctiluca* bloom occurs in the Northern Arabian Sea. The regular occurrence of the bloom in the same area, role of wind in the nutrient enrichment, the influence of water current in the swarming of *Noctiluca* cells and the role of symbiont *Pedinomonas noctilucae* in *Noctiluca* blooming are to be worth detailed investigations.

**Table 22: Physico chemical parameters of the bloom and non bloom area (NEAS)**

| Parameter | *Noctiluca* bloom stations | | Non bloom region Station. 3 |
|---|---|---|---|
| | Station.1 | Station. 2 | |
| Temperature ($^0$C) | 25.71 | 25.56 | 26.01 |
| Salinity (ppt) | 35.96 | 35.98 | 36 |
| pH | 8.33 | 8.31 | 8.36 |
| Dissolved oxygen (ml $l^{-1}$) | 4.96 | 5.09 | 5.38 |
| Nitrate ($\mu$mol $l^{-1}$) | 4.735 | 5.038 | 1.678 |
| Phosphate ($\mu$mol $l^{-1}$) | BDL | BDL | BDL* |
| Silicate ($\mu$mol $l^{-1}$) | 0.201 | 0.015 | 1.602 |
| Chlorophyll *a* (mg $m^{-3}$) | 21.9 | 21.3 | 1.24 |
| Cell count (Cells $m^{-3}$) | 4x $10^6$ | | *Noctiluca miliaris* absent |

### 5.2.2. Red *Noctiluca scintillans* bloom off Kochi (August 2008)

Open ocean blooms of the dinoflagellate *Noctiluca* is a common feature all along the west coast of India towards the last phase of the productive seasons. *Noctiluca* is classified as a HAB species as they cause large scale mortality of caged fish (Smayda, 1997) and other fin fishes through oxygen depletion, gill clogging and production of $NH_3$ (Okaichi and Nishio, 1976; Naqvi *et al*., 1998). Alternate forms of the species, *Noctiluca scintillans* (Macartney) Kofoid & Swezy 1921 (syn. = *Noctiluca miliaris* Suriray) dominate the blooms of the North West (15$^o$ to 22$^o$ N) and South West coasts (18$^o$N to 15$^o$N). Extensive blooms of the green *Noctiluca* is a recurring phenomenon along the North West Coast (NWC) during the wane winter monsoon season (Feb- March). Winter monsoon corresponds to the period of peak primary production along the

NWC due to nutrient availability in the surface waters brought about by the combined influence of the cold and dry North easterlies, convective mixing and regenerated production (Sanjeevan *et al*., 2009). Green forms of *Noctiluca* that are autotrophic due to the presence of the photosynthetic endosymbiont, *Pedinomonas noctilucae* (Sweeney 1976; Elbrachter and Qi, 1998) dominate the blooms both in the open ocean and coastal waters of NWC (Padmakumar *et al*., 2008). Crashing stages of these blooms to a large extent contributes to the oxygen minimum zones (OMZ) in the intermediate depths of NWC due to bacterial decomposition of exported organic matter. Unlike this, blooms of the red *Noctiluca* which appears along the South West Coast (SWC) towards the end of the upwelling seasons (June- Sept.) are phagotrophic in nature, lack endosymbionts and feed predominantly on diatoms, bacteria, protozoans, copepods, eggs of copepods and fishes and detritus (Taylor, 1987; Kirchner *et al*., 1996; Nakamura, 1998; Quevedo *et al*., 1999; Strom 2001). Blooms of red *Noctiluca* thus become a competitor to the larvae, juveniles and adults of the oil sardine which shoals the coastal waters during the upwelling seasons for breeding and larval growth. The present paper reports the occurrence of red *Noctiluca scintillans* and its bloom from coastal waters of southwest coast of India.

The bloom spread over an area of 5 km$^2$ was recorded on 19th August 2008 during a cruise in FORV Sagar Sampada along the southwest coast of India (Figure 49 and 50 Lat.10$^{o}$00.103 N and Long. 75$^{o}$32.396 E). For the qualitative and quantitative analysis of phytoplanktons, 50 litres of discoloured surface water samples were taken using clean plastic bucket and filtered through 20 micron bolting silk. Filtrates were preserved in 1-3% neutralised formaldehyde solution.

The *Noctiluca* cells were counted with Sedgwick-Rafter counting chamber using a Nikon Eclipse microscope. *N. scintillans* specimens were examined primarily to identify the ingested food items. The phytoplankton species were identified using Hasle and Syversten (1997) for diatoms and Steidinger and Tangen (1997) for dinoflagellates. Temperature and salinity at the sampling stations were recorded using Seabird CTD. Dissolved oxygen was estimated following Winkler method. pH was measured using an electronic Ino Lab (WTW series) pH meter. Chlorophyll *a* was determined by filtering one litre of water sample through GF/F Whatman filter paper. The pigments were extracted using 10 ml of 90% acetone. The solution was centrifuged for about 20 minutes under 5000 rpm and the optical density of the supernatant solution were then measured in a Perkin Elmer UV-Visible spectrophotometer (Parsons *et al*., 1984). Nutrients (nitrite, nitrate, phosphate and silicate) were analysed using segmented flow Auto Analyzer (SKALAR) onboard the vessel by following standard procedures (Grashoff *et al*., 1983). Meterological parameters were obtained by continuous Automatic Weather Station (AWS). Mesozooplankton samples were collected by Multiple Plankton Net (MPN) and Bongo nets.

Examination of the red water samples collected revealed that the discolouration was caused by the predominance of *Noctiluca scintillans* (Figure 51). Average cell counts of 8.1x $10^8$ cells $L^{-1}$ were recorded from the bloom area. The bloom however was, not monospecific. Diatoms were present in high numbers with cell density reaching levels of 6.32x $10^8$ cells $L^{-1}$. The percentage composition of *N. scintillans* and diatoms in the bloom waters were 56.17% and 43.83% respectively. Diatoms belonging to fourteen genera were represented by *Asterionella japonica, Biddulphia mobiliensis, Cerataulina sp., Chaetoceros lorenzianes, Chaetoceros curvisetus, Chaetoceros sp., Coscinodiscus asteromphalus, Eucampia, Fragilariopsis curta, Guinardia spp., Lauderia spp., Navicula delicatula, Nitzschia spp., Pleurosigma acuminatum, Pseudonitzschia spp., Rhizosolenia, Thalassionema nitzschioides* and *Thalassiosira spp.*

*Noctiluca* (Latin- means shiner by night) is commonly known as ‘sea sparkles’ because of its ability to produce blue bioluminescence at night times. The bioluminescent characteristic of *N. scintillans* is produced by a luciferin- luciferase system located in thousands of spherically shaped organelles, or “microsources”, located throughout the cytoplasm of this single-celled protist. Nonluminescent populations within the genus *Noctiluca* lack these microsources. It may be bioluminescent except in parts of the northern and eastern Pacific Ocean (Taylor *et al*., 1995). It was observed that sparkling bioluminescence lighted up the wakes of the ship at night. This glowing trail of water formed by the passage of ship retains its common name ‘sea sparkle’.

**Figure 49: Map showing the location of *Noctiluca* bloom on Southwest coast of India**

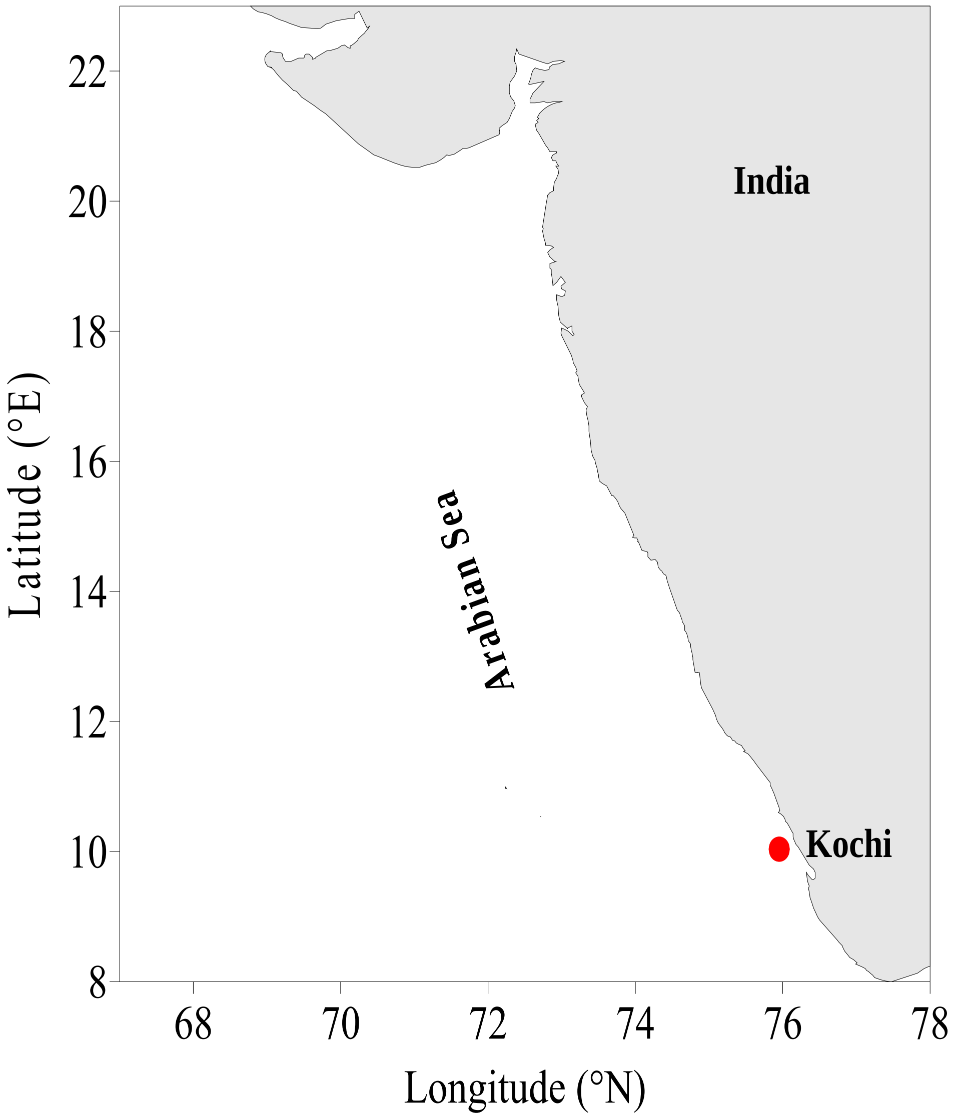
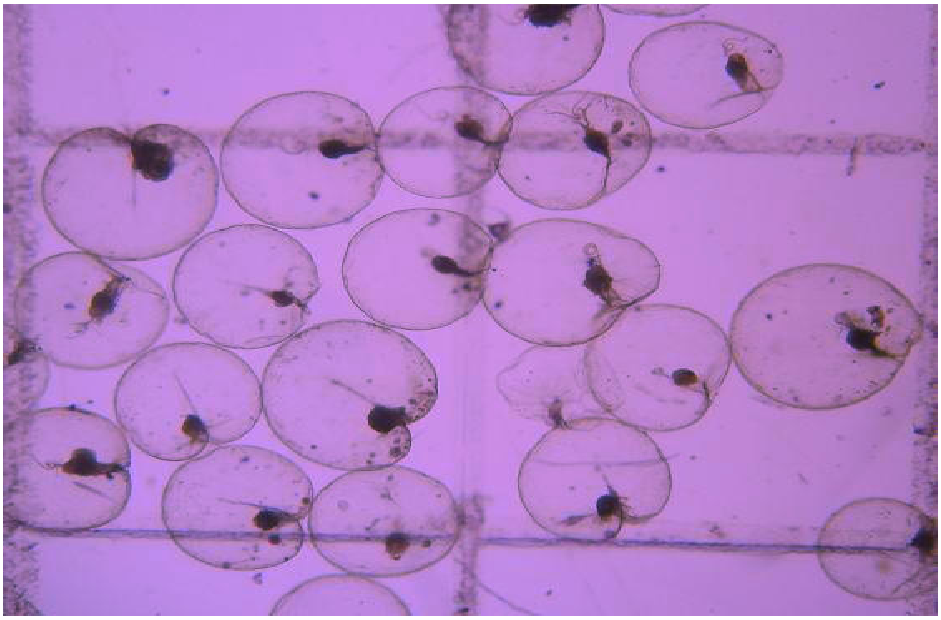


**Figure 50: Red *Noctiluca* bloom off Kochi (August 2008)**

**Figure 51: *Noctiluca* cells (40 x)**



*Noctiluca scintillans* has been reported as a voracious feeder preying on different micro organic food species of the pelagic food web (Fonda-Umani *et al*., 2004; Escalera *et al*., 2007; Sun *et al*., 2003). Green *N. scintillans* in nature primarily depends on the photosynthetic products of endosymbionts. However, the growth and proliferation of the red form of *N. scintillans* without endosymbionts depend very much on the size, quality and density of the prey (Buskey, 1995; Kiorboe and Titelman, 1998; Nakamura, 1998). *Noctiluca* collected during this bloom in the southwest Arabian Sea harboured diatoms (*Thalassiosira, Pseudonitzschia* etc.) in the food vacuoles suggesting that *N. scintillans* feeds on phytoplankton (Figure 52 and 53). Most of this algae, particularly species of *Pseudonitzschia*_are known to produce toxins that can cause fish kill and also lead to shell fish poisoning in humans. However, it is interesting to note that *Noctiluca* can feed toxic phytoplankton and thus function as vector for transfer of such toxins to higher trophic levels (Reguera *et al*., 1993; Blanco *et al*., 1998; Escalera *et al*., 2007).

*Noctiluca* is a competitor for the food of oil sardine (*Sardinella longiceps*) as both feed on diatoms like *Coscinodiscus, Nitzschia, Fragilaria* and *Thalassiosira* etc (Velappan Nair and Subrahmanyan, 1955) and the appearance of *Noctiluca* bloom may have a bearing on the decrease in catch of oil sardines from such areas. It is clear from our observations and enquiries (personal communication with fisher folks) that the commercial fishes particularly the shoaling species like mackerels, sardines, anchovies and fish larvae and zooplankton did not appear in such waters. There was no mortality of fish during the bloom period. The physicochemical characteristics like, slimy water and increased ammonia concentration of the affected waters were in some way unfavourable for live fishes that they completely avoided such areas.

The sea surface temperature (SST) during this period ranged from 26.03°C to 27.24°C. It has been reported that calm sea with relatively low temperature is favourable for triggering the appearance of the bloom (Saifullah and Chaghtai, 1990). Relatively stable low temperature, high salinity, calm sea, muggy weather and high prey concentration prevailed during the last phase of upwelling along the southwest coast favored the proliferation and blooming of *Noctiluca.* The salinity value of the bloom station was 34.11 psu.

In the bloom area the dissolved oxygen concentration was high (6.89ml $L^{-1}$) due to the increased photosynthetic activity of the diatom cells. This also indicates that the bloom was in its peak period. Normally *Noctiluca* bloom occurs in nutrient enriched waters during the course of plankton succession. High concentration of macronutrients like nitrate, phosphate and silicate in the surface layers during intense upwelling initially favours the proliferation of smaller diatoms. When the nutrient concentration decreases due to assimilation and weakening of upwelling, larger diatoms and dinoflagellates start to dominate and their low growth rate enables them to survive in such conditions. In the present study the bloom area showed lower concentration of nutrients except silicate. The low values of inorganic nutrients ($NO_3$-N, 0.44 µmol $L^{-1}$ and $PO_4$-P, 0.19 µmol $L^{-1}$) indicated that these were being actively utilized by the fairly large standing stock of phytoplankton. The relatively high value of silicates during the bloom (18.29 µmol $L^{-1}$) probably reflects the silicate excreted from *Noctiluca* which is known to be a consumer of diatoms

(Prasad and Jayaraman, 1954). Vertical distribution of physico-chemical parameters of the bloom area is represented in Figure 54.

**Figure 52: Food vacuoles near the gullet area inside *Noctiluca* cells (200 x)**

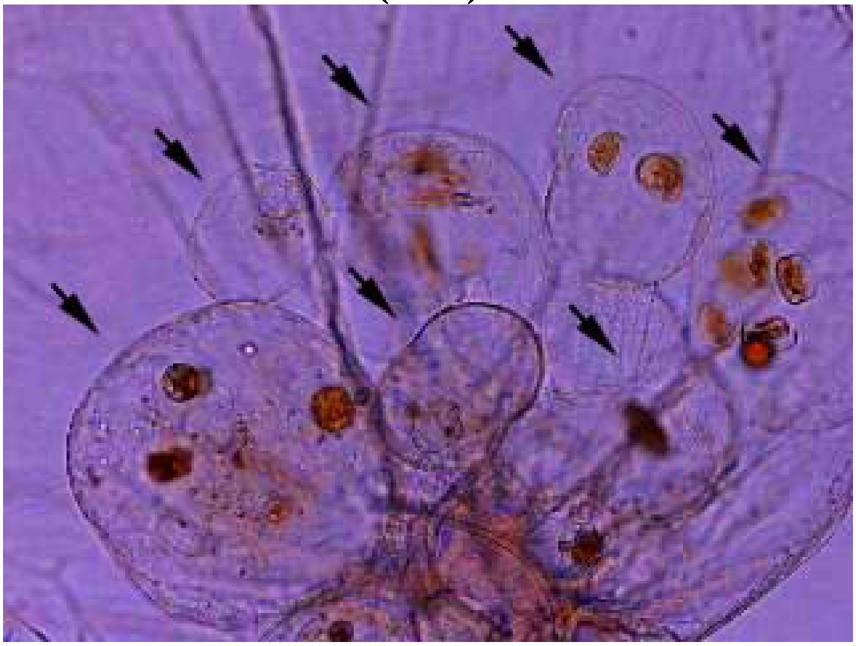
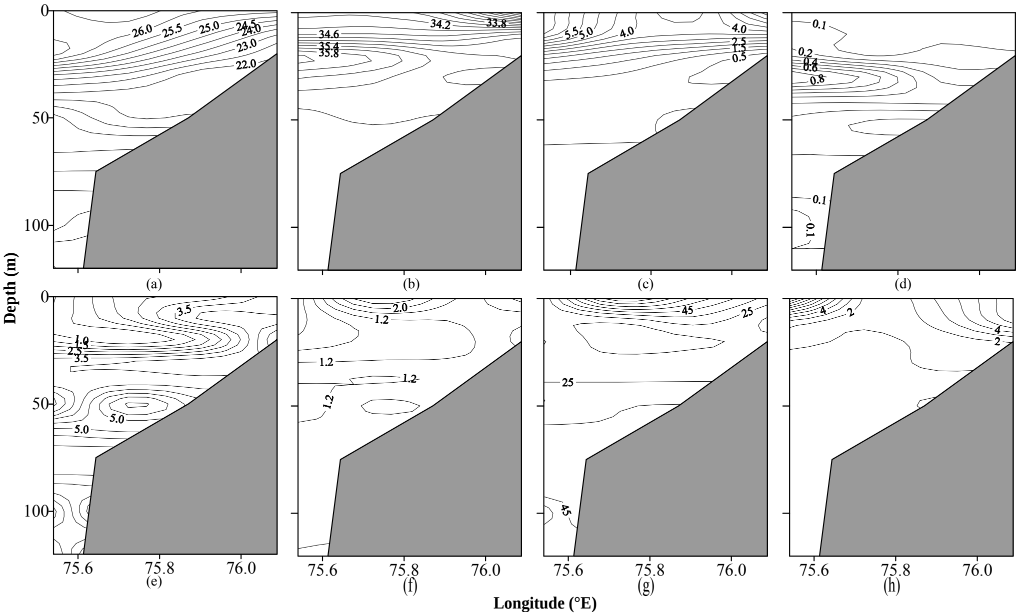


**Figure 53: Single food vacuole with diatom cells inside (400 x).**

**Figure 54:** Vertical distribution of **(a)** Temperature ($^0$C) **(b)** Salinity (psu) **(c)** Dissolved Oxygen (ml L$^{-1}$) **(d)** Nitrite (µmol L$^{-1}$) **(e)** Nitrate (µmol L$^{-1}$) **(f)** Silicate (µmol L$^{-1}$) **(g)** Phosphate (µmol L$^{-1}$) and **(h)** Chlorophyll *a* (µg L$^{-1}$) in the bloom area



The analysis of pigments in the bloom area revealed relatively high values of chlorophyll *a* (12.342 µg L$^{-1}$). These high values observed may be probably due to diatoms associated with *Noctiluca* as the heterotrophic *Noctiluca* cells observed here lacked the green endosymbiont *Pedinomonas noctilucae*. In the present study zooplankton biomass was lower in the bloom area (993.17 ml 1000m$^{-3}$) compared with the adjacent stations (1707.01 ml 1000m$^{-3}$). Copepods represented the major group in all the stations with a comparative decrease in bloom stations. The reasons for the reduced zooplankton biomass were 'animal exclusion' ascribable to the direct effects of external metabolites or ectocrines produced by the *Noctiluca* bloom and also by the competition for food resources between *Noctiluca* and zooplankton.

The reasons for the preponderance of *Noctiluca* are not clearly understood, but we hypothesize that *Noctiluca* multiplies rapidly and form aggregation only when the calm conditions prevail in the area, because turbulent conditions seem to be unfavourable for their rapid growth and blooming. Another factor is diatom abundance, if *Noctiluca* is present or carried into an area where there is rich diatom population, they multiply rapidly and form bloom provided the sea is calm. It is evident from the present study that the bloom of *Noctiluca* takes place only in the calm sea during or preceded by diatom bloom.

High primary production along the west coast during the monsoons owing to nutrient enrichment of the waters from upwelling and estuarine discharges probably sets the stage for blooming of non-autotrophic forms like *Noctiluca*. Normally along the west coast, red tides are generally reported between the last week of July to October, coinciding with the end of the upwelling season, when the weather is warmer with far longer hours of sunshine. The frequency of *Noctiluca* red tides has increased considerably in the coastal waters and it is believed to be linked with the eutrophication of coastal waters and the *Noctiluca* bloom probably is a biological indicator of eutrophication.

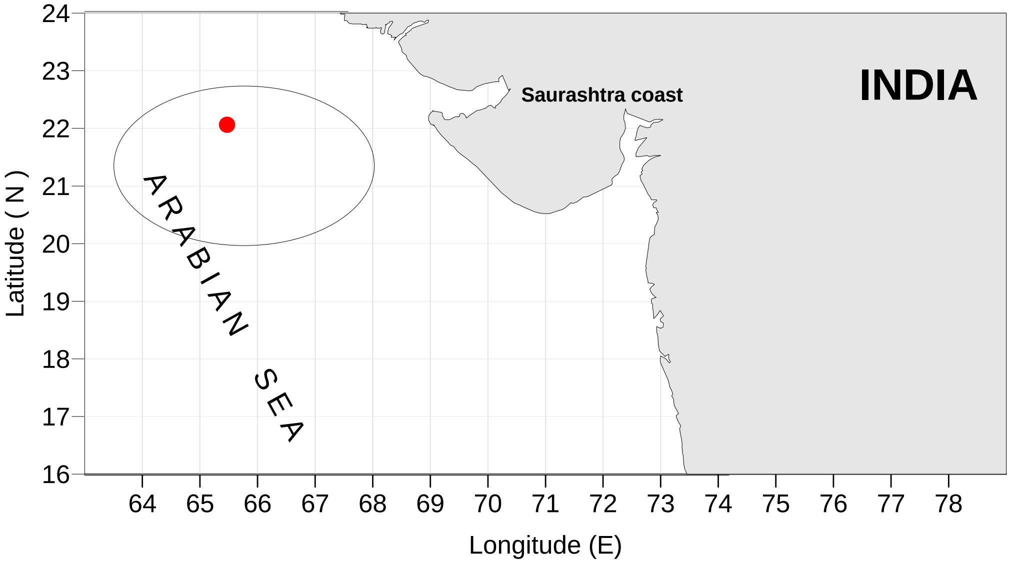
### 5.2.3 *Rhizosolenia* mats and occurrence of endosymbiont *Richelia intracellularis* (Cyanophyta) within the diatom *Rhizosolenia hebetata* in Northern Arabian Sea (March 2009)

Nitrogen is generally considered to be a major limiting nutrient for phytoplankton growth in coastal and oceanic waters. The fixation of atmospheric nitrogen in the oligotrophic ocean is an important source of new nitrogen to surface waters, stimulating phytoplankton productivity and fueling the biological pump. In tropical waters the non-heterocystous cyanobacterium *Trichodesmium* is largely responsible for nitrogen fixation (Karl *et al.,* 2002), but the heterocystous diazotroph cyanobacterium *Richelia intracellularis* provide quantitatively substantial inputs of nitrogen on regional scales (Carpenter *et al*., 1999). Symbiosis between cyanobacteria and marine organisms is abundant and wide spread among marine plants and animals. *Richelia intracellularis* Schmidt, a heterocystous cyanophyte is common in tropical and subtropical seas. It generally appears in symbiosis with phytoplanktonic species of the genus *Rhizosolenia* and *Hemiaulus* and with benthic diatoms of the genus *Pleurosigma* (Wood, 1965 and 1967) or as an epiphyte in *Chaetoceros compressus* or in *Rhizosolenia styliformis* var. *latissima* (Allen and Cupp, 1935; Sournia, 1968). The presence of a terminal heterocyst on each *Richelia* filament suggests that these blue green algae may have the ability to fix molecular nitrogen (Fay, *et al*., 1965; Venrick, 1974; Mague *et al*., 1977). Cyanobacteria contribute moderately large amount of nitrogen annually in the world ocean and are one quarter of the total input of nitrogen to the sea. The ability to utilize molecular nitrogen would seem to give a nutritional advantage in the inorganic nitrogen limited euphotic zone. Only a few workers have reported *Rhizosolenia- Richelia* association from Indian seas. Two records on occurrence of the species from the South East coast are found in the literature (Iyengar and Desikachary, 1944; Subrahmanyan, 1946).

The present communication reports the dominance of N-fixing (diazotroph) cyanobacterium *Richelia intracellularis* within the diatom *Rhizosolenia hebetata* Bailey forma *hebetata* in the phytoplankton collections from the Northern Arabian Sea.

This observation was based on phytoplankton samples collected during the FORV Sagar Sampada cruise from Northern Arabian Sea (Lat. 20°- 22° N and Long. 64°- 68° E, Figure 55) from ten stations covering an area of 1.2 x $10^5$ sq. km at the fag end of winter monsoon (Feb- March). The phytoplankton samples collected from these ten stations, one station (Lat. 22° 01.43 N, Long.65° 20.06 E) contained *Rhizosolenia* with endosymbiont *Richelia*. The physical and chemical characteristics of the water where *Rhizosolenia- Richelia* association was observed were compared with another station (Lat. 22° 03.15 N, Long. 66° 45.02 E) where this species was not found. The surface samples were obtained by filtering surface sea water through a 20 µ bolting silk and the filtrates preserved in 3% buffered formalin and Lugol's iodine. Subsurface samples (up to 120m) collected using Niskin bottles attached to CTD profiler and allowed to settle in glass sedimentation cylinders and concentrated to 50 ml after adding Formalin-Lugol's iodine solution. Physical parameters like temperature, salinity, density etc on a vertical profile were carried out employing the *Seabird 911 plus CTD* sensors to understand the oceanic processes. Sea surface temperature (SST) of the area was measured by ordinary thermometer. Nitrite, nitrate, phosphate and silicate were analysed using a segmented flow *Auto Analyzer (SKALAR)* onboard the vessel adopting standard procedures. Ammonium concentrations were determined by colorimetric methods. Dissolved oxygen was estimated following Winkler method. Chlorophyll *a* was measured spectrophotometrically using a double beam *Perkin Elmer* UV-Visible spectrophotometer following 90% acetone extraction method. The examination and photomicrographs of the samples were taken using a Nikon Eclipse microscope attached with Nikon DN 100 series digital camera. Organic matter was removed from the diatom cells using the methods of Hasle and Fryxel (1970) and the diatom species were identified with the help of the work of Hasle and Syversten (1997).

**Figure 55: Map showing the location of *Richelia-Rhizosolenia* association observed in Northern Arabian Sea**



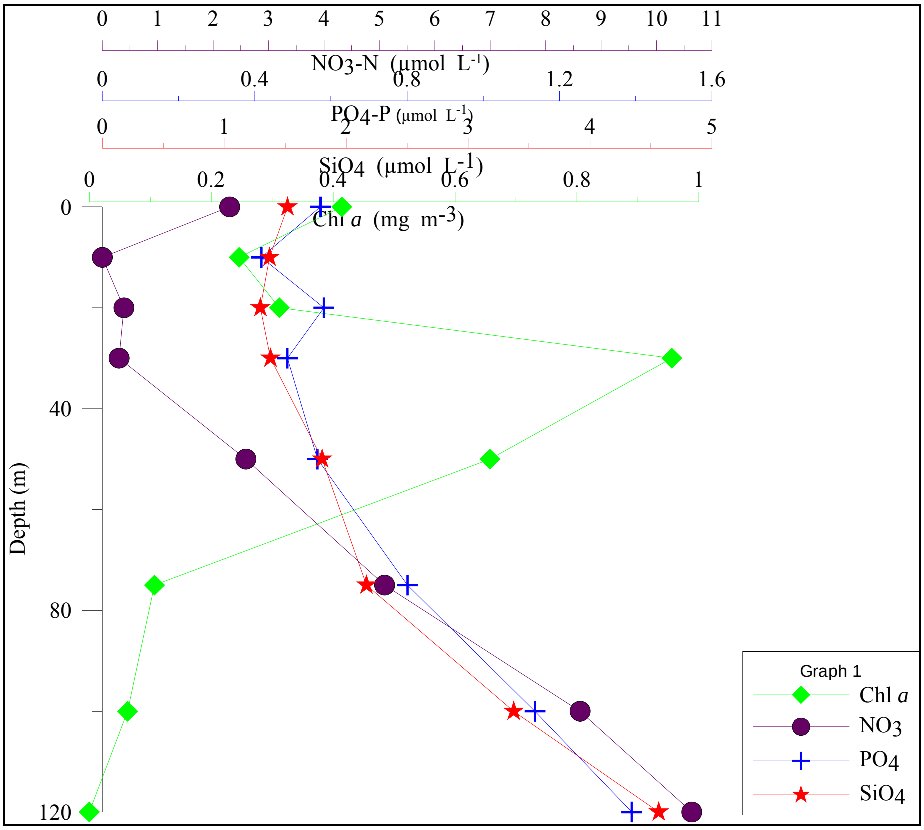
In general frustules of *Rhizosolenia* are solitary and often did not contain the endosymbiont *Richelia*. However, in the phytoplankton samples collected from the open ocean stations in Northern Arabian Sea numerous trichomes of *Richelia intracellularis* were observed as endosymbiont in *Rhizosolenia hebetata* (Figure 56 and 57). The presence of this endosymbiont was not total in *Rhizosolenia hebetata* in the collection examined. Moreover, within the *Rhizosolenia* mats individual diatoms with and without the symbiont co-occurred. The concentration of *Rhizosolenia* spp. was 91070 cells L$^{-1}$ and the genus was represented by four species *viz. R. hebetata*, *R. styliformis*, *R. imbricata* and *R. clevi*. Notwithstanding this *Rhizosolenia hebetata* formed the 80% of *Rhizosolenia* population and around 60% of this species harboured endophytic cyanophyte *Richelia*. The *Richelia* occupied the periplasmic space between the plasmalemma and the cell wall of the host. This symbiotic relation is more facultative than obligatory for *Rhizosolenia* can produce carbohydrate when enough nitrogen is available in the environment. The frustules of *Rhizosolenia* containing *Richelia*, in general had one trichome per cell or at most two, located at the ends of the cell and with the heterocysts oriented to the valve. The *R. hebetata* cells were varied in their size with diameter ranges from 8- 29 µm and length 210- 490 µm. Each trichome was composed of 8- 13 similar cells and one spherical heterocyst, with a well differentiated polar nodule. The diameter of the heterocyst varied between 9-13 µm and the total length of the trichome between 40- 71 µm (Figure 58). *Richelia* apparently did not persist outside its host; it was rarely seen as a free living trichome. Physico-chemical parameters of the area where *Richelia*- *Rhizosolenia* associations observed are presented in figure 59.

**Figure 56: *Rhizosolenia hebetata* with *Richelia intracellularis* x 400**

**Figure 57: *Rhizosolenia hebetata* without *Richelia* x 400**

**Figure 58: *Richelia intracellularis* x 400**

**Figure 59: Vertical distribution of chlorophyll *a* and nutrients in the *Richelia- Rhizosolenia* association observed area**



*Richelia* does not possess gas vesicles, it probably benefits from the buoyancy provided by the host diatom. The vertical distribution of *Richelia* corresponds to that of the host diatom. Viable cells of both have been recorded from the phytoplankton samples up to 100m depth. The majority of *Richelia- Rhizosolenia* associations have been recorded from the phytoplankton samples collected from 30 m or less. This is the reason for relatively high chlorophyll *a* (0.956 mg $m^{-3}$) at 30 m depth. Sea surface temperature and salinity of the area was 26.9°C and 36.48 psu respectively. Nutrient concentrations recorded in this area were as follows: 2.30 µmol $L^{-1}$ $NO_3$-N, 0.57 µmol $L^{-1}$ $PO_4$-P and 1.52 µmol $L^{-1}$

$SiO_4$. It is evident that the nitrate concentration (2.30 µmol $L^{-1}$) in the area where *Rhizosolenia- Richelia* association was observed was higher than that of the area where such a phenomenon was not observed (0.02 µmol $L^{-1}$). Ammonium concentration of the area was higher (4.11 µmol $L^{-1}$) compared to that of other open ocean stations, which could be attributed to the diazotrophic nature of cyanobacterium, which depicts the ability to produce ammonium from dinitrogen through the process of nitrogen fixation (Chang *et al.,* 2000).

Northern Arabian Sea (NAS) is oligotrophic in nature with limited source of nitrogen during all the seasons except winter monsoon (January- March). The main nutrient source in the NAS is by convective mixing during winter monsoon and such enrichment initiates multispecies phytoplankton bloom in this area (Madhupratap *et al.,* 1996). It is likely that besides convective mixing, inorganic nitrogen resulting from *Rhizosolenia- Richelia* symbiotic association supports increased primary production in the NAS.

### 5.2.4 *Trichodesmium erythraeum* bloom South Eastern Arabian Sea (June 2009)

*Trichodesmium* is a common non-heterocystous colonial marine diazotroph in oligotrophic tropical and subtropical oceans. Several authors have reported its importance in nitrogen fixation (Capone and Carpenter, 1982; Zehr *et al*., 2001; Lugomela *et al*., 2002; Capone *et al*., 2005). Nitrogen fixation by *Trichodesmium* cells represents an important input of new nitrogen into the euphotic zone, with daily fixation rates of approximately 30 $mg^{-1}$ N $m^{-2}$ $d^{-1}$ (Carpenter and Romans, 1991). Red tide phenomenons by *Trichodesmium* bloom have been reported earlier during the pre-monsoon (March to May) months from the EEZ of India by a number of researchers (Devassy *et al.*, 1978; Adhikary and Sahu, 1991; Santhanam *et al.*, 1994; Satpathy *et al.*, 1996; Jyothibabu *et al.*, 2003). Generally the bloom of this filamentous algae occurred during hot weather with brilliant sunlight and stable high salinity (Sellner 1997; Suvapepant, 1992). The occurrence of bloom is quite unusual during the onset phase of summer monsoon in the SEAS, where the key factor driving the productivity is the process of coastal upwelling. The present paper reports an unusual occurrence of *Trichodesmium erythraeum* bloom along the shelf waters of SEAS during the onset phase of monsoon as well as the associated coastal upwelling of 2009.

Blooms of *Trichodesmium erythraeum* were observed in three locations (Figure 60 and 61) during *FORV Sagar Sampada* cruise 267 along the SEAS, from 29th May to 11th June 2009. First one off Kollam (Bloom-1, 08°59.492 N, 75°59.334 E) with a pale brown discolouration of the surface water, spreading over an area of around 10 km$^2$ on 3rd June 2009. The brown colour of the *Trichodesmium* bloom shows the healthy nature of the bloom. The second one off Kochi (Bloom-2, 09°56.183 N, 75°54.948 E) and the third one off Kannur (Bloom-3, 11°59.891 N, 74°35.153 E) stretching around an area of more than 20 km$^2$ of a thick layer in saw dust like appearance and in pink reddish discolouration on 4th and 10th June 2009 respectively. The red or pink discolouration was due to the water soluble accessory pigments called phycoerythrin, an extra cellular leachate. The *Trichodesmium* filaments appear in light green after the leach out of accessory pigments making the chlorophyll *a* visible in cells, indicating the initial decay phase of the bloom.

**Figure 60: Map showing the location of *Trichodesmium* blooms**

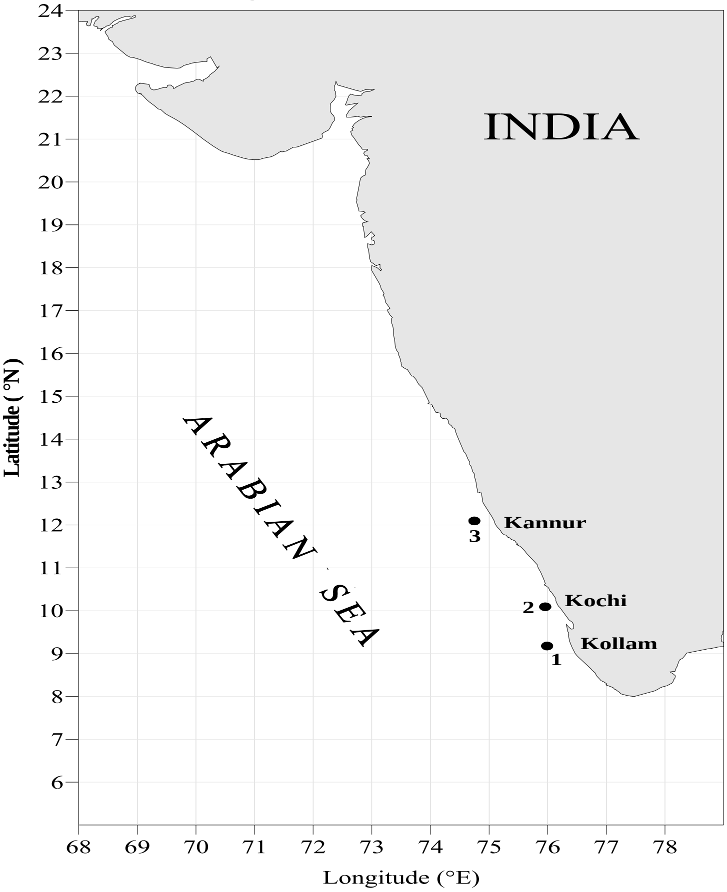


**Figure 61: *Trichodesmium* bloom off Kochi**

In order to understand the environment of the blooming area, continuous recording of weather data on wind speed, direction, rainfall etc. were studied onboard using Automated Weather Station (AWS). Hull mounted ADCP (BB 75KHz) was used to record vertical current profiles in 4m bin using the bottom track facility. The system was run via VMDAS (Vessel Mounted Data Acquisition Software) and the data were post processed using WinADCP during the entire cruise. Vertical profiling of parameters like temperature, salinity, density etc was also done using the CTD (Seabird 911 plus CTD) attached sensors to understand the oceanic processes. Sea surface temperature (SST) of the bloom regions were measured by thermometer attached to a bucket. The rosette system equipped with 10 liters Niskin bottles, attached to the CTD profiler was used for the collection of water samples for *Trichodesmium* enumeration from various depths in the upper water column. Surface accumulation of *Trichodesmium* samples were also collected using a plastic bucket and ~10 liters filtered and prepared for counting. Nitrite, nitrate, phosphate and silicate were analysed using a segmented flow Auto Analyzer (SKALAR) onboard the vessel by following standard procedures. Ammonium concentrations were determined manually by colorimetric methods. Photosynthetic pigments such as chlorophyll *a* and phaeophytin were measured spectrophotometrically using a double beam UV-Visible spectrophotometer (Parsons *et al*., 1984). Mesozooplankton samples were collected by Multiple Plankton Net (MPN) and Bongo nets.

Qualitative and quantitative analysis of bloom samples revealed that in all the three bloom areas *Trichodesmium erythraeum* contributes 90% of the surface phytoplankton population and the rest are predominantly formed of diatoms and dinoflagellates. Analysis of bloom samples revealed that the elongated rafts of *T. erythraeum* called "tufts" causes water discolouration. The cell density was 1.14x $10^6$ filaments $L^{-1}$, 1.968x $10^6$ filaments $L^{-1}$ and 1.51x $10^6$ filaments $L^{-1}$ off Kollam, off Kochi and off Kannur respectively. However, an analysis of the column phytoplankton depicted the presence of spiky balls of *T. thiebautii* called "puffs" as a major constituent. The colony consists of 10-30 trichomes in *T. erythraeum* and 30-50 trichomes in *T. thiebautii*. Positive buoyancy of *Trichodesmium* is well known and *T. erythraeum* is more buoyant than *T. thiebautii*. *T. erythraeum* has copious presence of gas vacuoles and hence was found in abundance in the surface waters (Carpenter, 1983; Capone *et al*., 1997; Lugomela *et al*., 2002).

The 2009 monsoon set in over Kerala on 23rd May, one week ahead its normal date of 1st June. And during 8th- 20th June, there was a prolonged hiatus in the advance of the monsoon along the region (IMD end of-season report 2009). In all the three transects where the occurrence of bloom was recorded, the wind pattern was westerly to northerly and moderate with an average magnitude of 5 m/s (Figure 62). Though the wind is mostly cross shore in the area, it is more northwest along the southern part, especially south to Kollam (9°N) and so induce offshore transport. The orientation of the coast line may also have a positive influence in the triggering of upwelling in the region (Smitha *et al*., 2008). Though the upward lifting of subsurface isotherms starts from March onwards (Shenoi *et al*., 2005) chemical and biological indications of the process are evident only with the commencement of the summer monsoon. With the onset in May end, weak to moderate upwelling occurs off the Kanyakumari coast (8°N lat) and spreads northwards along the coast as monsoon advances, reaching up to the Goa coast (15.5°N lat) during the peak monsoon. Signature of upwelling in the surface waters was observed in the southern part (Figure 63) up to Kollam (9°N), and it was confined to the coast, particularly off Kollam around 50m depth (34 km off shore). Whereas inter spring characteristics prevailed in the offshore surface waters of the transect, surface waters off Kochi and Kannur showing higher SST (>28.5°C) and stratified waters due to the abundant sunlight and weak wind. Vertical profiles of temperature (Figure 64) from CTD show upward shifting of isolines (26°C) towards the coast in the subsurface layers in these two transects. Table 23 shows the met-ocean parameters of the three bloom areas.

**Figure 62: *In-situ* record of wind pattern during the observation**

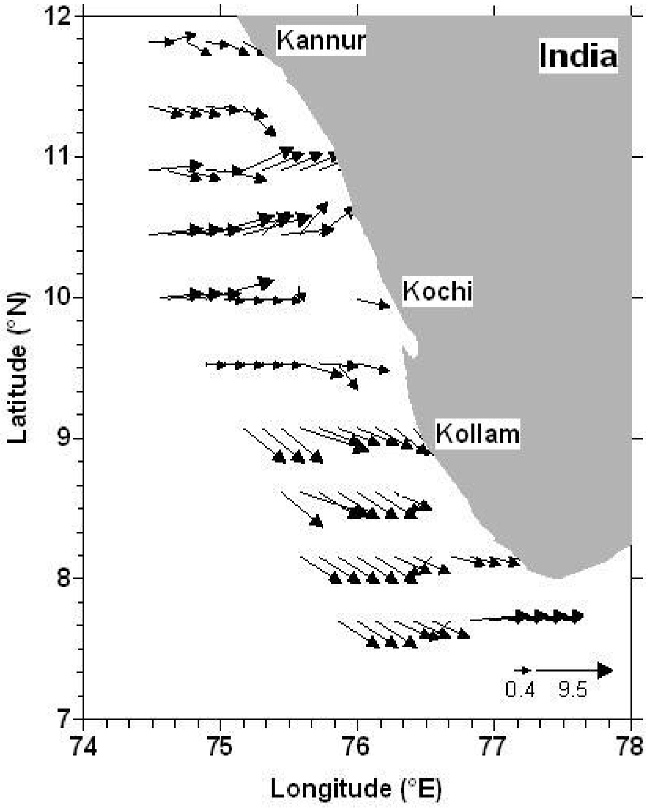


**Figure 63: Distribution of SST during the onset phase of upwelling**

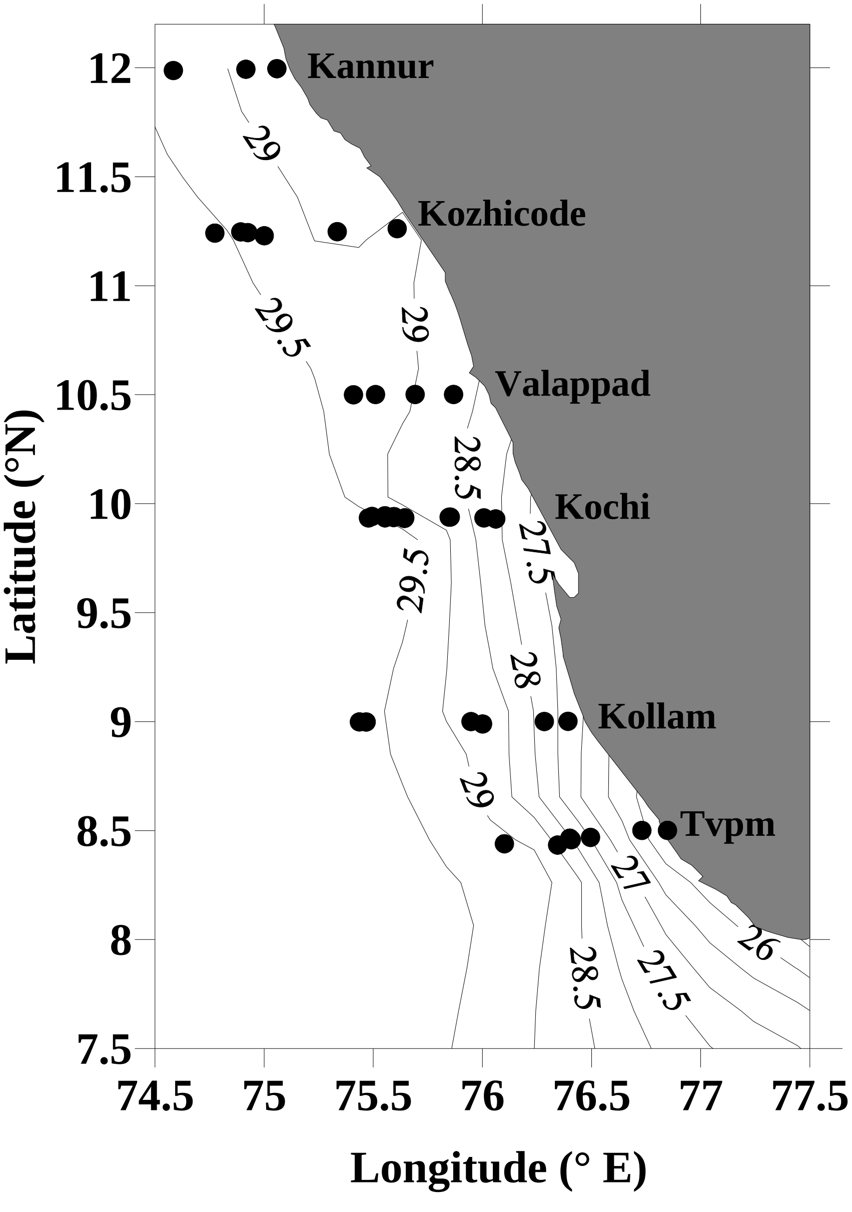
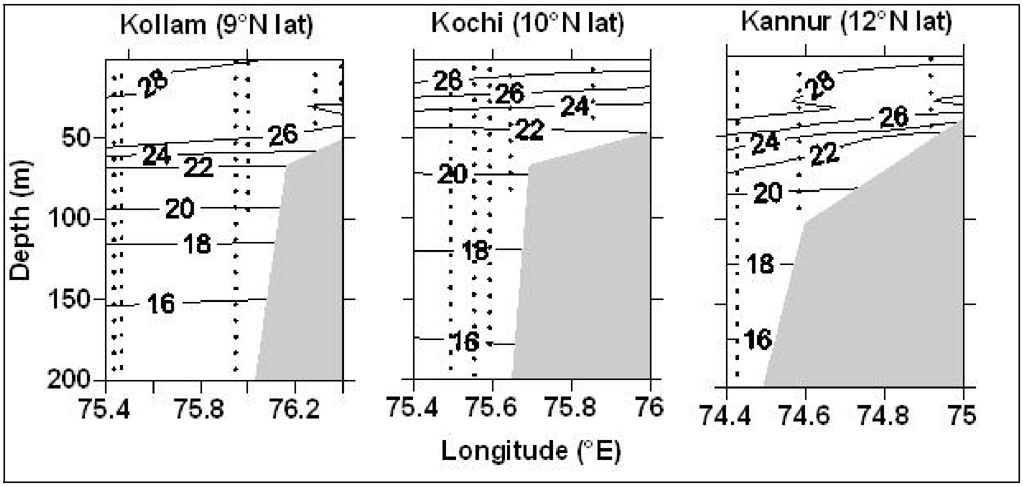


**Figure 64: Vertical section of temperature along the bloom transects. (....) indicate the sampling points**



The vector plot of surface ADCP currents (Figure 65) shows an overview of the prevalent conditions from 29th May to 13th June 2009. The near surface current pattern (24 m level) shows the presence of a well established WICC (West India Coastal Current) towards south, along the coast. The current is weaker (<100 mm/s) in the north and got strengthened up to 700 mm/ s along the middle as well as southern part of the study area. The slight deflection towards offshore seen in the pattern at 9°N and at the southern latitudes coincides with the upwelling areas showing the offshore transport and mixing up of water with the coastal current.

Generally the bloom of this filamentous algae occurred during hot weather with brilliant sunlight and stable high salinity (Suvapepant, 1992; Sellner, 1997) and Carpenter (1983) points out that *Trichodesmium* growth is not stimulated in classical upwelling areas.

**Figure 65: Near surface (24m) current pattern from ADCP during the onset phase of upwelling**

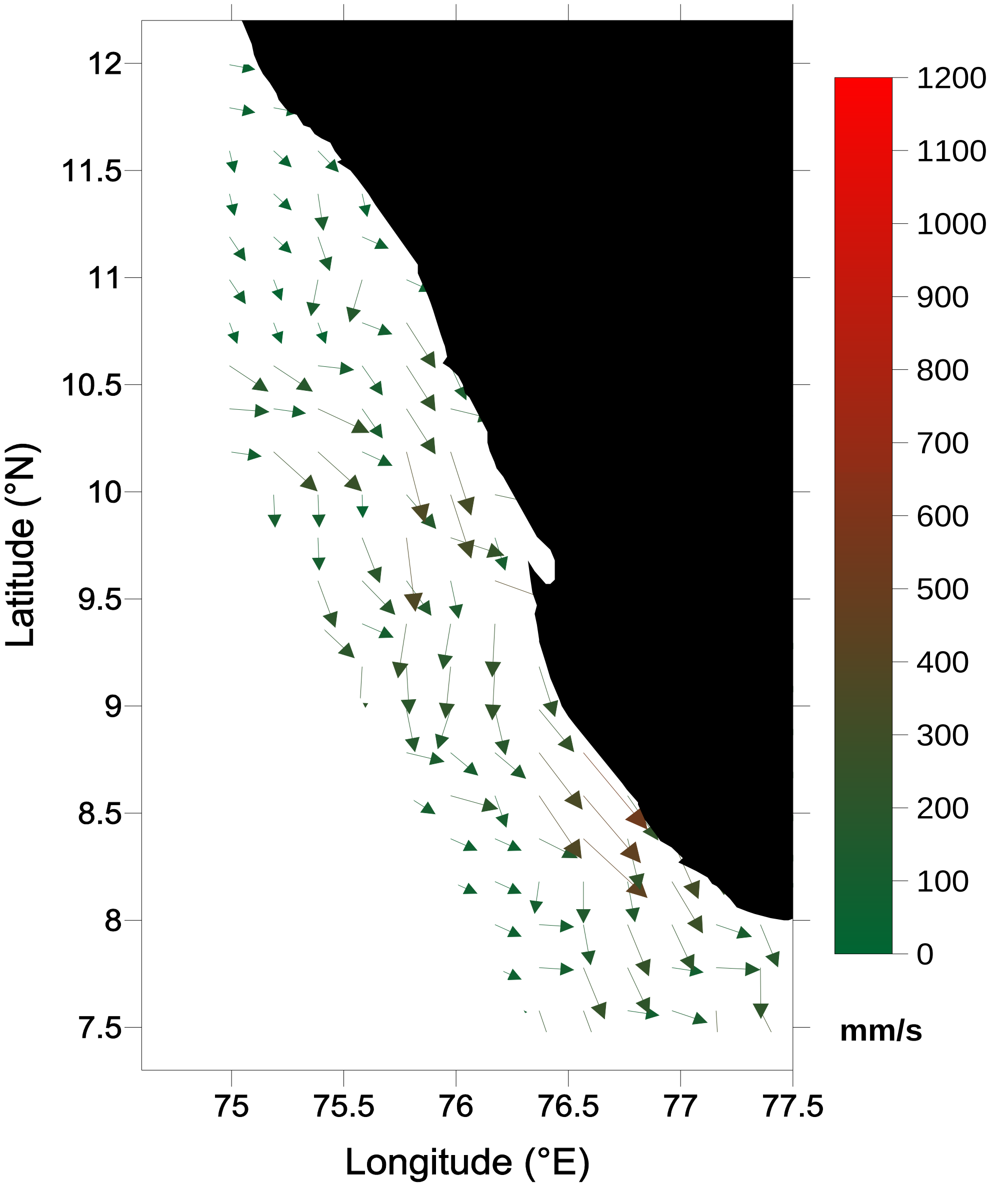


**Table 23: Met-ocean parameters of the three bloom areas**

| Parameters | off Kollam | off Kochi | off Kannur |
|---|---|---|---|
| Water colour | Pale brown | Straw yellow | Pink reddish |
| Wind speed (m/ sec) | 4.6 | 4.9 | 5.1 |
| Wind direction (°) | 299 | 270 | 282.2 |
| Air Temperature (°C) | 29.7 | 31.5 | 28.4 |
| Humidity (%) | 82.2 | 79.3 | 83.1 |
| Pressure (mbar) | 1010 | 1006.8 | 1007.5 |
| Solar radiation ( mw/ sq. cm) | 79.2 | 76.2 | 7.8 |
| SST (°C) | 28.7°C | 29.48 | 29.03 |
| Salinity (psu) | 35.13 psu | 35.17 | 35.47 |
| Mixed Layer Depth- MLD (m) | 10 | 10 | 16 |
| Isothermal Layer Depth-ILD (m) | 17 | 12 | 20 |
| Rain fall | Moderate rain | Nil | Nil |
| Weather | Calm | Calm | Calm |

The occurrence of *Trichodesmium* blooms during monsoon in an upwelling area can therefore be considered quite unusual. Observations show that upwelling was at its initial/ onset phase and was evident only at the southern part of the region up to Kollam (9$^o$N). The offshore extend of the process off Kollam was limited only up to 50m depth station (34 km from coast). The first bloom observed off Kollam is in and around an area where the station depth is ca 100 m (64 km from coast) and is noted that SST at these two locations differ by 1.457°C separated by a distance of 30 km. Off Kochi (10°N) and Kannur (12°N), no signature of upwelling was noticed in the surface and the water characteristics were more or less of a hot weather due to the break in monsoon during the period. During the observation SST falls in the range 28.52 to 29.22$^o$C and salinity 34.55 to 35.47 psu in the bloom regions. The warm sea surface with moderate salinity and sunlight were not subject to much change during this observation and were typical of the upper few meters of the tropical ocean waters like the pre-monsoon months. Since *Trichodesmium* is a stenohaline form, stable salinity condition with 32 psu or above support the growth and abundance of the species. The salinity remained almost constant in the three bloom area and there was no evidence of the dilution of sea water due to fresh water influence or rainfall because of the irregularity in the onset phase of the southwest monsoon. This irregularity and the associated delay in the occurrence of coastal upwelling might have helped the persistence of pre-monsoon condition in the area, which sustains the *Trichodesmium* bloom which was developed during the pre-monsoon months.

The average nutrient data of SEAS for June 2008 was $NO_3$-N 0.093 µmol $L^{-1}$, $PO_4$-P 0.061 µmol $L^{-1}$ and $SiO_4$ 0.972 µmol $L^{-1}$. However, higher values of $PO_4$-P, $SiO_4$ (0.108 µmol $L^{-1}$ and 1.29 µmol $L^{-1}$) and low values of $NO_3$-N (0.028 µmol $L^{-1}$) were recorded in 2009 where the bloom occurred. It is possible that elevated phosphate concentration is due to the microbial decomposition of organic matter and the silicate concentration could be associated to under utilization by the cyanobacteria bloom. The prolonged growth of phytoplankton in the stratified photic zone of the west coast during the pre-monsoon period seems to be the cardinal reason for the reduction of $NO_3$-N to very low limits. In such situations the growths of phytoplankton which require $NO_3$-N seem to be restricted, while *Trichodesmium* with its ability to fix molecular nitrogen flourishes in the area. Ammonium concentration of the bloom water (0.843 µmol $L^{-1}$) was slightly higher than that of non bloom area (BDL). This could be ascribed to the diazotrophic nature of *Trichodesmium* (Chang *et al*., 2000) and also due to the decomposition of ungrazed *Trichodesmium* bloom (Nair *et al*., 1992).

Dissolved oxygen was higher (6.85 ml $L^{-1}$) in the bloom areas possibly due to photosynthetic release of $O_2$ by the highly dense algal biomass. Similar increase in DO was also reported by (Capone *et al*., 1997). Chlorophyll *a* and phaeophytin showed higher values in the bloom area (chlorophyll *a* 14.66 µg $L^{-1}$ and phaeophytin 2.21 µg $L^{-1}$) compared to non-bloom (chlorophyll *a* 0.273 µg $L^{-1}$ and phaeophytin 0.134 µg $L^{-1}$). High phaeophytin suggests that the peak of the bloom was already over at the time of collection.

Zooplankton samples collected from the bloom area using Bongo nets contained large quantities of *Trichodesmium* which were removed as far as possible before determining the displacement volume. In all the three bloom areas zooplankton biomass was high (11.59 ml $m^{-3}$) compared to the non bloom area (2.39 ml $m^{-3}$). Copepods shows maximum numerical abundance and percentage composition among zooplanktons followed by chaetognaths, jellyfishes, amphipods, lucifer, gastropods, cladocerans, fish eggs and larvae. Among the copepods, harpacticoid copepod *Macrosetella gracilis* forms the dominant one. Microscopic analysis showed adult *Macrosetella gracilis* and its larvae found attached to the *Trichodesmium* filaments. The creeping larvae of this copepod require substratum for development and the adults graze on *Trichodesmium* filaments. Larvae, copepodites and adults have specialized hooks for attachment. This observation supports Bjornberg's (1965) laboratory observation that this algae serves as substratum for the development of copepods. Among fish eggs and larvae in the zooplankton samples, eggs were more abundant than larvae. Presence of fish eggs and larvae in association with the bloom indicates congregation of fish for spawning in the bloom area. Hence the occurrence of fish eggs and larvae in association with *Trichodesmium* bloom appears to be an adaptation by the adults to provide food and protection for the developing eggs and larvae.

Harmful effects associated with bloom may vary from negligible amounts to rather severe mortality of marine fauna. Number of fish mortalities by *Trichodesmium* blooms has been reported by earlier workers from Indian waters (Chacko, 1942; Devanesen, 1942). Whereas no fish mortality was observed during the present bloom in all the three areas. Information on fish landing gathered from different fishing harbors at Kollam, Kochi and Kannur shows that *Sardinella gibbosa*, *S. longiceps*, *Rastrelliger kanagurta* and *R. neglectus* formed the major constituent to fishery in the area. Gut content analysis of these species showed that *Trichodesmium* forms 55- 65 % of the total stomach contents. Many reports have reported that *Trichodesmium* forms the food for marine copepods and fishes (Bryceson and Fay, 1980; Carpenter, 1983). The present observation on the bloom and the associated environment and productivity pattern does not indicate any direct inhibitory influence on fishery in the bloom region. In conclusion, it is apparent that *Trichodesmium* bloom is ecologically significant to the productivity patterns of SEAS.

### 5.2.5 *Chattonella marina* bloom off Kochi (September 2009)

The raphidophyte flagellate, *Chattonella marina* (Subrahmanyan) Hara et Chihara is a well known causative organism of red tides and associated mass mortality of marine fauna throughout the world oceans. *C. marina* is able to produce haemolytic, haemagglutinating compounds and reactive oxygen species (ROS) including superoxide anion radicals ($O_2^-$), hydrogen peroxide ($H_2O_2$) and hydroxyl radicals ($OH^-$) (Onoue and Nozawa, 1989; Oda *et al.*, 1994), the maximum production of which occurs during the exponential growth phase. They are also known to produce neurotoxins, which were originally characterised form the dinoflagellate *Gymnodinium breve*. These polyether compounds are ichthyotoxic at nanomolecular concentrations with the gills acting as the main absorptive area for brevetoxins from the water column. *C. marina* has caused mass mortality of fishes, leading to great economic losses in many countries, and ROS production has been implicated as one of the major factors leading to fish mortality (Marshall *et al.,* 2002; Kawano *et al*., 1996).

The occurrence of red tides along the coasts of India has been fairly wide spread however, only a few reports are available on toxic red tides and associated mortality of marine fauna and shellfish poisoning (Hornell, 1917; Subrahmanyan, 1954; Karunasagar, 1992; Naqvi *et al*., 1998; Jugnu and Kripa, 2009). *Chattonella marina* (=*Hornellia marina*) was first described by Subrahmanyan (1954) from the coastal waters of Southwest coast of India with green discolouration of surface water and accompanied mortality among fishes and crustaceans. From the published reports it was clear that the *Chattonella* bloom was earlier recorded only twice from the Indian EEZ (Subrahmanyan, 1954; Jugnu and Kripa, 2009). The present communication gives an insight on the *Chattonella marina* bloom which developed off Kochi in September 2009.

During the routine monitoring of harmful algal blooms along the west coast of India onboard FORV Sagar Sampada, a rusty brownish red discolouration of surface water was observed off Kochi (Figure 66, Lat10°00.13 N, Long.75°58.86 E) on 26th September 2009. The bloom area was located approximately 3 nautical miles from the Cochin bar mouth, which discharges large quantities of estuarine waters to Arabian Sea during the southwest monsoon. From the microscopic analysis of fresh bloom samples, it was observed that the discolouration was by the blooming of an ichthyotoxic raphidophycean member *Chattonella marina* (Subrahmanyan) Hara et Chihara (Figure 67).

**Figure 66: *Chattonella marina* bloom site off Kochi (SW coast of India)**

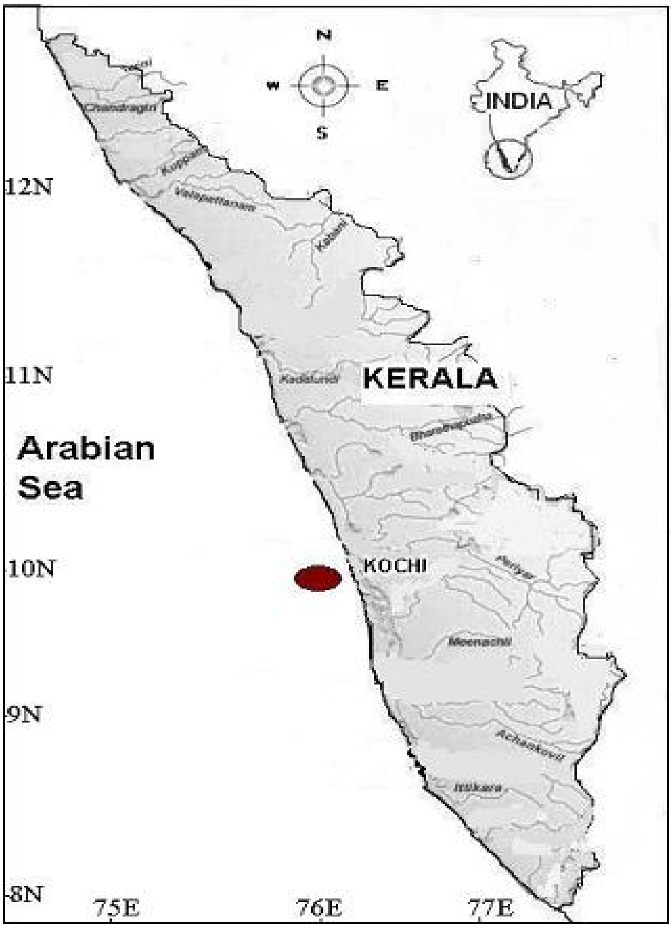
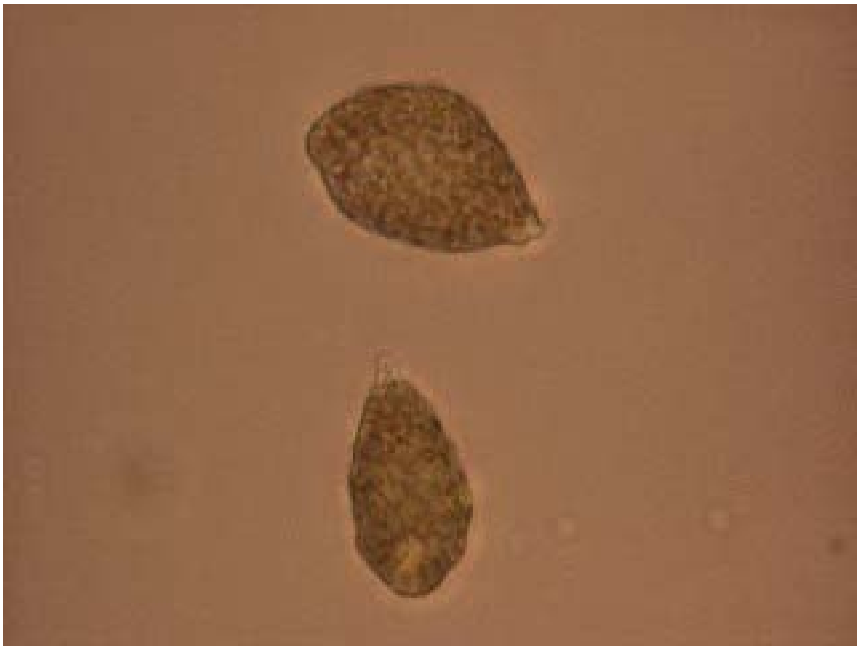


**Figure 67: Microphotographs of live cells of *C. marina* x 400**



For the qualitative and quantitative analysis of phytoplankton, 10 litres of discoloured surface water samples were taken using clean plastic bucket and filtered through 20 µ bolting silk and the filtrates were collected. Since the fixed *Chattonella* cells were deformed and shrank making it difficult to identify, unpreserved samples were first examined for identification and counted with Sedgwick-Rafter counting chamber using a *Nikon Eclipse* microscope following planktonic marine flagellate identification key by Throndsen (1997), and then preserved in 3% buffered neutral formalin/ Lugol's iodine solution for further analysis. The phytoplankton species were identified using standard keys (Tomas 1997). Size analysis of cells was done using an ocular-micrometer. Temperature and salinity at the sampling stations were recorded using *Seabird 911 plus CTD*. The Sea Surface Temperature was measured using a bucket thermometer. Salinity values from the CTD were calibrated against the values obtained using the *Guildline Autosal* onboard. Dissolved oxygen was estimated following Winkler method. pH was measured using an electronic *Ino Lab* (WTW series) pH meter. Chlorophyll *a* was determined by filtering one litre of water sample through GF/F Whatman filter paper. Filter papers with filtrates were placed in extraction vials containing 10 ml of 90% acetone and the extraction were performed under cold temperature in the dark over a 24 hours period. Chlorophyll *a* was measured spectrophotometrically (*Thermo UV1*) according to the methods described by Parsons *et al* (1984). Nutrients (nitrite, nitrate, phosphate and silicate) were analysed using segmented flow Auto Analyzer (*SKALAR*) onboard the vessel by following standard procedures (Grasshoff *et al*., 1983). Meteorological parameters were obtained by continuous Automated Weather Station (*AWS*). Degree of stratification in terms of static stability parameter (E) was computed following Pond and Pickard (1983), $E = {}^{-}1/\rho\ \partial\rho/\partial z - g/C^2$, where ‘g’ is the acceleration due to gravity, ‘ρ’ is the density which is a function of salinity, temperature and pressure, ‘C’ is the speed of sound. Procedure by Onoue and Nozawa (1989) was used for the separation of neurotoxin from the *C. marina* bloom samples and ichthyotoxicity test were carried out using juveniles of *Oreochromis mossambicus*. Mesozooplankton samples were collected from mixed layer by Multiple Plankton Net (*Hydrobios*) and from surface by Bongo nets. The samples were preserved in 4% formalin prepared in sea water after determining the biomass by displacement volume method.

The present *Chattonella marina* bloom was characterized by rusty brownish red discolouration of surface waters. Healthy individual of *Chattonella* normally contains numerous bright green, disc shaped chloroplasts distributed all over the body at the peripheral region. In previous reports of *Chattonella* bloom from Indian EEZ (Hornell, 1917; Subrahmanyan, 1954; Jugnu and Kripa, 2009) the water discolouration was greenish, showing the healthy and growing phase of the bloom. But here in our observation the brownish red discolouration was due to the dominance of unhealthy cells with yellow chloroplasts, showing the declining phase of the bloom. Phototaxis of *Chattonella* was observed during the present study. Brownish patches which aggregated along the ships shade during the course of sample collection indicated that *Chattonella* preferred lower light regime.

The physico-chemical parameters of the *Chattonella marina* bloom area was shown in figure 68 and 69. Temperature has been recognized as a major factor that controls *Chattonella* abundance (Nakamura and Watanabe, 1983). The observed sea surface temperature (SST) and salinity of the *Chattonella* bloom area was 25.56°C and 34.87 psu respectively, and is in the suitable range for the *Chattonella marina* bloom as reported by Yamaguchi *et al* (1991). Thermohaline stratification of the water column and the weak wind, which strengthens the stratification, is an important triggering factor to the development of harmful algal blooms (HABs) and was well documented (Amano *et al.*, 1998, Smayda, 1990). The vertical distribution of temperature and salinity (figure 70 and 71) in the *Chattonella* bloom area indicated thermohaline stratification in the water column with difference in temperature 2.14°C and salinity 0.21 psu. The degree of stratification is examined in terms of the static stability parameter (E) computed and presented in (Figure 72). The bloom station which is located in the shelf waters off Kochi (depth < 30 m), the stability maximum occurs at 8 m depth. These stratifications favours the *Chattonella* cells in their vertical movements (Handy *et al.*, 2005) thereby minimizing zooplankton grazing pressure and allowing the cells to obtain nutrients at depths and light at the surface.

Microscopic observations of unfixed bloom samples revealed the presence of *Chattonella marina* in the bloom area with cell density 1.59 x $10^7$ cells $L^{-1}$. Other phytoplankters were few in number represented by *Coscinodiscus asteromphalus* var. *centralis*, *Thalassiosira* sp., *Nitzschia longissima*, *Skeletonema costatum*, *Guinardia delicatula*, *Rhizosolenia* spp., *Psuedo-nitzschia* spp., *Ceratium* spp., *Dinophysis* spp., and *Prorocentrum* sp. Among these *Skeletonema costatum* was dominant with cell density 2.3 x $10^4$ cells $L^{-1}$. The present bloom was preceded by a multispecies diatom bloom dominated by *Skeletonema* and *Thalassiosira* spp. in the previous month (Aug 2009, from FORV data centre). A unique or unusual feature of the *Chattonella* bloom is that it occurred in cold water right after the diatom bloom, which developed during the early upwelling periods. The relation between bloom of *Skeletonema costatum* prior or in combination with other (Raphidophycean) red tide species were previously reported (Graneli *et al.,* 1995). *S. costatum* probably produces stimulants for growth of red tide species (Iwasaki, 1979).

**Figure 68: Vertical distribution of Temperature, salinity and DO in the *Chattonella* bloom area**

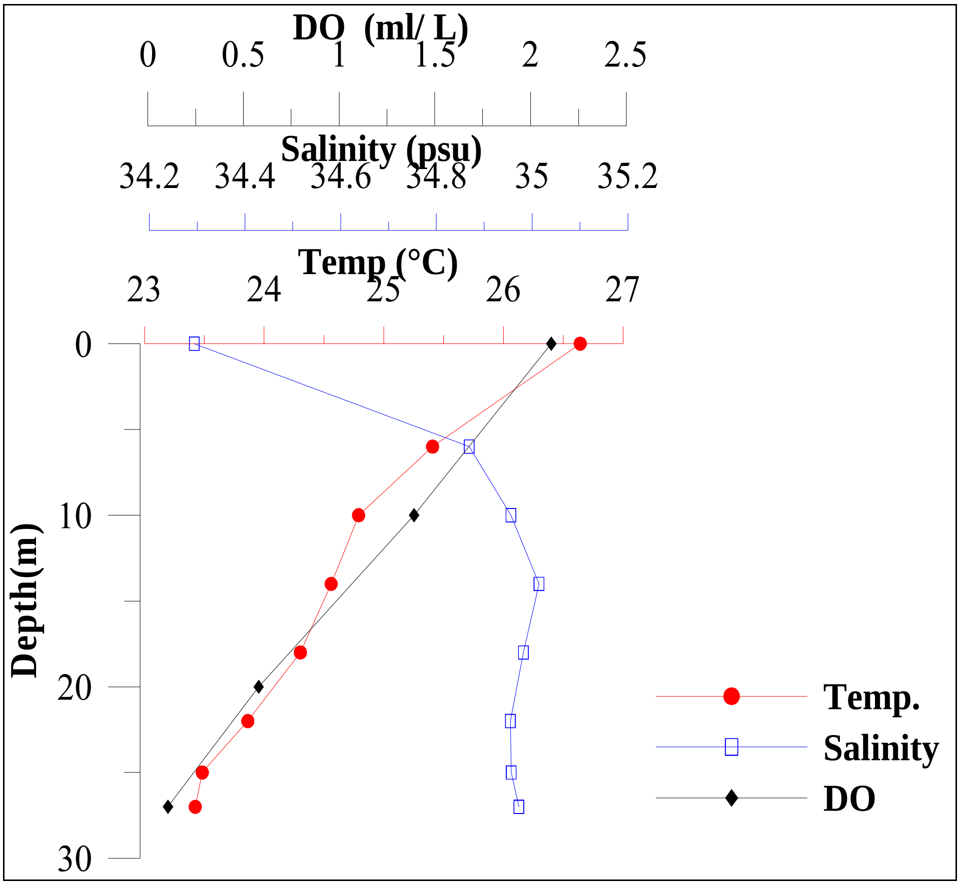


**Figure 69: Vertical distribution of Chl *a* and nutrients in the bloom area**

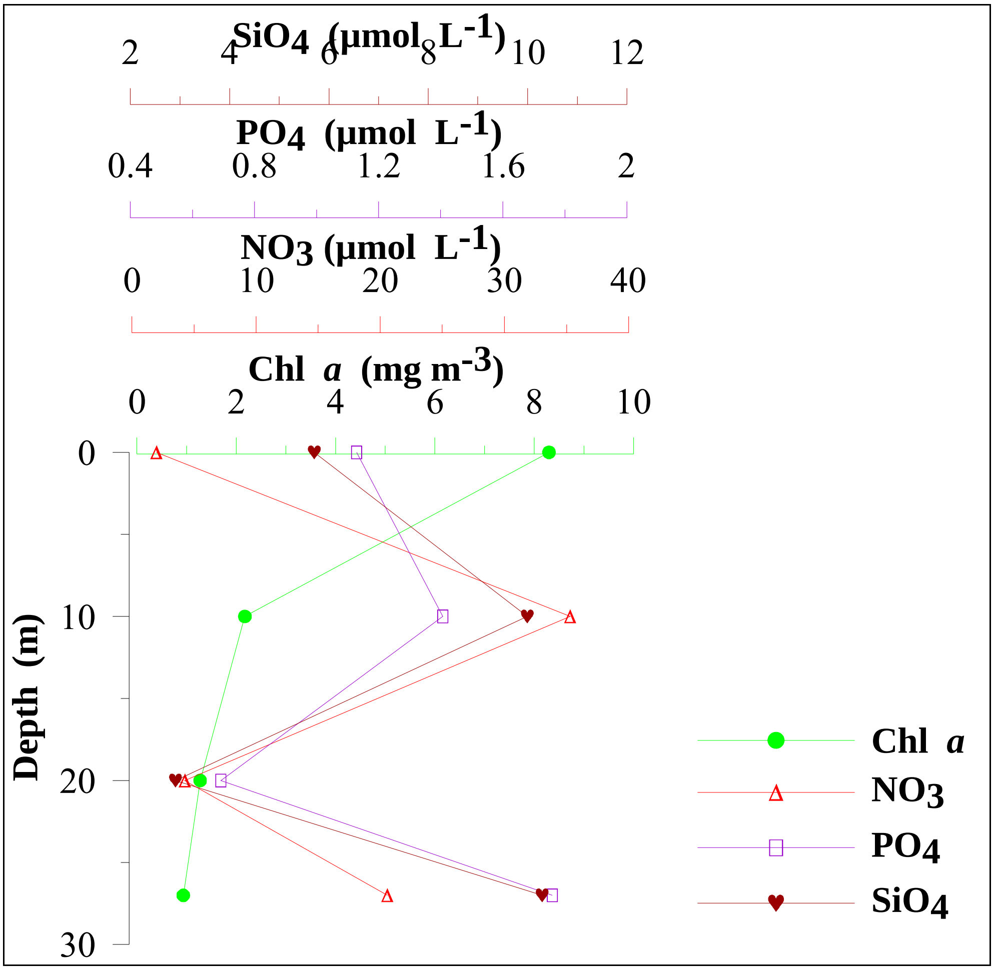


**Figure 70: Vertical section of Salinity along 10°N**

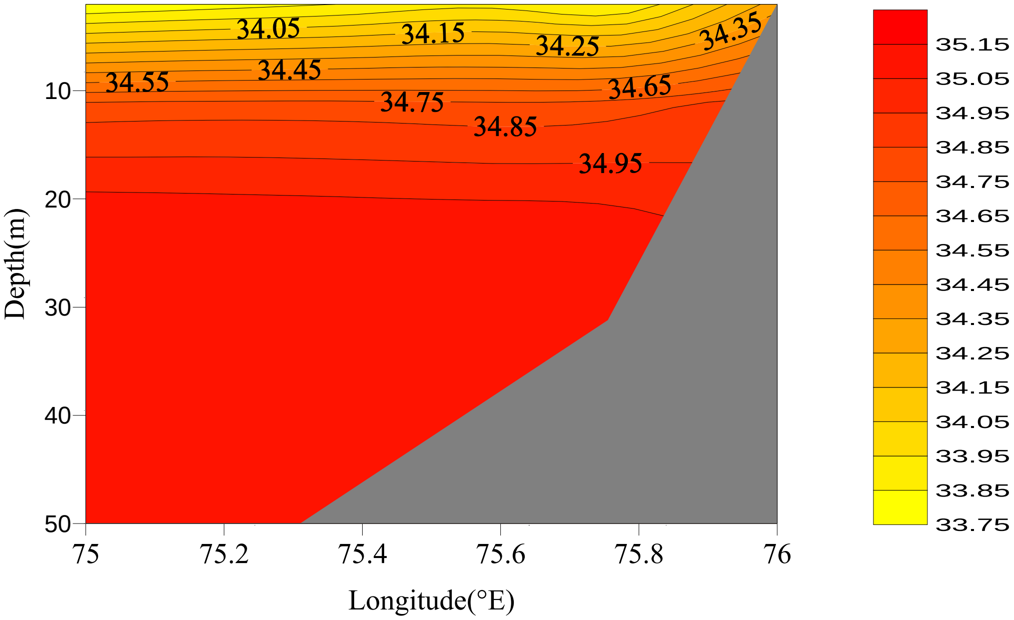


**Figure 71: Vertical section of temperature along 10°N**

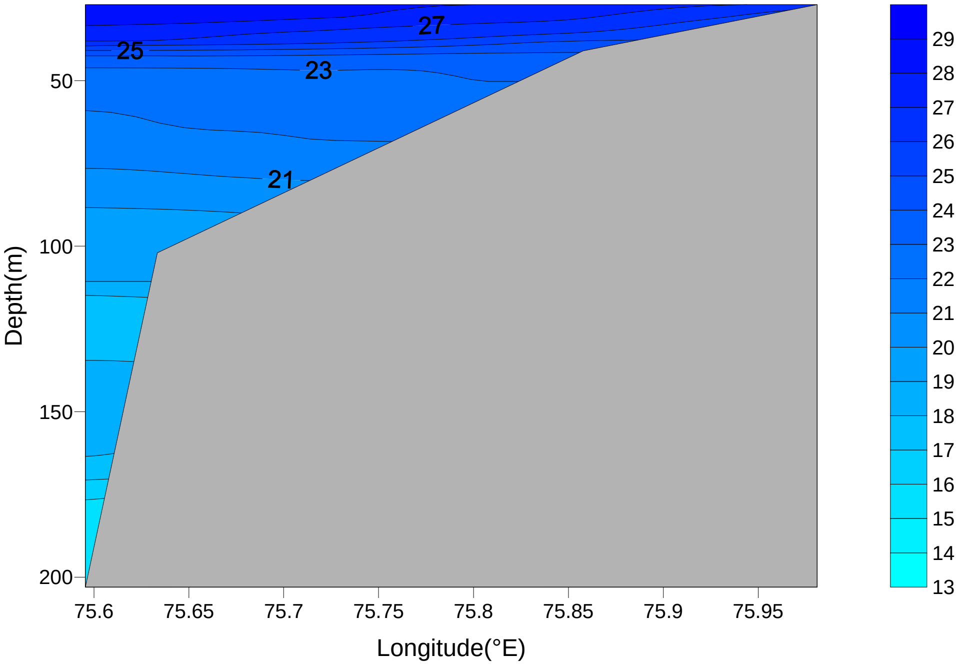
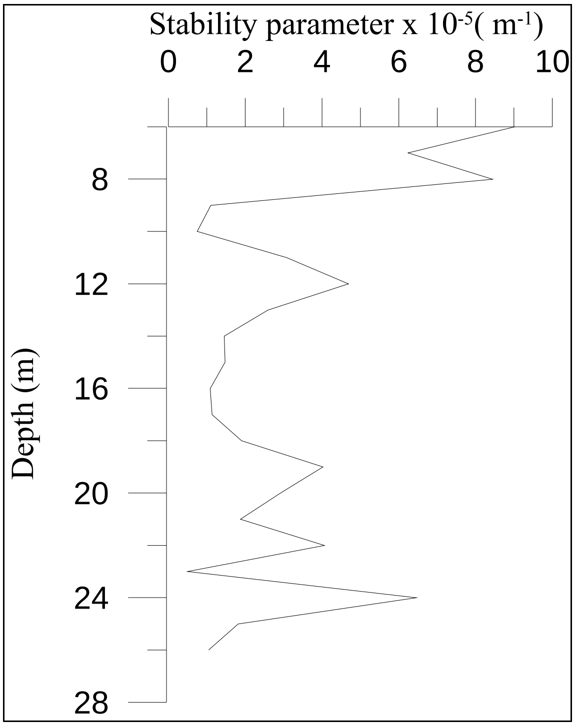


**Figure 72: Graph showing the degree of stratification in terms of static stability parameter 'E'.**



Dissolved oxygen values in the *Chattonella* bloom area (2.1 ml $L^{-1}$) was very low compared to the normal values reported from the southwest coast during the monsoon period (4.5 to 6.5 ml $L^{-1}$, Balachandran *et al.*, 1989). The low DO value in the present observation shows that the bloom was in declining phase.

Zooplankton bio-volume was low in *Chattonella* bloom area (1.37 ml $m^{-3}$) compared to that of non bloom area (3.14 ml $m^{-3}$). Copepods represented the major group with 1.36 x $10^{5}$ individuals $m^{-3}$. Zooplankton grazing did not appear to have a major impact on the bloom of *Chattonella* sp., thus reflecting zooplankton avoidance of the *Chattonella* bloom or high death rates of zooplankton exposed to the bloom (Hansen *et al.*, 2001). Reduced zooplankton grazing pressure during massive red tide could be attributed to the dense population HAB species, and also due to the production of grazing inhibiting compounds or toxins that deter grazers or lethal to grazers.

Mikhail (2007) reported chlorophyll *a* value of 90 µg $L^{-1}$ from Alexandria waters during a *Chattonella sp.* bloom. In this observation, concentration of chlorophyll *a* was 8.3 µg $L^{-1}$ showing the declining phase of the bloom. Nutrient levels were on a higher side in the *Chattonella* bloom area with $NO_3$-N, $PO_4$-P and $SiO_4$ concentration of 1.96 µmol $L^{-1}$, 1.13 µmol $L^{-1}$ and 5.70 µmol $L^{-1}$ respectively. Nutrient measurements made during the bloom imply that high nutrients, particularly inorganic nitrogen, may have played a role in initiation of this bloom. Eutrophication caused by the upwelling and heavy estuarine discharge during the SW monsoon is the reason for increased nutrient concentrations. Since *Chattonella* blooms are considered to start after the germination of cysts, the presence of nutrient rich surface water seems to play an important role in supporting a relatively hasty growth of cells during the initial phase of the bloom.

According to Hara *et al* (1994) the genus *Chattonella* comprises seven species, among these two species, viz., *C. marina* and *C. antique* are capable of producing extremely potent toxins fatal to diverse animal groups as well as to human beings. Hence, it was decided to test the toxicity, if any, in the case of current *C. marina* bloom. 'Alcohol extracts' of the *Chattonella* cells concentrated from the fresh bloom samples were used for bioassay on *Oreochromis mossambicus*. A series of toxicity tests were conducted and in each case the characteristic nuerotoxic symptoms leading to death of the fish were observed. A few dead fishes and crabs were observed along with the present *C. marina* bloom and might be due to its detrimental effects to fish associated with reduction in DO, obstruction of oxygen exchange in gills by ROS production and also due to the excretion of neurotoxins which result in haemoagglutination and haemolysis in fish blood.

Novel blooms of raphidophycean members and associated fish mortality is increasing globally in the recent years. The same holds true along the West coast of India where mortality of fish and other marine organisms caused by ichthyotoxic phytoplankton, bacterial/viral pathogens and anoxia is on the rise, while little is known about the raphidophycean *Chattonella* blooms. The present observation gives an insight to the *Chattonella* bloom and associated hydrographical features in the coastal waters of the west coast of India. Detailed study is required to elucidate the role of cyst germination in the bloom onset, development, and toxin production and associated environmental parameters since it is essential for effective management and mitigation of *Chattonella* bloom outbreaks.

The matter presented in this chapter has been published in various journals as listed below,

1. Padmakumar *et al.* (2008). ”Green tide” of *Noctiluca miliaris* in the Northern Arabian Sea. *Harmful Algae News (IOC- UNESCO*), No. 36.
2. Padmakumar *et al.* (2010). Preponderance of heterotrophic *Noctiluca scintillans* during a multispecies diatom bloom along the southwest coast of India. *International Journal of Oceans and Oceanography*, Vol. 4(1): 55-63.
3. Padmakumar *et al.* (2010). Occurrence of endosymbiont *Richelia intracellularis* (Cyanophyta) within the diatom *Rhizosolenia*

*hebetata* in Northern Arabian Sea. *International Journal of Biodiversity and Conservation*, Vol. 2(4): 70-74.

4. Padmakumar *et al.* (2010). Blooms of *Trichodesmium erythraeum* in the South Eastern Arabian Sea during the onset of 2009 summer monsoon. *Ocean Science Journal*, Vol. 45(3): 153-159.
5. Padmakumar *et al.* (2010). Monospecific bloom of noxious raphidophyte *Chattonella marina* in coastal waters of southwest coast of India. *Advances in Oceanography and Limnology* (Accepted, manuscript ID- TAOL-2010-0002).

# Summary and Conclusion

During recent years India has experienced an escalating and worrisome trend in the incidence of 'harmful algal blooms' (HABs) in the coastal waters. HAB events are characterised by the proliferation and occasional dominance of specific species of toxic or harmful algae. The causes behind this increase are debated, with possible explanations ranging from natural mechanism of species dispersal and enhancement (eg- climate change) to a host of human related phenomena such as pollution related nutrient enrichment, climate shifts or transport of algal species via ship ballast water. Whatever be the reasons, our coastal waters are now subjected to an unprecedented variety and frequency of HAB events. Besides eutrophication, zooplankton standing crop and their grazing are important factors in the population dynamics of harmful algae. Zooplankton can also act as vector of toxins to higher trophic levels. Accumulation and transport of these toxins through feeding interactions in pelagic food webs can also cause vectorial intoxication of consumers at higher trophic levels who are not direct consumers of toxic phytoplankton.

The present study "Algal blooms and zooplankton standing crop along the southwest coast of India" was conducted for monitoring the occurrence of algal blooms and its effect on other planktonic organisms along the southwest coast of India during the period 2006-09. During the course of this study, five algal blooms were observed and were dominated by the diatoms. *Thalassiosira partheneia* bloom was observed three times during the study period, twice at off Alleppey during the monsoon season of 2006 and 2007 and once off Kochi during the monsoon season of 2007. Off Kochi *Thalassiosira mala* bloom was observed during the monsoon period of 2006 and off Calicut, *Coscinodiscus asteromphalus* var. *centralis* caused an extensive bloom during the monsoon of 2006. The diatom *T. partheneia* bloom off Alleppey was found to co exist with the heterotrophic dinoflagellate *Noctiluca scintillans,* in very high cell density. However, when *T. partheneia* bloomed during monsoon of 2007 the dinoflagellate species of the genus *Ceratium* co existed in high cell density. It is note worthy that all these algal blooms were observed during the southwest monsoon period.

Invariably highest zooplankton biomass (dry weight) was observed along the southwest coast during the monsoon seasons, with rather low zooplankton diversity. It is likely that the reduction in diversity could be a factor influenced by the presence of algal blooms. On the contrary *Thalassiosira partheneia* bloom off Alleppey during monsoon seasons of 2006 and 2007, zooplankton biomass was found to be rather high with the dominance of copepods. While the blooming of *T. partheneia* off Kochi low zooplankton biomass was noticed. Similarly zooplankton biomass and abundance were low when a bloom of *T. mala* occurred off Kochi. *Coscinodiscus asteromphalus* var. *centralis* bloom off Calicut was accompanied by a very high biomass of copepods and copepodites. An inexplicable relationship is found to exist between diatoms blooms and copepod abundance.

The small centric diatoms like *Thalassiosira mala* and *T. partheneia* were previously not recorded to bloom in Indian waters.

During the present study blooms of *Thalassiosira* species occurred during the monsoon seasons. Diatoms being a significant food source of pelagic and benthic organisms can also cause ecological imbalance by enhanced rate of reproduction. *Thalassiosira* is a genus of phytoplankton with more than 100 species enjoying cosmopolitan distribution. *Thalassiosira* species are of significance among the phytoplankton and they become dominant during the spring season in the coastal ecosystem. *Thalassiosira mala* is probably the first marine planktonic diatom to be reported as being harmful to shellfish.

Upwelling, river discharge and mud banks along the southwest coast of India during the southwest monsoon have considerable influence on the coastal productivity. During the study, along the west coast, maximum production of phytoplankton takes place during the monsoon period after which there is a decline in the standing crop. The magnitude of algal blooms during the monsoon season in the coastal waters of west coast is of a very high order surpassing those known from some of the most productive waters of the world. The present investigations on salinity, temperature and nutrients have shown that optimum conditions are obtained during the southwest monsoon period.

Two types of *Noctiluca scintillans* (= *N. miliaris*) formed blooms in the Arabian Sea during the study period. The first one was the green *Noctiluca scintillans* in the Northern Arabian Sea appearing during the winter monsoon period. Innumerable motile prasinophyte endosymbiont (*Pedinomonas noctilucae*) were found harboured in the *Noctiluca* cells, resulting in a deep green hue to the surface waters. Convective mixing during winter cooling in the Northern Arabian sea was the main reason for this recurrent bloom. During the convective mixing in the northern

Arabian Sea, the upward transport of nutrients from the base of mixed layer and upper thermocline makes the surface water eutrophic which trigger the phytoplankton bloom. Food vacuoles were not observed in the *Noctiluca* cells. Zooplankton biomass was very high in the green *Noctiluca* bloom area when compared with that of non-bloom area. Copepoda, Chaetognatha, Cladocera, Fish eggs, Amphipoda, Heteropoda, Jellyfish, Lucifer, Oikopleura, Salps, Doliolids and Siphonophores were abundant in the zooplankton.

The second *Noctiluca* bloom was along the southwest coast with red discolouration and was caused by the red *Noctiluca scintillans*. These *Noctiluca* cells are without the green endosymbiont *Pedinomonas noctilucae*, but contained a number of food vacuoles harbouring diatom cells, giving the red discoloration. Green *N. scintillans* primarily depends on the photosynthetic products of endosymbionts. However, the growth and proliferation of the red form of *N. scintillans* without endosymbionts depend very much on the size, quality and density of the prey. The reasons for the preponderance of *Noctiluca* are not clearly understood, but it is clear that *Noctiluca* multiplies rapidly and form aggregation only when calm conditions prevail. Turbulent conditions seem to be unfavourable for their rapid growth and blooming. Prevalence of calm conditions and abundance of diatoms was found to be subscribe to the formation of blooms by *Noctiluca*. The present study has clearly shown that bloom of *Noctiluca* takes place only in the calm sea either before or during a diatom bloom. Zooplankton biomass was usually low in the *Noctiluca* bloom area and was dominantly supported by Copepods only. ‘Animal exclusion’ caused by the direct toxic effects of external metabolites or ectocrines produced by the *Noctiluca* bloom and high competition for food resources could be a contributory factor for copepod declension.

Generally the bloom of nitrogen fixing filamentous cyanobacteria *Trichodesmium erythraeum* was occurred in the Arabian Sea during the premonsoon period accompanied with stable saline conditions with brilliant sunlight. Therefore it was believed that *Trichodesmium* growth is not stimulated in classical upwelling areas. But during the present study unusual occurrence of *Trichodesmium erythraeum* bloom was observed along the southwest coast during the onset of summer monsoon in 2009. The occurrence of *Trichodesmium* blooms during monsoon in an upwelling area can therefore be considered quite unusual. Observations show that upwelling was at its initial/ onset phase and was evident only at the southern part of the region up to Kollam ($9^{o}$N). Off Kochi (10°N) and Kannur (12°N), no signature of upwelling was noticed in the surface and the water characteristics were more or less of a hot weather due to the break in monsoon during the period. During the observation SST falls in the range 28.52 to $29.22^{o}$C and salinity 34.55 to 35.47 psu in the bloom regions. The warm sea surface with moderate salinity and sunlight were not subject to much change during this observation and were typical of the upper few meters of the tropical ocean waters very similar to conditions encountered during the premonsoon months. The irregularity and the associated delay in the occurrence of coastal upwelling might have helped the persistence of pre-monsoon condition in the area, which sustained the *Trichodesmium* bloom which was developed during the premonsoon months.

In all the three *Trichodesmium* bloom areas, zooplankton biomass was high compared to the non bloom areas. Copepods showed maximum numerical abundance and percentage composition among the zooplankton. Among the copepods, harpacticoid copepod *Macrosetella gracilis* forms the dominant one. Adults and larvae of this species were found attached to the *Trichodesmium* filaments. Among fish eggs and larvae in the zooplankton samples, eggs were more abundant than larvae. Presence of fish eggs and larvae in association with the bloom indicates congregation of fish for spawning in the bloom area. Hence the occurrence of fish eggs and larvae in association with *Trichodesmium* bloom appears to be an adaptation by the adults to provide food and protection for the developing eggs and larvae.

*Rhizosolenia* mats were observed in the Northern Arabian Sea during the winter cooling period and were dominated by *Rhizosolenia hebetata*. Diazotrophic cyanobacteria *Richelia intracellularis* was observed inside the *Rhizosolenia* cells. Zooplankton biomass was very low in the area where *Rhizosolenia* mat was observed and was represented by few salps and large copepods. Reduction in zooplankton standing crop could be due to the unpalatability of *Rhizosolenia* and possibly the presence of ectocrines repellants.

The raphidophyte flagellate, *Chattonella marina* is a well known causative organism of red tides and associated mass mortality of marine fauna throughout the world oceans. Ichthyotoxic *Chattonella marina* bloom was observed off Kochi during the southwest monsoon period of 2009. Temperature has been recognized as a major factor that controls *Chattonella* abundance. The observed sea surface temperature and salinity of the *Chattonella* bloom area was in the suitable range for the *Chattonella marina* bloom. Thermohaline stratification of the water column and the weak wind, which strengthens the stratification, are important triggering factors to the development of harmful algal blooms. The vertical distribution of temperature and salinity in the *Chattonella* bloom area indicated thermohaline stratification in the water column. These stratifications favours the *Chattonella* cells in their vertical movement minimizing zooplankton grazing pressure and allowing the cells to obtain nutrients at depths and light at the surface.

Zooplankton bio-volume was low in *Chattonella* bloom area compared to that of non bloom area. Zooplankton grazing did not appear to have a major impact on the bloom of *Chattonella* sp. This may be indicative of the fact that zooplankton avoid the *Chattonella* bloom area or heavy mortality of zooplankton occurs when they are exposed to the bloom. Reduced zooplankton grazing pressure during massive red tide could be attributed to the dense population of HAB species, and also to the production of grazing inhibiting compounds or toxins which either deter grazers or lethal to grazers. A series of toxicity tests were conducted on *Oreochromis mossambicus* and in each case the characteristic nuerotoxic symptom leading to death of the fish was observed. A few dead fishes and crabs were observed along with *C. marina* bloom. It is likely that high cell densities occluded proper oxygen transfer from the water through gills causing asphyxiation and death of fish. Further obstruction of oxygen exchange in gills by ROS production and presence of neurotoxins resulting in haemoagglutination and haemolysis in fish blood could also have lethal effects on fishes.

The occurrence of algal blooms is a regular feature of the southwest monsoon seasons along the southwest coast of India. The reason for the build up of algal bloom might be enhanced rate of cell division of the algae caused by the nutrients supplied by the coastal upwelling. Zooplankton grazing was unable to keep pace with the growth of these algae leading to the formation of algal blooms. Diatoms normally flourishing during the summer monsoon and in the later stages dinoflagellate dominates the region.

In the present study potentially harmful micro algae like *Pseudonitzschia* spp., *Thalassiosira mala*, *Coolia monotis*, *Dinophysis accuminata*, *D. caudata*, *D. fortii*, *D. miles*, *D. tripos*, *Gonyaulax* sp., *Prorocentrum lima*, *Ceratium furca*, *C. fusus and Chattonella marina* were recorded from the coastal waters of southwest coast of India, indicating the possibility of potential menace of harmful algal blooms in the west coast of India. Among these micro algae a few have the ability to produce potent toxins. These toxic species use chemical defences or poisonous substances to dampen herbivorous feeding, leading to starvation and death of the consumer populations, which could have a cascading effect on the trophic pathway. In other cases, when toxic species are grazed, copepods or other planktonic herbivores can act as vector of toxins across the marine food webs. Hence it is recommended that regular monitoring of the occurrence of these toxic micro algae, presence of the toxins in water, zooplankton and shellfishes are important measures for decreasing the negative impacts of HABs to marine ecosystems and food web.

Several authors argue that there has been a steady increase globally in harmful phytoplankton blooms during the last three decades. Concern has been expressed with respect to the potential role that human activities have played in this increase. However, there are some indications of escalation of occurrence of HABs. There is a degree of subjectivity associated with the definition of algal blooms. The utilization of coastal resources has been expanding in recent decades. What is harmful today in a region heavily exploited for fishing and aquaculture might not have been noticed in the period prior to such activities. The regular cruises conducted by FORV Sagar Sampada during the last 15 years has resulted in gathering large quantum of sea truth data making it possible to know more about the status of the coastal and oceanic features of tropical seas. Observations in the Indian seas show that only a small number of species play important role in forming blooms. Dinoflagellates pose a bigger threat to the trophic chain than the diatoms. There is a lack of information of the time series of HAB incidence from the Indian seas. Biogeographically the present studies shows that there is a spreading of HAB along the Indian coast. It would be helpful to develop time and space series of data on HAB in the coming years so that the role of specific species set on bloom formation and the physico chemical trigger that leads to bloom formation by these select species could be defined and the science behind the phenomena in the tropical seas is properly delineated for the scientists interested in this field of research. It is possible that bloom formation in surface waters in the tropical seas is more predictable and this feature would help in understanding tropical harmful algal blooms better. It is necessary to accurately identify and establish early monitoring programmes in order to decrease the negative impact of HAB. The effects of these blooms in seafood quality, economic liabilities on fisherfolks, correct assessment of factors triggering blooms and subsequent effects in the trophodynamics are areas which need elaborate studies.

# References

Achuthankutty, S. R., S. R. Sreekumaran Nair, P. Haridas and M. Madhupratap (1989). Zooplankton composition of the Kalpeni and Agatti atolls, Lakshadweep archipelago. *Indian J. Mar. Sci.*, Vol. 18: 151-154.

Adams, J. A., D. D. Seaton, J. B. Buchanan and M. R. Longbottom (1968). Biological observations associated with the toxic phytoplankton bloom off the east coast. *Nature*, 220: 24-25.

Adhikary, S. P and J. Sahu (1991). Studies on the *Trichodesmium* bloom of Chilka Lake, East coast of India. *Phykos*, 30: 101-107.

Aiyar, R. G (1936). Mortality of fish of the Madras coast in June 1935. *Current Science*, 5: 488.

Allen, W. E and E. E. Cupp (1935). Plankton diatoms of the Java Sea. *Annales du Jardin Botanique de Buitenzorg*, 44 (2): 101-174, 127 figs.

Alvarez-Salgado, X. A., G. Roson, F. F. Perez, F. G. Figueiras and Y. Pazos (1996). Nitrogen cycling in an estuarine upwelling system, the Ria de Arousa (NW Spain). I. Short-time-scale patterns of hydrodynamic and biogeochemical circulation. *Mar. Ecol. Prog. Ser.*, 135: 259-273.

Amano, K., M. Watanable, K. Kohata and S. Harada (1998). Conditions necessary for *Chattonella antique* red tide outbreaks. *Limnology and Oceanography*, 43: 117-128.

Anderson, D. M (1995). Toxic red tides and harmful algal blooms: A practical challenge in coastal oceanography. *Reviews of Geophysics, Supplement*: 1189-1200.

Anderson, D. M (2004). The growing problem of harmful algae. *Oceanus magazine*, 43(1).

Anderson, D. M (2009). Approaches to monitoring, control and management of harmful algal blooms (HABs). *Ocean and Coastal Management*, 52: 342-347.

Anderson, D. M and A. W. White (1992). Marine biotoxins at the top of the food chain. *Oceanus*, 35(3): 55-61.

Anderson, D.M and A. W. White (eds.) (1989). Toxic dinoflagellates and marine mammal mortalities. Woods Hole Oceanog. Inst. Tech. Report WHOI- 89-36 (CRC-89-6).

Anoop, A. K., P. K. Krishnakumar and M. Rajagopalan (2007). *Trichodesmium erythraeum* (Ehrenberg) bloom along the southwest coast of India (Arabian Sea) and its impact on trace metal concentration in seawater. *Estuarine Coastal and Shelf Science,* 71: 641- 646.

Ansotegui, A., J. M. Trigueros and E. Orive (2001). The use of pigment signature to assess phytoplankton assemblage structure in estuarine waters. *Estuarine Coastal and Shelf Science*, 52: 689-703.

Antony, G., K. N. Kurup, T. S. Naomi, K. Solomon and K. J. Mathew (1997). Zooplankton abundance and secondary production in the seas around Andaman- Nicobar Islands. *Indian J. Fish*., 44 (2): 141-154.

Atkinson, A (1996). Subantarctic copepods in an oceanic, low chlorophyll environment: ciliate predation, food selectivity and impact on prey populations. *Mar. Ecol. Prog. Ser.,* 130: 85-96.

Azov, Y (1986). Seasonal patterns of phytoplankton productivity and abundance in near shore oligotrophic waters off the Levant basin (Mediterranean). *Journal of Plankton Research*, Vol. 8(1): 41-53.

Baars, M. A and S. S. Oosterhius (1997). Zooplankton biomass in the upper 200 m in and outside the seasonal upwelling areas of the Western Arabian Sea. *IOC Workshop Report,* 142: 36-49.

Bakun, A., C. Roy and S. Lluch-Cota (1998). Coastal upwelling and other processes regulating ecosystem productivity and fish production in the western Indian Ocean. *In*: Large Marine Ecosystems of the Indian Ocean: Assessment, Sustainability and Management. K. Sherman, E. Okemwa & M. Nitiba (Eds.) Malden, Massachusettes: Blackwell Sciences Inc., pp. 103-141.

Balachandran, V. K., M. S. Rajagopalan and V. K. Pillai (1989). Chlorophyll *a* and pheo-pigment as indices of biological productivity in the inshore surface waters off Cochin. *Indian J. Fish.*, 36 (3): 227-237.

Balakrishnan Nair, N and D. M. Thampy (1980). Organic production in the sea. In: *A text book of Marine ecology*, 255-275.

Banse, K (1959). On upwelling and bottom- trawling off the southwest coast of India. *J. Mar. Biol. Asso. India,* 1(1): 33-49.

Banse, K (1995). Zooplankton: Pivotal role in the control of ocean production. *ICES Journal of Marine Science,* 52: 265-277.

Banse, K., Sumitra-Vijayaraghavan and M. Madhupratap (1996). On the possible causes of the seasonal phytoplankton blooms along the west coast of India. *Indian J. Mar. Sci.*, 25**:** 283-289.

Bates, S. S., C. J. Bird., A. S.W. De Freita, R. Fosall, M. Gilligan, L. A. Hanie, G. R. Johnson, A. W. Mc Calloh, P. Odense, R. Pocklington, M. A. Quillon, P.G. Sim, J. C. Smith, D. V. Subha Rao, E. C. D.

Todd, J. A. Walter, J. H. C. Wright (1989). Pennate diatom *Nitzschia pungens* as the primary source of domoic acid- a toxin in shell fish from eastern Prince Edward Island Canada, *Can. J. Fish. Aquat. Sci*., 46: 1203-1215.

Bates, S. S., D. L. Garrison and R. A. Horner (1998). Bloom dynamics and physiology of domoic acid- producing *Pseudo-nitzschia* species. *In*: Physiological Ecology of Harmful Algal Blooms. Anderson, D.M., Cembella, A.D., Hallegraeff, G.M. (Eds.), Springer-Verlag, Heidelberg, p. 267.

Beaulieu, J. L., M. Castonguay, M. Levasseur, F. Gregoire, S. Michaud, E. Bonneau and S. S. Bates (1996). Role of PSP (Paralytic Shellfish Poisoning) toxins in an Atlantic mackerel (*Scomber scombrus*) mortality in Nova Scotia in 1993. *Can. Ind. Rep. Fish. Aquat. Sci*., 236:1-17.

Bhargava, R. M. S., P. M. A. Bhattathiri, V. P. Devassy and K. Radhakrishnan (1978). Productivity studies in the southern Arabian Sea. *Indian J. Mar. Sci*., 7 (11): 267-270.

Bhat, R.V. (1981). A report on an outbreak of mussel poisoning in coastal Tamil Nadu, India. National Institute of Nutrition, Hyderabad.

Bhattathiri, P. M. A., A. Pant, Surekhs Sawant, M. Gauns, S. G. P. Matondkar and R. Mohanraju (1996). Phytoplankton production and chlorophyll distribution in the eastern and central Arabian Sea in 1994-1995. *Current Science*, 71(11): 857-862.

Bhimachar, B. S and P. C. George (1950). Abrupt setbacks in the fisheries of the Malabar and Kanara coasts and 'red water' phenomenon as their probable cause. *Proc. Ind. Acad. Sci.,* 31(6): 339-335.

Bjornberg, T. K. S (1965). Observations on the development and the biology of the Miracidae Dana (Copepoda: crustacean). *Bulletin of Marine Sciences*, *Gulf Caribb*., 15: 512-520.

Blanco, J., A. Morono, Y. Pazos, J. Maneiro and J. Marino (1998). Trends and variations of the abundance of main PSP and DSP producing species in the Galician Rias: environmental and biological influences. In: *Harmful Algae*, B. Reguera, J. Blanco, M. L. Fernandez, & T. Wyatt (Eds.), Xunta de Galicia and IOC-UNESCO, Santiago de Compostela, Spain, pp. 204-207.

Boalch, G. T (1984). Algal blooms and their effects on fishing in English Channel. *Hydrobiologia*. 116/ 117: 449-452.

Boyce, D. G., M. R. Lewis and B. Worm (2010). Global phytoplankton decline over the past century. *Nature*, 466: 591-596.

Brongersma-Sanders, M (1957). Mass mortality in the sea. *In*: Treatise on Marine Ecology and Paleoecology 1, Hedgpeth, J. W. (ed.), Geological Society of America Memoir, 67: 941-1010.

Bryceson, I and P. Fay (1980). Nitrogen fixation and the autecology of *Oscillatoria erythraea* (Erhenberg) Kuetzing a planktonic cyanophyte from the coastal waters of Tanzania: a preliminary investigation. p.471-494. In: *Symposium on the coastal and marine environment of the Red Sea, Gulf of Aden and tropical Western Indian Ocean in Khartoum*, Sudan. *Buitenz.,* 44:101-174.

Buskey, E. J and D. A. Stockwell (1993). Effects of a persistent “brown tide” on zooplankton populations in the Laguna Madre of South of Texas. In: Toxic phytoplankton blooms in the sea, Smayda, T. J and Shimizu, Y (Eds.), Elsevier, Amsterdam, pp. 659-666.

Buskey, E. J. (1995). Growth and bioluminescence of *Noctiluca scintillans* on varying algal diets. *Journal of Plankton Research*, 17(1), 29-40.

Buskey, E. J., H. Liu, C. Collumb and J. Bersano (2001). The decline and recovery of a persistent Texas brown tide algal bloom in the Laguna Madre (Texas, USA). *Estuaries*, 24: 337-346.

Cadee, G. C (1986). Increased phytoplankton primary production in the Marsdiep area (Western Dutch Wadden Sea). *Neth. J. Sea Res.,* 20: 285-290.

Camdevy'ren, H., N. Demy'r, A. Kanik and S. Kesky'n (2005). Use of principle component scores in multiple linear regression models for prediction of chlorophyll *a* in reservoirs. *Ecological Modelling*, 181: 581-589.

Campbell, R. G., G. J. Teegarden, A. D. Cembella and E. G. Durbin (2005). Zooplankton grazing impacts on *Alexandrium* spp. in the near shore environment of the Gulf of Maine. *Deep-Sea Research II*, 52: 2817-2833.

Capone, D. G. and E. J. Carpenter (1982). Nitrogen fixation in the marine environment. *Science*, 217: 1140-1142.

Capone, D. G., J. A. Burns, J. P. Montoya, A. Subramaniam, C. Mahaffey, T. Gunderson, A. F. Michaels and E. J. Carpenter (2005). Nitrogen fixation by *Trichodesmium spp*.: An important source of new nitrogen to the tropical and subtropical North Atlantic Ocean. *Global Biogeochem. Cyc*., 19: 1-17.

Capone, D. G., J. P. Zehr, H. W. Paerl, B. Bergman and E. J. Carpenter (1997). *Trichodesmium* a globally significant marine bacteria. *Science*, 276: 1221-1229.

Carlsson, P., E. Graneli and P. Olsson (1990). Grazer elimination through poisoning, one of the mechanisms behind *Chrysochromulina polylepis* blooms? In: Toxic Marine Phytoplankton. Graneli, E., Sundström, B., Edler, L. and Anderson, D. M. (Eds.), Elsevier, New York, pp. 116-122.

Carpenter, E. J (1983). Physiology and ecology of marine planktonic *Oscillatoria* (*Trichodesmium*). *Mar. Biol. Lett.*, 4: 69-85.

Carpenter, E. J, J. P. Montoya, J. Burns, M. Mulholland, A. Subramaniam and D. G. Capone (1999). Extensive bloom of a $N_2$-fixing diatom/ cyanobacterial association in the Tropical Atlantic Ocean. *Mar. Ecol. Prog. Ser.*, 185: 273-283.

Carpenter, E. J. and K. Romans (1991). Major role of the cyanobacterium *Trichodesmium* in nutrient cycling in the North Atlantic Ocean. *Science*, 254: 1356-1358.

Carreto, I. J., H. R. Benavides., R. M. Negri and P. D. Glorioso (1986). Toxic red tide in the Argentine sea. Phytoplankton distribution and survival of the toxic dinoflagellate *Gonyaulax excavata* in a frontal area. *Journal of Plankton Research*, 8 (1): 15-28.

Casotti, R., S. Mazza, C. Brunet, V. Vantrepotte, A. Ianora and A. Miralto (2005). Growth inhibition and toxicity of the diatom aldehyde 2-trans, 4-trans-decadienal on *Thalassiosira weissflogii* (Bacillariophyceae). *J. Phycol*. 41: 7-20.

Castonguay, M., M. Levasseur, J. L. Beaulieu, F. Gregoire, S. Michaud, E. Bonneau and S. S. Bates (1997). Accumulation of PSP toxins in Atlantic mackerel: seasonal and ontogenic variations. *J. Fish. Biol.*, 50:1203-1213.

Cembella, A. D., J. C. Therriault and P. Beland (1988). Toxicity of cultured isolates and natural populations of *Protogonyaulax tamarensis* (Lebour) Taylor from the St. Lawrence estuary. *J. Shellfish Res*. 7: 611- 622.

Chacko, P. I (1942). An unusual incidence of mortality of marine fauna. *Current Science*, 11: 404.

Chan, J and E. J. Carpenter (1985). Blooms of dinoflagellate *Gyrodinium aureolum* in a Long Island estuary: box model analysis of bloom maintenance. *Mar. Biol.,* 89, 83-93.

Chang, J., K. P. Chiang and G. C. Gong (2000). Seasonal variation and cross-shelf distribution of the nitrogen fixing cyanobacterium, *Trichodesmium*, in the southern east China Sea. *Continental Shelf Research*, 20: 479- 492.

Clarke, K. R (1993). Non parametric multivariate analysis of changes in community structure. *Australian Journal of Ecology*, 18: 117-143.

Clarke, K. R and R. M. Warwick (1994). Change in marine communities: an approach to statistical analysis and interpretation. 2nd edition, PRIMER-E, Plymouth.

Coale, K. H., K. S. Johnson, S. E. Fitzwater, R. M. Gordon, S.Tanner, F. P. Chavez, L. Ferioli, C. Sakamoto, P. Rogers, F. Millero, P. Steinberg, P. Nightingale, D. Cooper, W. P. Cochlan, M. R. Landry, J. Constantinou, G. Rollwagen, A. Trasvina and R. Kudela (1996). A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature*, 383: 495-501.

Cowles, T. J., R. J. Olson and S. W. Chisholm (1988). Food selection by copepods: discrimination on the basis of food quality. *Marine Biology*, 100: 41-49.

Cullen, J. J (1982). The deep chlorophyll maximum comparing vertical profiles of chlorophyll *a*. *Canadian Journal of Fisheries and Aquatic Science*, 39: 791- 803.

Cupp, E. E (1943). Marine plankton diatoms of the west coast of North America. In: Bulletin of the Scripps Institution of oceanography of the University of California La Jolla, California (Eds.) H. U. Sverdrup, R. H. Fleming, L. H. Miller, C. E. Zobell, Cambridge University press London. Volume 5, No.1, pp. 1-238.

Cupp, E.E (1937). Seasonal distribution & occurrence of marine diatoms and dinoflagellates at Scotch Cap, Alaska. *Bull. Scripps. Inst. Oceanogr*, 4:71- 100.

Currie, R. I., A. E. Fisher and P. M. Hargraeves (1973). Arabian Sea upwelling. In: The biology of the Indian Ocean, B. Zeitzschel (ed.), Berlin-Heidelberg, New York- Springer. Vol. 3: 37-52.

Cushing, D. H (1989). A difference in structure between ecosystems in strongly stratified waters and in those that are only weakly stratified. *J. Plankton Res*., 11: 1-13.

Cushing, D.H (1959). The seasonal variation in oceanic production as problem in population dynamics. *Journal du Conseil Prmanent International pl'Exploration de la Mer*., 24: 455-464.

Dale, B and C. M. Yentsch (1978). Red tide and paralytic shellfish poisoning. *Oceanus,* 21: 41-49.

Dale, B., A. Madsen, K. Nordberg and T. A. Thorsen (1993). Evidence for prehistoric and historic blooms of the toxic dinoflagellate *Gymnodinium catenatum* in the Kattegat- Skagerrak region of Scandinavia. *In*: Toxic phytoplankton blooms in the sea. T. J. Smayda and Y. Shimuzu (Eds.). Elsevier, Amsterdam, pp. 489- 494.

Dale, B., D. G. Baden, B. M. Bary, L. Edler, S. Froga, I. R. Jenkinson, G. M. Hallegraeff, T. Okaichi, K. Tangen, F. G. R. Taylor, A.. W. White, C. M. Yentsch and C. S. Yentsch (1987). The problems of toxic dinoflagellate blooms in aquaculture. *In*: Proceedings from a workshop and international conference, Sherkin Island station, 1-61.

Damodaran, R (1973). Studies on the benthos in the mud banks of the Kerala coast. *Bull. Dept. Mar. Sci., University of Cochin,* 6: 1- 126.

Daranas, A. H., M. Norte and J. J. Fernandez (2001). Toxic marine microalgae. *Toxicon*, 39:1101-1132.

Dela-Cruz, J., P. Ajani, R. Lee, T. Pritchard and I. Suthers (2002). Temporal abundance pattern of the red tide dinoflagellate *Noctiluca scintillans* along the southeast coast of Australia. *Mar. Ecol. Prog. Ser.*, 236: 75-88.

Delgado, M and M. Alcaraz (1999). Interaction between red tide microalgae and herbivorous zooplankton: the noxious effects of *Gyrodinium corsicum* (Dinophyceae) on *Acartia grani* (Copepoda: Calanoida). *J. Plankton Res.*, 21 (12): 2361-2371.

DeMott, W. R and F. Moxter (1991). Foraging on cyanobacteria by copepods: response to chemical defences and resource abundance. *Ecology*, 72: 1820- 1834.

Desikachary, T.V (1959). Cyanophyta. Indian Council of Agricultural Research, New Delhi, pp. 686.

Desikachary, T.V., Prema., A. K. S. K. Prsaad, P. M. Sreelatha, V. T. Sreedharan, and R. Subrahmanyan (1987b). Marine diatoms from the Arabian Sea & Indian Ocean. Fasc. IV, Madras Science Foundation, Madras.

Devanesen, D. W (1942). Plankton studies in the fisheries branch of the Department of Industries and Commerce, Madras. *Current Science*, 11: 142-143.

Devassy, V. P (1974). Observation on the bloom of a diatom *Fragilaria oceanica* Cleve. *Mahasagar*, 7: 101-105.

Devassy, V. P and P. M. A. Bhattathiri (1974). Phytoplankton ecology of the Cochin backwaters. *Indian J. Mar. Sci.*, 3: 46.

Devassy, V. P. and S. R. S Nair (1987). Discolouration of water and its effect on fisheries along the Goa coast. *Mahasagar*, 20: 121- 128.

Devassy, V. P., P. M. A. Bhattathiri and S. Z. Qasim (1978). *Trichodesmium* phenomenon. *Indian J. Mar. Sci.*, 73:168-186.

Devassy, V.P and S. R Bhat. (1991). The Killer tides. *Sci. Rep.*, 16-19.

Dharani, G., A. Nazar, L. Kanagu, P. Venkateshwaran, T. S. Kumar, K. Ratnam, R. Venkatesan and M. Ravindran (2004). On the recurrence of *Noctiluca scintillans* bloom in Minnie Bay, Port Blair: Impact on water quality and bioactivity of extracts. *Current Science*, 87 (7): 990-994.

Doucette, G.J., Cembella, A.D., Martin, J.L., Michaud, J., Cole, T.V.N., Rolland, R.M., (2005). PSP toxins in North Atlantic right whales (*Eubalaena glacialis*) and their zooplankton prey in the Bay of Fundy, Canada. *Marine Ecology Progress Series*, 306: 303-313.

Dugdale, R and F. Wilkerson (1992). Nutrient limitation of new production in the sea. *In*: Primary productivity and biogeochemical cycles in the sea. Falkowski P.G, Woodhead, A. D (Eds.), Plenum press, New York, 107-122.

Durbin, E., Teegarden, G., Campbell, R., Cembella, A., Baumgartner, M.F., Mate, B.R., (2002). North Atlantic right whales, *Eubalaena glacialis*, exposed to paralytic shellfish poisoning (PSP) toxins via a zooplankton vector, *Calanus finmarchicus*. *Harmful Algae*, 1: 243-251.

Dussart, B. H (1965). Les different categories de plankton. *Hydrobiologia*, 26: 72-74.

Dwivedi, R. M., M. Raman, S. Parab, S. G. P. Matondkar and S. Nayak (2006). Influence of northeasterly trade winds on intensity of winter bloom in the Northern Arabian Sea. *Current Science*, 90 (10): 1397-1406.

Eashwar, M., T. Nallathambi, K. Kubereaja and G. Govindarajan (2001). *Noctiluca* blooms in Port Blair Bay, Andamans. *Current Science*, 81(2): 203-206.

Edwards, A. M and J. Brindley (1996). Oscillatory behaviour in three component plankton population model. *Dyn. Stab. Syst*., 11: 347-370.

Edwards, A. M and J. Brindley (1999). Zooplankton mortality and the dynamical behaviour of plankton population models. *Bull. Math. Biol*., 61: 303-339.

Elbrachter, M and R. Boje (1978). On the ecological significance of *Thalassiosira partheneia* in the Northwest African Upwelling Area. *In*: Upwelling ecosystems, Boje, R., Tomczak, M. (Eds.). Springer Verlag, Berlin, p. 24-31.

Elbrachter, M. and Y. Z. Qi (1998). Aspects of *Noctiluca* (Dinophyceae) population dynamics. In: Physiological ecology of harmful algal blooms, D. M. Anderson, A. D. Cembella, M. G. Hallegraeff (Eds.), NATO ASI Series, vol. G 41. Springer- Verlag, Berlin. pp 315-335.

Engstrom, J., M. Viherluoto and M. Viitasalo (2001). Effects of toxic and non-toxic cyanobacteria on grazing, zooplanktivory and survival of the mysid shrimp *Mysis mixta*. *J. Expt. Mar. Biol. Ecol*., 257: 269-280.

Escalera, L., Y. Pazos, A. Morono and B. Reguera (2007). *Noctiluca scintillans* may act as a vector of toxigenic microalgae. *Harmful Algae*, 6(3): 317-320.

Falconer, I. R (1993). Measurement of toxins from blue-green algae in water and food stuffs. In: Algal toxins in seafood and drinking water. Falconer I. R. (ed.), Academic, p. 165-175.

Falkowski, P. G., T. S. Hopkins and J. J. Walsh (1980). An analysis of factors affecting oxygen depletion in the New York Bright. *J. Mar. Res.*, 38: 479-506.

Fay, P., W. D. P. Stewart, A. E. Walsby and G. E. Fogg (1965). Is the heterocyst the site of nitrogen fixation in blue-green algae? *Nature*, 220: 810-812.

Fernandes, L. F and F. P. Brandini (2004). Diatom associations in shelf waters off Parana State, Southern Brazil: annual variation in relation to environmental factors. *Brazilian Journal of Oceanography*, 52(1): 19-34.

Fiedler, P. C (1982). Zooplankton avoidance and reduced grazing responses to *Gymnodinium splendens* (Dinophyceae). *Limnology and Oceanography*, 27(5): 961-965.

Fonda-Umani, S., A. Beran, S. Parlato, D. Virgilio, T. Zollet, A. De Olazabal, B. Lazzarini and M. Cabrini (2004). *Noctiluca scintillans* (Macartney) in the Northern Adriatic Sea: long-term dynamics, relationships with temperature and eutrophication, and role in the food web. *Journal of Plankton Research*, 26: 545-561.

Forsyth, D. J., M. R. James and M. Cryer (1990). Alteration of seasonal and diel patterns in vertical migration of zooplankton by *Anabaena* and planktivorous fish. *Arch. Hydrobiol.*, 117: 385-404.

Franks, P. J. S and D. M. Anderson (1992). Toxic phytoplankton in the southwestern Gulf of Maine: testing hypothesis of physical control using historical data. *Marine Biology,* 112: 165-174.

Franks, P. J. S., D. M. Anderson and B. A. Keafer (1989). Fronts, upwelling and coastal circulation: spatial heterogeneity of *Ceratium* in the Gulf of Maine. *In*: Red tides- Biology, Environmental sciences and toxicology, T. Okaichi, D. M. Anderson and T. Nemoto (Eds.), Elsevier, 153-156.

Fremy, J. M (1991). Marine biotoxins: a short review. In: Proceedings of symposium on Marine Biotoxins, Centre National d'Etudes Veterinaires et Alimentaires, Maisons Alfort, Paris, France. pp. 3-6.

Fritz, L., M. A. Qulliam, J. L. C. Wright, A. M. Beale and T. M. Work (1992). An outbreak of DA poisoning attributed to the pennate diatom *Pseudonitzschia australis*. *J. Phycol*., 28: 439-442.

Furnas, M., A. Mitchell, M. Skuza and J. Brodie (2005). In the other 90%: phytoplankton responses to enhanced nutrient availability in the Great Barrier Reef Lagoon. *Marine Pollution Bulletin*, 51: 253-265.

Gaarder, T., and H. H. Gran (1927). Investigations of the production of plankton in the Oslo Fjord. *Rapp. Proc. Verb. Cons. Expl. Mer.*, 42: 1-48.

George, P. C (1953). The marine plankton of the coastal waters of Calicut with observations on the hydrological conditions. *Journal of the Zoological Society of India*, 5 (1): 76-107.

Geraci, J. R., D. M. Anderson, R. J. Timperi, D. J. Aubin, G. A. Early, J. H. Prescott and C. A. Mayo (1989). Humpback whales (*Megaptera novaeangliae*) fatally poisoned by dinoflagellate toxin. *Can. J. Fish. Aquat. Sci.*, 46:1895-1898.

Glibert, P. M., D. M. Anderson, P. Gentien, E. Graneli and K. G. Sellner (2005). The global, complex phenomena of harmful algal blooms. *Oceanography,* 18: 136-147.

Goebel, N. L., S. R. Wing and P. W. Boyd (2005). A mechanism for onset of diatom blooms in a fjord with persistent salinity stratification. *Estuarine, Coastal and Shelf Science*, 64: 546-560.

Goes, J. I., S. Caeiro and H. R. Gomes (1999). Phytoplankton- zooplankton inter-relationships in tropical waters- Grazing and gut pigment dynamics. *Indian J. Mar. Sci.*, 28: 116-124.

Goldman, J. C and D. J. Jr McGillicuddy (2003). Effect of large marine diatoms growing at low light on episode new production. *Limnology and Oceanography*, 48:1176-1182.

Gomes, H. R., J. I. Goes, S. G. P. Matondkar, S. G. Parab, A. R. N. Al-Azri and P. G. Thoppil (2008). Blooms of *Noctiluca miliaris* in the Arabian Sea- An *in situ* and satellite study. *Deep-Sea Research I*, 55: 751-765.

Gopakumar, G., Bindhu Sulochanan and V. Venkatesan (2009). Bloom of *Noctiluca scintillans* (Macartney) in Gulf of Mannar, South east coast of India. *J. Mar. Biol. Ass. India,* 51(1): 75-80.

Gopinathan, C. P and P. Parameswaran Pillai (1976). Red tide and its deleterious effect on fishery. *Sea food export journal*, 37-39.

Gopinathan, C. P., A. Regunathan, D. S. Rao, K. J. Mathew and A. V. S. Murty (1984). Source of mud of Alleppey Mud bank: mud-cone and the message it conveys. *Bull. Cent. Mar, Fish. Res. Inst.,* 31: 18-20.

Gopinathan, C.P., Gireesh , R. and Smitha, K.S (2001) . Distribution of chlorophyll 'a' and 'b' in the eastern Arabian Sea (West coast of India) in relation to nutrient during post monsoon. *J. Mar. Biol.* Ass. *India*, 43(1&2): 21-30.

Gopinathan, C.P., P.V.R. Nair and A.K.K. Nair (1974). Studies on the phytoplankton of Cochin backwaters, a tropical estuary. *Indian. J. Fish.,* 21: 501-513.

Goswami, S. C (1985). Zooplankton standing stock and composition in the coastal waters of Goa, west coast of India. *Indian Journal of Marine Sciences*, 15: 264-266.

Gowda, G., T. R. C. Gupta, K. M. Rajesh, H. Gowda, C. Lingadhal and A. M. Ramesh. (2001). Seasonal distribution of phytoplankton in Netravathi estuary, Mangalore. *J. Mar. Biol. Ass. India*, 43 (1 &2): 31-40.

Graneli, E and L. Risinger (1995). Was the *Chrysochromulina polylepis* bloom in 1988 caused by a release of cobalt or vitamin $B_{12}$ from a previous bloom of *Skeletonema costatum*? Harmful algal blooms *In*: Proceedings of the 6th International Conference on Toxic Marine Phytoplankton, Lavoisier, Nantes, France, p 223-229.

Graneli, E., P. Carlsson, P. Olsson, B. Sundstrom, W. Graneli and O. Lindahl (1989). From anoxia to fish poisoning: the last ten years of phytoplankton blooms in Swedish marine waters. In: Novel phytoplankton Blooms, Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms. Cosper, E. M., Bricelj, V. M., Carpenter, E. J. (Eds.), Springer Verlag, Berlin, pp. 407-427.

Graneli, E., P. Olsson, P. Carlsson, W. Graneli and W. Nylander (1993). Weak top down control of dinoflagellate growth in the coastal Skaggerrak. *J. Plankton Res*., 15: 213-237.

Grasshoff (1964). Kiel. Meeresforsch. 20: 5.

Grasshoff, K., M. Ehrhardt, K. Kremling and T. Almgren (1983). Method of seawater analysis. Verlag Chemie, Weinheim, Germany, 419 pp.

Gregg, W. W., N. W. Casey and C. R. McClain (2005). Recent trends in global ocean chlorophyll. *Geophys. Res. Lett.,* 32: 1-5.

Guo, C and P. A. Tester (1994). Toxic effect of the bloom forming *Trichodesmium* sp. (Cyanophyta) to the copepod *Acartia tonsa*. *Nat. Toxins*, 2: 222-227.

Guzman, J. B., I. G. Lizarraga, D. L. Cortes and F. H. Sandoval (2004). The use of pigment "fingerprint" in the study of harmful algal blooms. *Rev. Biol. Trop.,* 52 (Suppl.1): 17-26.

Hallegraeff (1995). Harmful algal blooms: a global overview. Manual on harmful marine micro algae. *IOC-UNESCO Manual and Guides* No. 33, 1-22.

Hallegraeff, G. M (1993). A review of harmful algae blooms and the apparent global increase. *Phycologia*, 32: 79-99.

Hallegraeff, G. M., D. M. Anderson, A. D. Cembella (Eds.) (1995). Manual on Harmful marine micro algae. *IOC-UNESCO, Manuals and Guides*, 33: 546 pages.

Hamm, C. E., R. Merkel, O. Springer, P. Jurkojc, C. Maier, K. Prechtel and V. Smetacek. (2003). Architecture and material properties of diatom shells provide effective mechanical protection. *Nature*, 421: 841-843.

Handy, S. M., K. J. Coyne, K. J. Portune, E. Demir, M. A. Doblin, C. E. Hare, S. C. Cary and D. A. Hutchins (2005). Evaluating vertical migration behaviour of harmful raphidophytes in the Delaware Inland Bays utilizing quantitative real time PCR. *Aquatic Microbial Ecology,* 40: 121-132.

Hansen, P. B., E. Dahl and D. S. Danielssen (2001). On blooms of *Chattonella* in the North Sea/ Skagerrankin April- May 1998. *In*: Proceedings of 9th International Conference on Harmful Algal Blooms, G. M. Hallegraeff, S. I. Blackburn, C. J. Bolch and R. J. Lewis (eds.), Australia: UNESCO Tasmania, p 78-81.

Hansen, P. J (1989). The red tide dinoflagellate *Alexandrium tamarense*: effects on behaviour and growth of a tintinnids ciliate. *Mar. Ecol. Prog. Ser.*, 53:105-116.

Hansen, P. J (1991). Quantitative importance and trophic role of heterotrophic dinoflagellates in a coastal pelagial food web. *Mar. Ecol. Prog. Ser.*, 73: 253-261.

Hara, Y., K. Doi and M. Chihara (1994). Four new species of *Chattonella* (Raphidophyceae, Chromophyta) from Japan. *Japanese Journal of Phycology,* 42: 407-420.

Hardy, A. C. and E. R. Gunther (1935). The plankton of the South Georgia whaling grounds and adjacent waters, 1926-1927. *Discovery Reports*, 11: 1- 456.

Hargrave, B. T and G. H. Geen (1970). Effects of grazing on two natural phytoplankton populations. *J. Fish. Res. Bd. Can.*, 27: 1395-1403.

Haridas, T and T. S. S. rao (1981). Distribution of pelagic harpacticoid copepods from the Indian Ocean. *Mahasagar*, 14(2): 151-154.

Harris, R., P. H Wiebe, J. Lenz., H. R. Skjoldal and M. Huntley (2000). ICES Zooplankton methodology manual. Academic press, 684 pp.

Harvey H. W., L. H. N. Cooper, M. V. Lebour and F. S, Russell (1935). Plankton production and its control. *Journal of Marine Biological Association of United Kingdom*, 20: 407- 441.

Harvey, H. W (1934). Measurement of phytoplankton populations. *J. Mar. Biol. Ass. U.K.*, 19: 761-768.

Hasle, G. R and E. E. Syversten (1997). Marine Diatoms. Chapter 2 In: *Identifying Marine phytoplankton* C. R. Tomes (Eds.), Academic press, UK, pp 5-387.

Hasle, G. R and E. E. Syversten (1997). Marine Diatoms. Chapter 2 In: Identifying Marine phytoplankton, Carmelo R. Tomes (ed.), Academic press, UK pp. 5-387.

Hasle, G. R G. A. and Fryxell (1970). Diatoms: cleaning and mounting for light and electron microscopy. *Transactions of American Microscopical Society*, 89(4): 469- 474.

Hawser, S. P., J. M. O'Neil, M. R. Roman and G. A. Codd (1992). Toxicity of blooms of the cyanobacterium *Trichodesmium* to zooplankton. *J. Appl. Phycol.*, 4: 79-86.

Hendey, N.I (1964). An introductory account of the smaller algae of the coastal waters. Part V. Bacillariophyceae (Diatoms*)*. Ottokoeltz Science Publishers, Koenigstein, Germany, pp. 317.

Hitchcock, G. L., P. Lane, S. Smith, J. Lou and P. B. Ortner (2002). Zooplankton spatial distribution in coastal waters of the northern Arabian Sea, August 1995. *Deep-Sea Res. II*, 49: 2403-2423.

Ho, K.C and I. J. HodgKiss (1991). Red tides in subtropical waters. An overview of their occurrence. *Asian Mar. Biol.,* 10: 77-94.

Hornell, J (1917). A new protozoan cause of widespread mortality among marine fishes. *Madras Fisheries Investigations Bulletin No.* 11: 53-56.

Horner, A. Rita., David. L. Garrison and F . Gerald Plumey (1997). Harmful algal blooms and red tide problems on the U. S. west coast. *Limnology and Oceanography*, 42 (5, part 2): 1076-1088.

Horner, R. A., J. R. Postel, C. Halsband-Lenk, J. J. Pierson, G. Pohnert and T. Wichard (2005). Winter- spring phytoplankton blooms in Dabob Bay, Washington, *Progress in Oceanography*, 67: 286-313.

Horstman, D. A (1981). Reported red water outbreaks and their effects on fauna of the west and south coasts of South Africa 1959-1980. *Fish. Bull. S. Af.,* 15: 71-88.

ICES, (1984). Report of the ICES special meeting on the causes, dynamics and effects of Exceptional Marine Blooms and related events. *International Council Meeting Paper* 1984/E, 42 (mimeo).

Igarashi, T., M. Satake and T. Yasumoto (1996). Prymnesin-2: a potent ichthyotoxic and Hemolytic glycoside isolated from the red tide alga *Prymnesium parvum*. *J. Am. Chem. Soc.,* 118: 479-480.

Imai, I. and K. Itoh (1987). Annual life cycle of *Chattonella* spp., causing noxious red tides in the inland sea of Japan. *Marine Biology*, 94: 287-292.

IOBC (1968a). Plankton atlas, International Indian Ocean Expedition, 1:1:18, NIO/ CSIR, New Delhi.

IOBC (1968b). Plankton atlas, International Indian Ocean Expedition, 1:2:9, NIO/ CSIR, New Delhi.

Iwasaki, H (1979). Physiological ecology of red tide flagellates. *In*: Biochemistry and Physiology of Protozoa, 2nd ed., M Levandowsky, S Hunter editors, New York: Academic Press, p 357-393.

Iyengar, M. O. P and T. V. Desikachary (1944). A systematic account of some marine myxophyceae of the South Indian coast. *J. Madras Uni.,* 16: 37-68.

Iyer, C. S. P., R. S. Robin, M. S. Sreekala and S. Shyam Kumar (2008). *Karenia mikimotoi* bloom in Arabian Sea. *Harmful Algae News*, No. 37, 9-10.

Jacob, P. K and M. Devidasa Menon (1948). Incidence of fish mortality on the west coast. *J. Bombay. Nat. Hist. Soc.*, 47: 455-457.

Jacob, R. M., K. Ramachandran Nair, R. Vasathakumar (1981). Zooplankton in relation to hydrography and pelagic fisheries in the inshore waters of Vizhinjam, Trivandrum. *J. Mar. Biol. Ass. India*, 23(1&2): 62-76.

Jagadeesan, L., N. Arivuselvan, G. Thirumaran, P. Anantharaman and T. Balasubrahmanian (2010). Biomass and biochemical composition of zooplankton along the Arabian Sea, West coast of India. *Advance Journal of food science and technology*, 2(2): 96-99.

Jansen, S., C. W. Riser, P, Wassmann and U. Bathmann (2006). Copepod feeding behaviour and egg production during a dinoflagellate bloom in the North Sea. *Harmful Algae*, 5:102-112.

Jayakumar, D. A., S. W. A. Naqvi, P. V. Narvekar and M. D. George (2001) Methane in coastal and offshore waters of the Arabian Sea. *Mar. Chem.*, 74: 1-13.

Jeffery, B., T. Barlow, K. Moizer, S. Paul and C. Boyle (2004). Amnesic shellfish poison. Food Chem. *Toxicol*., 42, 545-557.

Jeffrey, S. W (1961). Paper-chromatography separation of chlorophylls and carotenoids from marine algae. *Biochem. J.*, 80: 336-342.

Jeffrey, S. W (1968). Quantitative thin-layer chromatography of chlorophylls and carotenoids from marine algae. *Bioch. Biophy. Acta*, 162: 271-285.

Jeffrey, S.W and M. Vesk (1997). Introduction to marine phytoplankton and their pigment signatures, pp. 37-84. *In*: Phytoplankton pigments in oceanography S.W. Jeffrey, R.F.C. Mantoura & S.W. Wright (Eds.). *Monogr. Oceanogr. Method*, 10, UNESCO.

Jensen, S., C. W. Riser, P. Wassmann and U. Bathmann (2006). Copepod feeding behaviour and egg production during a dinoflagellate bloom in the North Sea. *Harmful Algae*, 5: 102-112.

Jugnu, R and Kripa. (2009). Effect of *Chattonella marina* [(Subrahmanyan) Hara et Chihara 1982] bloom on the coastal fishery resources along Kerala coast, India. *Indian Journal of Marine Sciences*, 38(1): 77-88.

Jugnu, R and V. Kripa (2008). Prevalence of non toxic and harmful algal blooms along Kerala coast. *Marine Fisheries Information Service T&E Ser.*, No. 195.

Jyothibabu, R., N. V. Madhu, N. Murukesh, P. C. Haridas, K. K. C. Nair and P. Venugopal (2003). Intense bloom of *Trichodesmium erythraeum* (cyanophyte) in the open waters along east coast of India. *Indian J. Mar. Sci.*, 32: 165-167.

Karl, D., A. Michaels, B. Bergman, D. Capone, E. Carpenter, R. Letelier, F. Lipschultz, H. Paerl, D. Sigman and L. Stal (2002). Dinitrogen fixation in the world's oceans. *Biogeochemistry*, 57/58: 47-98.

Karlson, B., C. Cusack and E. Bresnan (Eds.) (2010). Microscopic and molecular methods for quantitative phytoplankton analysis. IOC Manuals and Guides No. 55. UNESCO, Paris p.120.

Karunasagar and Karunasagar (1990). Effects of eutrophication and harmful algal blooms on coastal aquaculture and fisheries in India. In: *Advances in Aquatic biology and Fisheries,* Vol. 14: 162-172.

Karunasagar, I and I. Karunasagar (1992). *Gymnodinium nagasakiense* red tide off Someshwar, West coast of India and mussel toxicity. *Journal of Shellfish Research,* 11: 477-478.

Karunasagar, I., B. Joesph., K. K. Philipose and I. Karunasagar (1998). Another outbreak of PSP in India. *Harmful Algae News*, 17: 1.

Karunasagar, I., H. S. V. Gowda., M. Subhurah., M. N. Venugopal and I. Karunasagar (1984). Outbreak of paralytic shellfish poisoning in Mangalore, West coast of India. *Current Science*, 53: 247.

Katti, R. J., C. Gupta and H. P. C. Shetty (1988). On the occurrence of 'Green tide' in the Arabian sea off Mangalore. *Current Science*, 57(7): 380.

Kawano, I., T. Oda, A. Ishimatsu and T. Muramatsu (1996). Inhibitory effects of the iron chelator Desferrioxamine (Desferal) on the generation of activated oxygen species of *Chattonella marina*. *Marine Biology,* 126: 765-771.

Kiorboe, T and J. Titelman (1998). Feeding, prey selection and prey encounter mechanisms in the heterotrophic dinoflagellate *Noctiluca scintillans*. *Journal of Plankton Research,* 20*,* 1615-1636.

Kirchner, M., G. Sahling, G. Uhlig, W. Gunkel and K. W. Klings (1996). Does the red tide forming dinoflagellate *Noctiluca scintillans* feed on bacteria? *Sarsia* 81, 45-55.

Kirk, K and J. Gilbert (1992). Variations in herbivore response to chemical defences: zooplankton foraging on toxic cyanobacteria. *Ecology*, 73: 2208.

Kirn, S. L., D. W. Townsend and N. R. Pettigrew (2005). Suspended *Alexandrium* spp. hypnozygote cysts in the Gulf of Maine. *Deep-Sea Research II*, 52 (19-21), 2543-2559.

Kleppel, G. S (1993). On the diets of calanoid copepods. *Marine Ecology Progress Series,* 99: 183-195.

Koppelmann, R., H. Fabian and H. Weikert (2003). Temporal variability of deep-sea zooplankton in the Arabian Sea. *Mar. Biol.*, 142: 959-970.

Kotani, Y., T. Kyoichi, Yamaguchi., S. Okubo., K. Matui and T. Nakamura (2001). Historical and current status of red tides and shellfish poisonings in Japan. *In*: Country report of HAB in Japan for HAMM.

Kremp, A (2001). Effects of cyst resuspension on germination and seeding of two bloom-forming dinoflagellates in the Baltic Sea. *Mar. Ecol. Prog. Ser.,* 216: 57-66.

Krey, J and B. Babenerd (1976). Phytoplankton production. Atlas of International Indian Ocean Expedition. Universitat Kiel, Institut fur Meereskunde, Kiel. 70 pp.

Kristiansen, S and E. E. Hoell (2002). The important of silicon for marine production. *Hydrobiol.*, 484: 21-31.

Kudela, R. M (2008). Silicon: Nitrogen interactions in the marine environment. *In*: Nitrogen in the Marine Environment, Capone, D., Bronk, D., Mulholland, M., Carpenter, E. (Eds.),. Elsevier, New York, pp. 1589-1626.

La Barbera-Sanchez, A., S. Hall, and E. Ferraz-Reyes (1993). *Alexandrium* sp., *Gymnodinium catenatum* and PSP in Venezuela. *In:* Toxic phytoplankton blooms in the sea. Proc. 5th Int. Conf. on Toxic Marine Phytoplankton. Elsevier, p. 763-768.

Lalithambika Devi, C. B., P. P. Meenakshi Kunjamma and B. Narayan (1992). Zooplankton studies in the southwest coast of India. Proceedings of 4th Kerala Science Congress, pp 264-266.

Lam, C. W. Y and K. C. Ho (1989). Red tides in Tolo harbour, Hong Kong, *In*: Red Tides: Biology, Environmental Science, and Technology, T.Okaichi, D.M. Anderson and T. Nemoto (Eds.), Elsevier, New York: 49-52.

Landsberg, J (2002). The effects of harmful Algae Blooms on aquatic organisms. *Rev. Fish. Sci,* Vol. 10, No. 2, p. 1-412.

Landsberg, J. H and K. A. Steidinger (1998). A historical review of *Gymnodinium breve* red tides implicated in mass mortalities of the manatee (*Trichechus manatus latirostris*) in Florida, USA. In:

Harmful algae, Reguera B, Blanco J, Fernández ML, Wyatt T (eds.) Xunta de Galicia and IOC of UNESCO Publishers, p 97-100.

Lassus, P., A. Herbland and C. Lebaut (1991). *Dinophysis* blooms and toxic effects along the French coast. *World Aquaculture*, 22: 49-54.

Leandro, L. F., G. J. Teegarden, P. B. Roth, Z. Wang and G. J. Doucette (2010). The copepod *Calanus finmarchicus*: A potential vector for trophic transfer of the marine algal biotoxin, domoic acid. *Journal of Experimental Marine Biology and Ecology*, 382: 88-95.

Lefebvre, K. A., C. L. Powell, M. Busman, G. J. Doucette, P. D. R. Moeller, J. B. Silver, P. E. Miller, M. P. Hughes, S. Singaram, M. W. Silver and R. S. Tjeerdema (1999). Detection of domoic acid in Northern anchovies and California sea lions associated with an unusual mortality event. *Natural Toxins,* 7: 85- 92.

LeFevre, J and J. R. Grall (1970). On the relationships of *Noctiluca* swarming off the western coast of Brittany with hydrological features and plankton characteristics of the environment. *J. Exp. Mar. Biol. Ecol.,* 4: 287-306.

Legendre, L (1990). The significance of micro algal blooms for fisheries and for the export of particulate organic carbon in oceans. *J. Plankton Res*., 12: 681-699.

Leising, A. W., J. J. Pierson, C. Halsband-Lenk, R. Horner and J. Postel (2005). Copepod grazing during spring blooms: Does *Calanus pacificus* avoid harmful diatoms? *Progress in Oceanography*, 67: 384-405.

Lenz, J (1973). Zooplankton biomass and its relation to particulate matter in the upper 200 m of the Arabian Sea during the NE monsoon. *In*: The biology of the Indian Ocean. Zeitzschel, B (ed.). Springer-Verlag, New York. 239- 241.

Lester, K. M, C. A. Heil, M. B Neely, D. N. Spence, S. Murasko, T. L. Hopkins, T. T. Sutton, S. E. Burghart, R. N. Bohrer, A. W. Remsen, G. A. Vargo, J. J. Walsh (2008). Zooplankton and *Karenia brevis* in the Gulf of Mexico. *Continental Shelf Research*, 28: 99-111.

Lucas, C. E (1936). On certain inter-relations between phytoplankton and zooplankton under experimental conditions. *J. Conseil, Conseil Perm. Intern. Exploration Mer,* 11: 343-362.

Lugomela, C., T. J. Lyima, I. Bryceson and A. K. Semesi (2002). *Trichodesmium* in coastal waters of Tanzania: diversity, seasonality, nitrogen and carbon fixation. *Hydrobiologia*, 477: 1-13.

Lukatelich, R. J and A. J. McComb (1986). Nutrient levels and the development of diatom and blue green algal blooms in a shallow Australian estuary. *Journal of Plankton Research*, 8 (4): 597-618.

Mackas, D. L., K. L. Denman and M. R. Abbott (1985). Plankton patchiness: biology in the physical vernacular. *Bull. Mar. Sciences,* 37: 652-674.

Maclean, J. L (1989). Indo- Pacific red tides, 1985-1988. *Marine Pollution Bulletin*, 20 (7): 304- 310.

Madhupratap, M., K. N. V. Nair, T. C. Gopalakrishnan, P. Haridas, K. K. C. Nair, P. Venugopal and M. Gauns (2001). Arabian Sea oceanography and fisheries of the west coast of India. Current Science, 81(4): 355-361.

Madhupratap, M., P. Haridas, N. Ramaiah and C. T. Achuthankutty (1992). Zooplankton of the west coast of India: abundance, composition, temporal and spatial variability in 1987. In: Oceanography of the Indian Ocean, B.N. Desai (ed.), Oxford and IBH, New Delhi, 99-112.

Madhupratap, M., S. Prasannakumar, P. M. A. Bhattathiri, M. Dileepkumar, S. Raghukumar, K. K. C. Nair and N. Ramaiah (1996). Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. *Nature*, 384: 549-551.

Madhupratap, M., S. R. Sreekumaran, P. Haridas and G. Padmavati (1990). Response of zooplankton to physical changes in the environment: coastal upwelling along the central west coast of India. *Journal of Coastal Research*, 6(2): 413-426.

Mague, T. H., F. C. Mague and O. Holm-Hansen (1977). Physiology and chemical composition of nitrogen fixing phytoplankton in the central North Pacific Ocean. *Marine Biology*, 41: 213-227.

Manabe, T and S. Ishio (1991). Bloom of *Coscinodiscus wailesii* and DO deficit of bottom water in Seto Inland sea. *Mar. Pollut. Bull.*, 23:181-184.

Maneiro, I., O. D'Aleo, C. Guisande and B. Reguera (1998) Interactions between the DSP agent *Dinophysis acuminata* and the microzooplankton community. *In*: Harmful algae, Reguera B, Blanco J, Fernández M.L, Wyatt T (eds.). Xunta de Galicia and IOC of UNESCO Publishers, p 386-389.

Marasovic., Ivona, Miroslav Gacic., Vedrana Kovacevic., Nada Krustulovic., Gorzdan Kuspilic (1991). Development of the red tide in the Katsela bay (Adriatic sea). *Marine chemistry*, 32: 375-385.

Margalef, R (1958). Temporal succession and spatial heterogeneity in phytoplankton. In: Perspectives in marine biology, Buzzati-Traverso A. A (ed). University California Press, Berkeley, p 323-348.

Margalef, R (1968). Perspectives in ecological theory. The University of Chicago Press Chicago: 111 pp.

Marshall, J. A., M. Hovenden, T. Oda and G. M. Hallegraeff (2002). Photosynthesis does influence superoxide production in the ichthyotoxic alga *Chattonella marina* (Raphidophyceae). *Journal of Plankton Research,* 24: 231-1236.

Marshall, S. M and A. P. Orr (1948). Further experiments on the fertilization of a sea loch (Loch Craiglin). The effect of different fertilizers on the phytoplankton. Journ. Mar. Biol. Assoc., Vol. XXVII, pp. 360-79.

Marshall, S. M and A. P. Orr (1955). On the biology of *Calanus finmarchicus*. 8. Food uptake, assimilation and excretion in adult and stage V Calanus. *J. Mar. Biol. Assoc. U.K,* 34: 495-529.

Mathew, K. J (1986). Relationship of euphausiids with other zooplankton and productivity in the continental shelf waters along the southwest coast of India. *J. Mar. Biol. Ass. India*, 28(1&2): 130-135.

Mathew, K. J., C. P. Gopinathan, A. Regunathan, D. S. Rao and A. V. S. Murty (1981). Mud- banks and the coastal ecosystem. Proc. Seminar on status of Environmental studies in India, pp. 243-254.

Mathew, K. J., C. P. Gopinathan, A. Regunathan, D. S. Rao and A. V. S. Murty (1984). Ecology of mud banks- Zooplankton, CMFRI Bulletin, 31: 35-39.

Mathew, K. J., P. A. Thomas, R. M. George, K. G. Girijavallabhan, P. Siraimeetan, T. S. Naomi, K. R. Nair, G. Anthony, G. S. Bhat and M. Selvaraj (1988). Plankton blooms along the Indian coasts, some highlights. *Mar. Fish. Inf. Serv. Tech. Ext. Ser.* No. 84:11-13.

Mathew, K. J., T. S. Naomi, G. Antony, D. Vincent, R. Anilkumar and K. Solomon (1989). Studies on zooplankton biomass and secondary and tertiary production of the EEZ of India. *Proc. First workshop Scient. Results FORV Sagar Sampada, DOD/ ICAR*, pp. 59-69.

Mathews, L and J. Brindley (1996). Patchiness in plankton population. *Dyn. Stab. Syst.,* 12: 39-59.

Menon, M. D and K. C. George (1977). On the abundance of zooplankton along the southwest coast of India during the years 1971-1975. *Proceedings of the Symposium on Warm Water Zooplankton, Special Publication, UNESCO/ NIO,* pp. 205-213.

Mikhail, S. K (2007). First monospecific bloom of the harmful raphidophyte *Chattonella antique* (Hada) Ono in Alexandria waters related to water quality and copepod grazing. *Chemistry and Ecology*, 23(5): 393-407.

Mohanty, A. K., K. Satpathy, G. Sahu, S. K. Sasmal, B. K. Sahu and C. Panigrahy (2007). Red tide of *Noctiluca scintillans* and its impact on the water coastal water quality of the near shore waters, off the Rushikulya River, Bay of Bengal. *Current Science*, 93 (5): 616- 618.

Moly Varghese and L. Krishnan (2009). Distribution of zooplankton in selected centres of Cochin backwaters, Kerala. *J. Mar. Biol. Ass. India*, 51(2): 194-198.

Montoya, N. G., R. Akselman, J. M. Franco and J. I. Carreto (1996). Paralytic shellfish toxins and mackerel (*Scomber japonicus*) mortality in the Argentine Sea. *In*: Harmful algae, Reguera B, Blanco J, Fernandez M. L, Wyatt T (Eds.). Xunta de Galicia and IOC of UNESCO Publishers, p 417-420.

Morris and Riley (1963). Anal. Chem. Acta.29: 272.

Morris Smith, A. E and H. E Glover (1981). Products of photosynthesis in phytoplankton off the Orinoko River and in the Caribbean Sea. *Limnology* Oceanography, 26: 1034- 44.

Morrison, J. M., L. A. Codispoti, S. Gaurin, B. Jones, V. Manghanani and Z. Zheng (1998). Seasonal variations of hydrographic and nutrient fields during the US JGOFS Arabian Sea Process Study, Deep-Sea Res. II, 45: 2053-2101.

Murata, M and T. Tasumoto (2000). The structure elucidation and biological activities of high molecular weight algal toxins: maitotoxin, prymnesins and zooxanthellatoxins. *Nat. Prod. Rep.*, 17: 293-314.

Murphy, J and J. P. Riley (1962). Anal.Chem.Acta.27: 31-36.

Nagabhushanam, A. K (1967). On an unusually dense phytoplankton bloom around Minicoy Island (Arabian sea) and its effect on tuna fisheries. Current Science, 36: 611.

Nagai, S., Y. Hori, T. Manabe and I. Imai (1995). Morphology and rejuvenation of *Coscinodiscus wailesii* Gran (Bacillariophyceae) resting cells found in bottom sediments of Harina-Nada, Seto Island Sea, Japan. Nippon Suisan Gakkaishi, 61: 179-185.

Nair, K. K. C., M. Madhupratap, T. C. Gopalakrishnan, P. Haridas and M. Gauns (1999). The Arabian Sea: Physical environment, zooplankton and myctophid abundance. *Indian J. Mar. Sci.*, 28: 138-145.

Nair, P. V. R and R. Subrahmanyan (1955). The diatom *Fragilaria oceanica* Cleve as an indicator of the abundance of the Indian sardine *Sardinella longiceps* cuv. and val. Current Science, 24: 41.

Nair, P. V. R., C. P. Gopinathan, V. K. Balachandran, K. J. Mathew, A. Regunathan, D. S. Rao and A. V. S. Murty (1984). Ecology of mud banks- Phytoplankton productivity in Alleppey mud bank. *Butt. Cent. Mar. Fish. Res. Inst.,* 31: 28-34.

Nair, S. R. S., V. R. Nair, C. T. Achuthankutty and M. Madhupratap (1981). Zooplankton composition and diversity in western Bay of Bengal. *Journal of Plankton Research*, 3: 493-508.

Nair, V. E., V. P. Devassy and M. Madhupratap (1992). Blooms of phytoplankton along the coast of India associated with nutrient enrichment and the response of zooplankton. *In*: *Marine coastal eutrophication, Science of the Total Environment*. R. A. Vollenweiden *et al*. (Eds.), Elsevier, Amsterdam. p. 819-828.

Nair, V. R and G. Peter (1980). Zooplankton from the shelf waters off the west coast of India. *Mahasagar*, 13 (1): 61-65.

Nair, V. R., G. Peter and V. T. Paulinose (1978). Zooplankton studies in the Indian Ocean from the Arabian Sea during the post monsoon period. *Mahasagar*, 11 (1&2): 35-43.

Nair, V. R., G. Peter and V. T. Poulinose (1977). Zooplankton studies in the Indian Ocean I. From Bay of Bengal during Southwest monsoon period. *Mahasagar*, 10: 45- 54.

Nakamura, Y and M. Watanable (1983). Growth characteristics of *Chattonella antique* (raphidophyceae). Part I. Effects of temperature, salinity, light intensity and pH on growth. *Journal of the Oceanographic Society of Japan,* 39: 110-114.

Nakamura, Y. (1998). Growth and grazing of a large heterotrophic dinoflagellate, *Noctiluca scintillans* in laboratory cultures. *Journal of Plankton Research* 20: 1615-1636.

Nakamura, Y., S. Suzuki and J. Hiromi (1996). Development and collapse of a *Gymnodinium mikimotoi* red tide in the Seto Inland Sea. *Aquat. Microb. Ecol.* 10:131-137.

Naqvi, S. W. A., George, M. D., Narvekar, P.V., Jayakumar, D. A., and 9 others. (1998). Severe fish mortality associated with red tide observed in the sea off Cochin. *Current Science,* 75(6), 543-544.

Naqvi, S. W. A., H. Naik and P. V. Narvekar (2003). The Arabian Sea. *In*: Biogeochemistry of Marine Systems, Black, K. and Shimmield, G (Eds.), Blackwell, Oxford, 156-206.

Nasser, A. K. V., P. Siraimeetan and P. M. Aboobakar (1998). Zooplankton abundance and distribution at Minicoy laggon, Lakshadweep. *Indian J. of Mar. Sci.*, 27: 346-350.

Nayak, B. B., I. Karunasagar and I. Karunasagar (2000). Bacteriological and physicochemical factors associated with *Noctiluca miliaris* bloom, along Mangalore, south west coast of India. *Indian J. Mar. Sci.*, 29: 139-143.

Nehring, S (1998). Non-indigenous phytoplankton species in the North Sea: supposed region of origin and possible transport vector. *Arch. Fish. Mar. Res.,* 46: 181-194.

Newell, G. E and R. C. Newell (1963). Marine plankton a practical guide. Hutchinson Educational, London.

Noe-Nygaard, F., K. F. Surlyk and S. Piasecki (1987). Bivalve mass mortality caused by toxic dinoflagellate blooms in Berrisian-Valanginian lagoon, Bornholm, Denmark. Palaios, 2: 263-273.

O'Neil, J. M and M. R. Roman (1992). Grazers and associated organisms of *Trichodesmium*. *In*: Marine pelagic cyanobacteria: *Trichodesmium* and other diazotrophs, Carpenter E. J. (ed.) Kluwer, p. 61-73.

Oda, T., A. Ishimatsu, S, Takeshita and T. Muramatsu (1994). Hydrogen peroxide production by the red tide flagellate *Chattonella marina*. *Bioscience Biotechnology and Biochemistry,* 58: 957-958.

Odum, E. P (1971). Fundamentals of Ecology. London: W. B. Saunders Company.

Okaichi, T (1989). Red tide problems in the Seto Island Sea, Japan. *In*: Biology, Environmental Science and Toxicology. Okaichi, T., Anderson, D. M., Nemoto, T. (Eds.). Elsevier, New York. 137-142.

Okaichi, T and S. Nishio (1976). Identification of ammonia as the toxic principle of red tide of *Noctiluca miliaris*. *Bulletin of Plankton Society of Japan*, 23: 75-80.

Omori, M and T, Ikeda, (1984*)*. Methods in Marine Zooplankton Ecology, John- Willy and Sons Pub., New York, 332 pp.

Onoue, Y and K. Nozawa (1989). Separation of toxin from harmful red tides occurring along the coast of Kagoshima Prefecture. *In*: Red tides- Biology, Environmental Science and Toxicology. Okaichi, T., Anderson D. M, Nemeto, T (Eds.), New York: Elsevier, p 371-374.

Onoue, Y., M. S. Haq and K. Nozawa (1990). Separation of neurotoxins from *Chattonella marina*. *Nippon Suisan Gakkaishi,* 56: 695

Owens, N. J. P., P. H. Burkil, R. F. C. Mantoura, E. M. S. Woodward, I. E. Bellan, J. Aiken, R. J. M. Howland and C. A. Llewellyn (1993). Size fractioned primary production and nitrogen assimilation in the northwestern Indian Ocean, *Deep Sea Res., II,* 40: 697-709.

Padmakumar, K. B., M. G. Sanilkumar, A. V. Saramma, V. N. Sanjeevan and N. R. Menon (2008). Green tide of *Noctiluca miliaris* in the Northern Arabian Sea, *IOC- UNESCO, Harmful Algae News*, No. 36, 12

Padmakumar, K.B., M. G. Sanilkumar, A. V. Saramma and N. R. Menon (2007). A ‘Red tide’ caused by the diatom *Coscinodiscus* on the southwest coast of India. IOC- UNESCO *Harmful Algae News,* No. 35.

Padmavathi, G and S. C. Goswami (1996). Zooplankton ecology in the Mandovi-Zuari estuarine system of Goa, west coast of India. *Ind. J. Mar. Sci., 25*: 268-273.

Paerl, H. W (1988). Nuisance phytoplankton blooms in coastal, estuarine and inland waters. *Limnology and Oceanography*, 33: 823-847.

Paerl, W. H (1997). Coastal eutrophication and harmful algal blooms: importance of atmospheric deposition and ground water as "new" nitrogen and other nutrient sources. *Limnology and Oceanography*. 42(5), Part II: 1154-1165.

Pant, A., S. G. P. Matondkar and S. C. Goswami (1984). Biomass relations between Phytoplankton and zooplankton in Goa waters. *Ind. J. Mar. Sci.,* 13: 116-118.

Parsons, T. R., Y. Maita, and C. M. Lalli (1984). A manual of chemical and biological methods for Seawater analysis, Pergamon Press, New York. pp 173.

Peter, G and V. R. Nair (1978). Vertical distribution of zooplankton in relation to thermocline. *Mahasagar*, 11: 169-175.

Pielou, E.C (1966). The measurement of diversity of different types of biological collections. *J. Theor. Biol.*, 13: 131- 144.

Pond, S. and Pickard, G. L (1983). Introductory Dynamic Oceanography. New York: Pergamon press, 329 pages.

Poulet, S. A., A. Ianora, A. Miralto and L. Meijer (1994). Do diatoms arrest embryonic development in copepods? *Mar. Ecol. Prog. Ser.* 111: 79-86.

Prabhu, M. S., S. Ramamurthy, M. D. K. Kuthalingam and M. H. Dhulkhed (1965). An unusual swarming of the planktonic blue green algae *Trichodesmium* spp. off Mangalore. *Current Science*, 34: 95.

Prakash, A and A. H. V. Sharma (1964). On the occurrence of red water phenomenon on the west coast of India. *Current Science*, 33(6): 168-170.

Prasad, B. R and R. Jayaraman (1954). Preliminary studies on certain changes in the plankton and hydrological condition associated with the swarming of *Noctiluca. Proc. Ind. Acad. Sci.,* 40B: 49-57.

Prasad, R. R (1953). Swarming of *Noctiluca* in the Palk Bay and its effect on 'Choodai' fishery, with a note on the possible use of *Noctiluca* as an indicator species. *Proc. Ind. Acad. Sci.,* 40: 49-57.

Prasad, R. R (1956). Further studies on the plankton of the inshore waters off Mandapam. *Indian J. Fish*., 3(1): 1-42.

Prasad, R. R (1968). IIOE Plankton Atlas. Map on total zooplankton biomass in the Indian Ocean. *IOBC, Cochin,* Vol. 1, Fasc. 29 maps.

Prasannakumar, S., M. Madhupratap, M. Dileep Kumar, M. Gauns, P. M. Muraleedharan, V. V. Sarma and S. N. DeSouza (2000). Physical control of primary productivity on a seasonal scale in central and eastern Arabian Sea *Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences)* 109 (4): 433-441.

Purushan, K. S., T. Balachandran and M. Sakthivel (1974). Zooplankton abundance off the Kerala coast during February and April 1970. *Mahasagar*, 7 (3& 4): 165-175.

Qasim, S. Z (1970). Some characteristics of *Trichodesmium* bloom in the Laccadives. *Deep Sea Research*, 17: 655.

Qasim, S. Z (1973). An appraisal of the studies on the maturation and spawning in marine teleosts from Indian waters. *Indian J. Fish.,* 20(1): 166-181.

Qasim, S. Z (1978). Distribution of chlorophyll *a* in the Indian Ocean. *Indian J. Mar. Sci.,* 7: 258-262.

Qasim, S. Z and C. V. G. Reddy (1967). The estimation of plant pigments of Cochin backwater during the monsoon months. *Bull. Mari. Sci.,* 17(1): 95-110.

Qasim, S. Z, P. M. A. Bhattathiri and V. P. Devassy (1972). The influence of salinity on the rate of photosynthesis and abundance of tropical phytoplankton. *Proc. Ind. Acad. Sci.,* 69: 51-94.

Qi, Y., Y. Hong, S. Lu and H. Qian (1995). An overview of harmful algal bloom (red tide) occurrences along the coast of China and research upon them. In: The Marine Biology of the south china sea II. Morton, B., G. Xu, R. Zou, J. Pan and G. Cai (Eds.), World Publishing Cooperation, Beijing PRC: 107-110.

Quevedo, M., R. Gonzalez-Quiros, and R. Anadon (1999). Evidence of heavy predation by *Noctiluca scintillans* on *Acartia clause* (copepoda) eggs off the central Cantabrian coast (NW Spain). *Oceanologica Acta,* 22: 127-131.

Raj, I. D and C. P. Ramamirtham (1981). Distribution of zooplankton biomass, fish eggs and larvae along the west coast of India. *J. Mar. Biol. Ass. India*, 23(1&2): 86-140.

Rajagopalan, M. S., P. A. Thomas, K. J. Mathew, G. S. D. Selvaraj, R. M. George, C. V. Mathew, T. S. Naomi, P. Kaladharan, V. K. Balachandran and G. Antony (1992). Productivity of the Arabian Sea along the southwest coast of India. *Bull. Cent. Mar. Fish. Res. Inst.,* 45: 9-37.

Rajesh, K. M., R. M. Mendon and T. R. C. Gupta, A. Padiyar and K. Chandramohan, *INFOFISH. Int.*, 2002, 1, 60-64.

Ramaiah, N and Vijayalakshmi Nair (1997). Distribution and abundance of copepods in the pollution gradient zones of Bombay harbour- Thane creek- Basin creek, west coast of India. *Ind. J. Mar. Sci.,* 26: 20-25.

Ramamirtham and R. Jayarman (1963). Some aspects of the hydrological conditions of the backwater around Wellington Island (Cochin). *J. Mar. Biol. Ass. India*: 170.

Ramamurhty, V. D., A. R. Selvakumar and R. M. S. Bhargava (1972). Studies on the bloom of *Trichodesmium erythraeum* in the waters of the Central West coast of India. *Current Science*, 41:803.

Ramamurthy, S (1965). Studies on the plankton of the North Kanara coast in relation to the pelagic fishery. *J. Mar. Biol. Ass. India*, 7 (1): 127-149.

Ramsdell, J. S (2007). The molecular and integrative basis to domoic acid toxicity. *In*: Phycotoxins: Chemistry and Biochemistry, Botana, L. (ed.), Blackwell Publishing Professional, Cambridge, pp. 223-250.

Rao, D. S., A. Regunathan, K. J. Mathew, C. P. Gopinathan and A. V. S. Murty (1984). Mud of the mud-banks: its distribution, physical and chemical characteristics. *Bull. Cent. Mar. Fish. Res. Inst.,* 31: 21-24.

Rao, D. S., C. P. Ramamirtham, A. V. S. Murty, S. Muthusamy, N. P. Kunhikrishnan and L. R. Khambadkar (1992). Oceanography of the Arabian Sea with particular reference to the southwest monsoon. *Bull. Cent. Mar. Fish. Res. Inst.,* 45: 4-8.

Rao, D., K. J. Mathew, C. P. Gopinathan, A. Regunathan and A. V. S. Murty (1980). Mud banks and coastal erosion in relation to fisheries. *Mar. Fish. Infbr. Serv. T & E Ser.,* 19: 1-10.

Rao, T. S. S (1973). Zooplankton studies in the Indian Ocean. *In*: The biology of the Indian Ocean, B. Zeitzschel (ed.), Berlin-Heidelberg, New York- Springer. Vol. 3: 234-255.

Rao, T.S.S (1973). Zooplankton studies in the Indian Ocean. In: B. Zeitzschel (ed.). The biology of the Indian Ocean, Ecological studies. Analysis Synthesis. Springer- Verlag, Berlin, 3: 243-256.

Raymont, J. E. E. (1963). Plankton and productivity in the Oceans. Part 2, Zooplankton, Pergamon Press Oxford, New York. Toronto. Sydney.

Raymont, J. E. G (1980). Plankton and productivity in the oceans, Part. I. Phytoplankton, Pergamon press, Oxford, 489 p.

Reghu Prasad, R., K. N. Krishna Kartha (1959). A note on the breeding of copepods and its relation to diatom cycle. *J. Mar. Biol. Ass. India*, 1(1): 77-84.

Reguera, B., I. Bravo, C. Maracaillou-Le Baut, P. Masselin, M. L. Fernandez, A. Miguez, and A. Martinez (1993). Monitoring of *Dinophysis spp*. and vertical distribution of okadoic acid on mussel rafts from Ria de Pontevedra (NW Spain). *In*: Toxic Phytoplankton Blooms in the Sea, T. J. Smayda, Y. Shimizu (Eds.), Elsevier, Amsterdam, pp 553-558.

Rengarajan, K (1983). Quantitative and seasonal abundance of siphonophores along the southwest coast of India and the Laccadive Sea. *J. Mar. Biol. Ass. India*, 25(1&2): 17-40.

Richardson, K (1997). Exceptional phytoplankton blooms. *In*: Advances in Marine Biology, J. H. S. Blaxter and A. J. Southward (Eds.), 31: 302-383.

Rick, H. J and C. D. Durselen (1995). Importance and abundance of the recently established species *Coscinodiscus wailesii* Gran et Angst in the German Bight. *Helgolander Meeresunters*, 49: 355-74.

Riley G. A., Stommel, H, Bumpus, D.F. 1949. Quantitative ecology of the plankton of the Western- North Atlantic. *Bull. Bingham Oceanogr. Coll.,* 12, 1-169.

Robin, R. S., M. Srinivasan and K. Chandrasekhar (2009). Distribution of zooplankton from Arabian Sea along southern Kerala (Southwest coast of India) during the cruise. *Current Research Journal of Biological Sciences*, 1 (3): 155-159.

Roman, M. R (1978). Ingestion of the blue green alga *Trichodesmium* by the harpacticoid copepod, *Macrosetella gracilis*. *Limnology and Oceanography*, 23(6): 1245-1248.

Roman, M., S. Smith, K. Wishner, X. Zhang and M. Gowing (2000). Mesozooplankton production and grazing in the Arabian Sea. *Deep-Sea Res. II*, 47: 1423-1450.

Roy, S., R. P. Harris and S. A. Pulet (1989). Inefficient feeding by *Calanus helgolandicus* and *Temora longicornis* on *Coscinodiscus wailesii*: quantitative estimation using chlorophyll-type pigment and effects on dissolved free amino acids. *Mar. Ecol. Prog. Ser.,* 52:145-53.

Sahayak, S., R. Jyothibabu, K. J. Jayalakshmi, H. Habeebrehman, P. Sabu, M. P. Prabhakaran, P. Jasmine, P. Shaiju, G. Rejomon, J. Thresiamma and K. K. C. Nair. (2005). Red tide of *Noctiluca miliaris* off south of Thiruvananthapuram subsequent to the ‘stench event’ at the southern Kerala coast. *Current Science*, 89 (9), 1472-1473.

Saifullah, S. M and Chaghtai (1990). Incidence of *Noctiluca scintillans* (Macartney) Ehrenb., blooms along Pakistan’s shelf. *Pakistan Journal of Botany,* 22: 94-99.

Sakshaug, E (1989). The physiological ecology of polar phytoplankton. *In*: Marine living systems of the Far North, Rey L and V. Alexander (Eds.). E. J. Brill, Leiden, Netherlands, pp 61-89.

Sandra Jansen, Christian Wexels Riser, Paul Wassmann and Ulrich Bathmann (2006). Copepod feeding behaviour and egg production during a dinoflagellate bloom in the North Sea. *Harmful Algae* (5), 102-112.

Sanilkumar, M. G (2009). Micro algae in the southwest coast of India. PhD Thesis, Cochin University of Science and Technology.

Sanjeevan, V. N., P. Jasmine, B. R. Smitha, T. Ganesh, P. Sabu, and T. Shunmugaraj (2009). Eastern Arabian Sea marine ecosystems. *International conference on Marine Ecosystems- Challenges and Opportunities (MECOS) organised by The Marine Biological Association of India, Book of abstracts*: 1-2.

Santhakumari, V and M. Saraswathy (1981). Zooplankton along the Tamil Nadu coast. *Mahasagar*, 14(4): 289-302.

Santhanam, P and P. Perumal (2003). Diversity of zooplankton in Parangipettai coastal waters, Southeast coast of India. *J. Mar. Biol. Ass. India*, 45(2): 144-151.

Santhanam, R and A. Srinivasan (1996). Impact of dinoflagellate *Dinophysis caudata* bloom on the hydrography and fishery potentials of Tuticorin Bay, South India. *In*: Harmful and toxic algal blooms, Yasumoto T, Oshima Y, Fukuyo Y (Eds.). Intergovernmental Oceanographic Commission of UNESCO, Sendai, p 41-44.

Santhanam, R., A. Srinivasan, V. Ramadhas and M. Devaraj (1994). Impact of *Trichodesmium* bloom on the plankton and productivity in the Tuticorin bay, southeast coast of India. *Ind. J. Mar. Sci.,* 23: 27-30.

Sarkar, S. K., B. N. Singh and A. Choudary (1986). Composition and variations in the abundance of zooplankton in the Hooghly estuary, West Bengal, India. *Proc. Indian Acad. Sci.,* 95: 125-134.

Sasamal, S. K., R. C. Panigrahy and S. Misra (2005). *Asterionella* blooms in the northwestern Bay of Bengal during 2004. *International Journal of Remote Sensing*, 26(17): 3853-3858.

Sasikumar, N., V. P. Venugopal, J. Azariah and K.V.K. Nair (1989). After effect of a dinoflagellate bloom on the hard bottom community in Kalpakkam coastal waters. *Mahasagar*, 22: 159.

Satpathy, K. K. and K. V. K. Nair (1996). Occurrence of phytoplankton bloom and its effect on coastal water quality. *Ind. J. Mar. Sci.*, 25: 145-147.

Satya Prakash and R. Ramesh (2007). Is the Arabian Sea getting more productive? *Current Science*, 92 (5): 667-671.

Schnack, S. B (1983). On the feeding of copepods on *Thalassiosira partheneia* from the Northwest African upwelling area. *Mar. Ecol. Prog. Ser.,* 11: 49-53.

Scholin, C. A., F. Gulland, G. J. Doucette, S. Benson, M. Busman, F. P. Chavez, J. Cordaro, R. DeLong, A. De Vogelaere, J. Harvey, M. Haulena, K. A. Lefebvre, T. Lipscomb, S. Loscutoff, L. J. Lowenstine, R. Marin III, P. E. Miller, W. A. McLellan, P. D. R. Moeller, C. L. Powell, T. Rowles, P. Silvagni, M. W. Silver, T. Spraker, V. L. Trainer and F. M. Van Dolah (2000). Mortality of sea lions along the central California coast linked to a toxic diatom bloom. *Nature*, 403, 80-83.

Sellner, K. G (1992). Trophodynamics of marine cyanobacteria blooms. *In*: Marine pelagic cyanobacteria: *Trichodesmium* and other diazotrophs, Carpenter E. J (ed.) Kluwer, p. 75-94.

Sellner, K. G (1997). Physiology, ecology and toxic properties of marine cyanobacteria bloom. *Limnology and Oceanography*, 42: 1089-1104.

Sellner, K. G., G. J. Doucette and G. J. Kirkpatrick (2003). Harmful algal blooms: causes, impacts and detection. *J. Ind. Microbiol. Biotechnol.,* 30: 383-406.

Selvaraj, G. S. D., V. J. Thomas and L. R. Khambadkar (2003). Seasonal variation of phytoplankton and productivity in the surf zone and backwater at Cochin. *J. Mar Biol. Assoc. India,* 45 (1): 9-19.

Sen Gupta, R and S. W. A. Naqvi (1984). Chemical oceanography of the Indian Ocean, north of the Equator, *Deep-Sea Research*, 31: 671-706.

Shannon, C. E and W. Weaver (1949). The Mathematical theory of communication. University of llinoio press, Urbana 117 pp.

Shaw, B. A., R. J. Andersen and P. J. Harrison (1995). Feeding deterrence properties of apo-fucoxanthinoids produced by *Phaeodactylum tricornutum*. *Mar. Biol.* 124: 467-472.

Shenoi, S. C., D. Shankar, V. V. Gopalakrishna and F. Furand (2005). Role of ocean in the genesis and annihilation of the core of the warm pool in the South Eastern Arabian Sea. *Mausam*, 56(1): 147-160.

Shinji, H and S. Akihiro (2002). Light utilization efficiency of size-fractionated phytoplankton in the subarctic Pacific, spring and summer 1999: high efficiency of large-sized diatom. *Journal of Plankton Research*, 24: 83-87.

Sieburth, J. M., V. Smetacek and J, Lenza (1978). Pelagic ecosystem structure: heterotrophic compartments and their relationship to plankton size fractions. *Limnology and Oceanography*, 23: 1256-1263.

Silas, E. G and K. J. Mathew (1986). Spatial distribution of Euphausiacea (Crustacea) in the southeastern Arabian Sea. *J. Mar. Biol. Ass. India*, 28 (1&2): 1-21.

Silas, E. G and P. P. Pillai (1972). Dynamics of zooplankton in a tropical estuary (Cochin back waters) with a review on the plankton fauna of the environment. *Bull. Dept. Mar. Sci. Univ. Cochin*, 7: 329-355.

Smayda, T. J (1990). Novel and nuisance blooms in the sea: evidence for a global epidemic. *In*: Toxic marine phytoplankton, Graneli, E., B. Sundstrom, L. Edler and D. M. Anderson (Eds.), Elsevier, New York, Amsterdam, London: 29- 40.

Smayda, T. J (1995). Environmental monitoring. IOC manuals and guides, No.33. Manual on harmful marine microalgae. *In:* G. M. Halegraeff, D.M. Anderson, A.D. Cembella and H.O. Envlodsen. (Eds.). UNESCO: 405-431.

Smayda, T. J (1997). Harmful algal blooms: their ecophysiology and general relevance to phytoplankton blooms in the sea. *Limnology and Oceanography*, 42:1137-1153.

Smayda, T. J (1997). What is a bloom? A commentary. *Limnology and Oceanography* 42 (5): 1132- 1136.

Smetacek, V (1981). The annual cycle of protozooplankton in the Kiel Bight. *Mar. Biol.*, 63, 1-11.

Smetacek, V. S., R. Scharek, L. I. Gordon, H. Eicken, E. Fahrbach, G. Rohardt and S. Moore (1992). Early spring phytoplankton blooms in ice platelet layers of the Southern Weddle Sea. Antarctica. *Deep Sea Research*, 39: 153- 168.

Smith, S. L and L. A. Codispoti (1980). Southwest monsoon of 1979: Chemical and biological response of Somali coastal waters. *Science*, 209: 597-600.

Smith, S., M. Roman, I. Prusova, K. Wishner, M. Gowing, L. A. Copispoti, R. Barber, J. Marra and C. Flagg (1998). Seasonal response of zooplankton to monsoonal reversals in the Arabian Sea. *Deep Sea Research* II, 45(10&11): 2369-2403.

Smitha, B. R., V. N. Sanjeevan, K. G. Vimalkumar and C. Ravichandran (2008). On the upwelling off the southern tip and along the West coast of India. *J. Coast. Res.*, 24 (4C): 95-102.

Sournia, A (1968). Diatomees planctoniques du canal de Mozambique et de I,ile Maurice. *Memoire. O.R.S.T.O.M.*, 31: 1-120.

Sournia, A, M. J. Chretiennot- Dinet and M. Ricard (1991). Marine phytoplankton: how many species in the world ocean? *J. Plankton Res.*, 13, 1093 -1099.

Sreekumaran., S. R. Nair, V. P. Devassy and M. Madhupratap (1992). Blooms of phytoplankton along the west coast of India associated with nutrient enrichment and the response of zooplankton. Marine coastal eutrophication. R.A. Volllenweider., R. Marchetii., R. Viviani, (Eds.). *In:* Science of the total environment. Elsevier Sci. Publ. Amsterdam, 819-828.

Srinivasan, M (1974). Distribution of chaetognaths with special reference to *Sagitta decipiens* as an indicator of upwelling along the west coast of India. *J. Mar. Biol. Ass. India,* 16 (1): 126-142.

Steedman, F. H. (ed.) (1976). Zooplankton fixation and preservation. *Monographs on Oceanographic Methodology,* 4; UNESCO, Paris.

Steele, J. H (1962). Environmental control of photosynthesis in the sea. *Limnology and Oceanography*, 7: 137-150.

Steele, J. H and E. W. Henderson (1993). The significance of interannual variability. *In*: Towards a Model of Ocean Biogeochemical processes, Evans, G. T., Fasham, M. J. R (Eds.) Springer- Verlag, Berlin, pp.237-260.

Steeman Nielsen, E. S (1937). The annual amount of organic matter produced by the phytoplankton in the sound off Helsingiir. Medd.

Komm. f. Danmarks Fiskeri-og Havundersogelacr. Serie: Plankton, Bd. III, No. 3, 38 pp.

Steidinger, K. A (2010). Research on the life cycle stages of harmful algae: A commentary. *Deep Sea Research* II, 57: 162- 65.

Steidinger, K. A and K. Haddad (1981). Biologic and Hydrographic aspects of Red tides. *BioScience*, 31(11): 814-819.

Steidinger., K. A and K. Tangen. (1997). Dinoflagellates. Chapter 3 *In*: Identifying Marine phytoplankton, C. R. Tomes (Ed.), Academic press, UK. pp 387-584.

Sterner, R. W (1989). Resource competition during seasonal succession towards dominance by cyanobacteria. *Ecology*, 70: 229-245.

Stoecker, D., R. R. L. Guillard and R. M. Kavee (1981) Selective predation by *Favella ehrenbergii* (Tintinnida) on and among dinoflagellates. *Biol. Bull.,* 160:136-145.

Strickland, J. D. H and T. R. Parsons (1972). A practical handbook of sea water analysis. Bulletin no. 167, Fisheries Research Board of Canada, Ottawa. 310 pages.

Strom, S. L (2001). Light aided digestion, grazing and growth in herbivorous protists. *Aquatic Microbial Ecology,* 23: 253-261.

Subrahmanyan, R (1946). A systematic account of the Marine plankton Diatoms of the Madras coast. *Proc. Ind. Acad. Sci.,* 24: 85-197.

Subrahmanyan, R (1954). On the life history and ecology of *Hornellia marina* gen. et sp. Nov., (Chloromonadineae), causing green discoloration of the sea and mortality among marine organisms off the Malabar coast. *Indian Journal of Fisheries,* 1: 182-203.

Subrahmanyan, R (1958). Ecological studies on the marine phytoplankton on the west coast of India. *Indian Bot. Soc.,* 1: 145-151.

Subrahmanyan, R (1959a). Studies on the phytoplankton of the west coast of India. Part- I. Quantitative and qualitative fluctuation of total phytoplankton crop, the zooplankton crop and their interrelationship with remarks on the magnitude of the standing crop and production of matter and their relationship to fish landings. *Proc. Ind. Acad. Sci.*, 50:113-187.

Subrahmanyan, R (1959b). Studies on the phytoplankton of the west coast of India. Part- II. Physical and chemical factors influencing the production of phytoplankton with remarks on the cycle of nutrients and on the relationship of the phosphate content to fish landings. *Proc. Ind. Acad. Sci.*, 50. 189- 252.

Subrahmanyan, R (1968). The Dinophyceae of the Indian seas. Part 1. Genus *Ceratium*: 129p.

Subrahmanyan, R (1971). The Dinophyceae of the Indian seas. Part 2. Genus *Peridinium*: 334p.

Subrahmanyan, R and A. H. V. Sharma (1960). Studies on the phytoplankton of the west coast of India Part III. Seasonal variations of the phytoplankters and environmental factors. *Indian J. Fish.*, 7: 307-336.

Subrahmanyan, R., C. P. Gopinathan and C. Thankappan Pillai (1975). Phytoplankton of the Indian Ocean- some ecological problems. *J. Mar. Biol. Ass. India*, 17(3): 608-612.

Subramanian, A and A. Purushothaman (1985). Mass mortality of fish and invertebrates associated with a bloom of *Hemidiscus hardmanianus* (Bacillariophyceae) in Parangipettai (southern India). *Limnology and Oceanography,* 30 (4): 910-911.

Sujata Mishra and Panigrahy (1996). Copepods of Bahuda estuary (Orissa), east coast of India. *Indian J. Mar. Sci.,* 25(2): 98-102.

Sun, J., D. Liu, Z. Wang, X. Shi, R. Li and M. Zhu (2003). Micro-zooplankton herbivory during red tide frequent occurrence period in spring in the East China Sea. *Chinese Journal of Applied Ecology*, 14(7): 1073-1080.

Suresh, V. R and K. J. Mathew (1997). Zooplankton ecology in Kavaratti atoll, Lakshadweep, India. *Indian J. Fish*., 44 (3): 271-277.

Suvapepant, S (1992). *Trichodesmium* blooms in gulf of Thailand. *In*: Marine pelagic cyanobacteria: Trichodesmium and other diazotrophs, E. J. Carpenter *et al.* (Eds.), Kluwer, p. 343-348.

Svedrup, H.V., Johnson, W. Martin and Richard, H. Fleming. 1942. The Oceans, their physics, chemistry and general biology. Prentice hall, Inc. New York. 1087p.

Sweeney, B. M (1976). *Pedinomonas noctilucae* (Prasinophyceae), the flagellate symbiotic in *Noctiluca* (Dinophyceae) in Southeast Asia. *Journal of Phycology* 12: 460-464.

Sweeney, B. M (1979). Opening remarks, session1: The organisms, p. 37-40. *In*: Toxic dinoflagellate blooms. *Proc. 2nd Int. Conf. Elsevier North Holland*.

Takano, H (1965). New and rare diatoms from Japanese marine waters-I. *Bulletin of Tokai Regional Fisheries Research Laboratory*, 42: 1-10.

Takano, H (1976). Scanning electron microscopy of diatoms-II. *Thalassiosira mala* Takano. *Bulletin of Tokai Fisheries Research Laboratory*, 87: 57-65.

Takano, H. 1956. Harmful blooming of minute cells of *Thalassiosira decipiens* in coastal water in Tokyo Bay. *Journal of Oceanographical Society of Japan* 12: 63-67.

Tarling, G. A., P. Ward, M. Sheader, J. A. Williams and C. Symon (1995). Distribution pattern of macrozooplankton assemblages in the southwest Atlantic. *Mar. Ecol. Prog. Ser.*, 120: 29-40.

Taylor, F. J. R and U. Pollingher (1987). Ecology of Dinoflagellates *In*: The biology of dinoflagellates, F. J. R Taylor (Ed.). Oxford, London: Blackwell. pp 398-529.

Taylor, F. J. R., Y. Fukuyo and J. Larzen (1995). Taxonomy of Harmful Dinoflagellates. Part-II, Taxonomy, Chapter. 15 *In*: Manual on Harmful Marine Microalgae, G. M. Hallegraeff, D. M. Anderson, A. D. Cembella (Eds.), IOC-UNESCO Manuals and Guides 33, pp. 283-317

Tester, A. P and K. A. Steidinger (1997). *Gymnodinium breve* red tide blooms: initiation, transport and consequences of surface circulation. *Limnology and Oceanography*, 42 (5), part 2: 1039-1051.

Thangaraja, M., A. Al-Aisry and L. Al-Kharusi (2007). Harmful algal blooms and their impacts in the middle and outer ROPME sea area. *International Journal of Oceans and Oceanography*, 2(1): 85-98.

Thoha, H., Q. Adnan, T. Sidabutar and Sugestiningsih (2007). Note on the occurrence of phytoplankton and its relation with mass mortality in the Jakarta Bay, May and November 2004. *Makara, Sains*, 11 (2): 63-67.

Thompson, P. K. M (1986). Seasonal distribution of cyclopoid copepods of the mud banks off Alleppey, Kerala coast. *J. Mar. Biol. Ass. India*, 28(1&2): 48-56.

Throndsen, J (1997). The Planktonic Marine flagellates. *In*: Identifying Marine Phytoplankton. Tomas C. R (ed.), New York: Academic press. p 591-729.

Tilstone, G. H., B. M. Miguez, F. G. Figueiras and E. G. Fermin (2000). Diatom dynamics in a coastal ecosystem affected by upwelling: coupling between species succession, circulation and biogeochemical processes. *Mar. Ecol. Prog. Ser.*, 205: 23-41.

Tiwari, L. R and V. R. Nair (1998). Ecology of phytoplankton from Dharamtar creek, west coast of India. *Ind. J. Mar. Sci.,* 27: 302-309.

Todd, C. D., M. S. Laverack and G. A. Boxshall (1996). Coastal Marine Zooplankton- a practical manual for students. Cambridge University Press. 106 pp.

Tomas, C. R (1997). Identifying Marine diatoms and dinoflagellates, New York: Academic press. 858 pages.

Trainer, V. L., W. P. Cochlan, A. Erickson, B. D. Bill, F. H. Cox, J. A. Borchert, and K. A. Lefebvre (2007). Recent DA closures of shellfish harvest areas in Washington State inland waterways. *Harmful Algae*, 6: 449- 459.

Turkoglu, Muhammet and Koray, Tufan (2002). Phytoplankton species succession and nutrients in the southern Black sea. (Bay of Sinop). *Turk. J. Bot.*, No. 26 (2002): 235- 252.

Turner, J. T and D. M. Anderson (1983). Zooplankton grazing during dinoflagellate blooms in Cape Cod embayment, with observations of predation upon tintinnids by copepods. P.S.Z.N.I: *Marine Ecology*, 4: 359-374.

Turner, J. T and P. A. Tester (1997) Toxic marine phytoplankton, zooplankton grazers, and pelagic food webs. *Limnology and Oceanography*, 42:1203-1214.

Turner, J. T, P. A. Tester and P. J. Hansen (1998). Interactions between toxic marine phytoplankton and metazoan and protozoan grazers. *In*: Physiological ecology of harmful algal blooms, Anderson D. M, Cembella A. D, Hallegraeff G. M (Eds.). NATO ASI Series 41. Springer, Berlin Heidelberg New York, pp 453-474.

Turner, J. T., G. J. Doucette, B. A. Keafer and D. M. Anderson (2005). Trophic accumulation of PSP toxin in zooplankton during *Alexandrium fundyense* blooms in Casco Bay, Gulf of Maine, April-June 1998. II. Zooplankton abundance and size fractioned community composition. *Deep-Sea Res.,* II, 52: 2784-2800.

Turner, J. T., G. J. Doucette, C. L. Powell, D. M. Kulis, B. A. Keafer and D. M. Anderson (2000). Accumulation of red tide toxins in larger size fractions of zooplankton assemblages from Massachusetts Bay, USA. *Mar. Ecol. Pro. Ser.*, 203, 95-107.

UNESCO (1994). Protocols for the Joint Global Ocean Flux Study (JGOFS), Core Measurements, IOC Manual and Guides 29, 170 pp.

UNESCO, (1968). *Zooplankton sampling Monographs on Oceanography Methodology,* 2, UNESCO, Paris.

Uye, S (1986). Impact of copepod grazing on the red tide flagellate *Chattonella antiqua*. *Mar. Biol*., 92: 35.

Uye, S and K. Takamatsu (1990). Feeding interactions between planktonic copepods and red tide flagellates from Japanese coastal waters. *Mar. Ecol. Prog. Ser.,* 59: 97-107.

Velappan Nair, R and R. Subrahmanyan (1955). The diatom *Fragilaria oceanica* Cleve, an indicator of abundance of the Indian oil *Sardine*, *Sardinella longiceps* Cuv. and Val. *Current Science*, 2: 41-42.

Venkataraman, G (1939). A systematic account of some south Indian diatoms. *Proc. Indian. Acad. Sci.*, 10: 293-368.

Venrick, E. L (1974). The distribution and significance of *Richelia intracellularis* Schmidt in the North Pacific Central Gyre. *Limnology and Oceanography*, 19: 437- 445.

Venugopal, P., P. Haridas, M. Madhupratap and T. S. S Rao (1979). Incidence of red water along south Kerala coast. *Indian J. Mar. Sci.*, 8: 94.

Vijayalakshmi, R (1978). Bathymetric Distribution of Chaetognaths in the Indian Ocean. *Indian . J. Mar. Sci.,* 7: 276-282.

Vijayalakshmi R. Nair (1980). Production and associations of zooplankton in estuarine and near shore waters of Goa. *Indian J. Mar. Sci.*, 9: 116-119.

Villareal, T. A (1989). Division cycles in the nitrogen fixing *Rhizosolenia* (Bacillariophyceae) *Richelia* (Nostocaceae) symbiosis. *European Journal of Phycology,* 24(4): 357- 365.

Villareal, T. A (1990). Laboratory culture and preliminary characterization of the nitrogen fixing *Rhizosolenia- Richelia* symbiosis. *Marine Ecology*, 11(2):117-132.

Vonshak, A (1986). Laboratory techniques for the cultivation of microalgae, In: CRC Handbook of Microalgae Mass Culture, A. Richmond (ed.), CRC Press, Inc., Florida, U.S.A. pp. 117-145.

Wang, C., X. Li, Z. Lai, S. Yao and C. Huang (2008). The study on seasonal trait of *Nitzschia* population in Zhelin Bay of eastern Guangdong. *Estuarine Coastal and Shelf Science*, 76: 319-326.

Wei, G., D. Tang and S. Wang (2008). Distribution of chlorophyll and harmful algal blooms (HABs): A review on space based studies in the coastal environments of Chinese marginal seas. *Advances in Space Research*, 41: 12-19.

White, A. W (1977). Dinoflagellate toxins as probable cause of an Atlantic herring (*Clupea harengus harengus*) kill, and pteropods as apparent vector. *J. Fish. Res. Bd. Can.,* 34: 2421-2424.

White, A. W (1979). Dinoflagellate toxins in phytoplankton and zooplankton fractions during a bloom of *Gonyaulax excavate*. *In*: Toxic dinoflagellate blooms, Vol. 1. Proc. 2nd Int. Conf. Elsevier-North Holland, p 381-384.

White, A. W (1980) Recurrence of kills of Atlantic herring (*Clupea harengus harengus*) caused by dinoflagellate toxins transferred through herbivorous zooplankton. *Can. J. Fish. Aquat. Sci.*, 37: 2262-2265.

White, A. W (1981) Marine zooplankton can accumulate and retain dinoflagellate toxins and cause fish kills. *Limnology and Oceanography*, 26: 103-109.

WHO (1984). “Aquatic (Marine and Fresh water) Biotoxins”. Environmental health criteria, No. 37, World Health Organisation, Geneva, Switzerland, 95 pp.

Wichard, T., S. A. Poulet, C. Halsband-Lenk, A. Albaina, R. Harris, D. Y. Liu, *et al*. (2005). Survey of the chemical defense potential of diatoms: screening of fifty one species for a, b, c, d-unsaturated aldehydes. *Journal of Chemical Ecology*, 31(4), 949-958.

Wilkerson, F and R. Dugdale (2008). Coastal upwelling. *In*: Nitrogen in the Marine Environment. Capone, D., Bronk, D., Mulholland, M., Carpenter, E. (Eds.), 2nd edition, Elsevier, New York, pp. 771-807.

Winkler, L.W (1888). Die Bestimmung des im Wasser gelosten Sauerstoffes. Chem. Ber., 21: 2843-2855.

Wood *et al* (1967). *J. Mar. Biol. Assoc. U.K.* 47: 23.

Wood, E. F. J (1965). *Marine Microbial Ecology*. Reinhold, New York, 56 pp.

Wood, E. F. J (1967). Microbiology of oceans and estuaries. Elsevier, New York, 319 pp.

Woodward, E. M. S., A. P. Rees and J. A. Stephen (1999). The influence of the south-west monsoon upon the nutrient biogeochemistry of the Arabian Sea, *Deep-Sea Res.*, II, 46: 571-591.

Work, T. M, A. M. Beale, L. Fritz, M. A. Quilliam, M. Silver, K. Buck, J. L. C. Wright (1993). Domoic acid intoxication of brown pelicans and cormorants in Santa Cruz, California. *In*: Toxic phytoplankton blooms in the sea. Developments in Marine Biology 3, T.J. Smayda & Y. Shimizu (Eds.), 643 -649. Elsevier, N.Y.

Wyatt, T and Horwood (1974). Model which generate red tides. *Nature*, 244: 238-240.

Wyrtiki, K (1971). Oceanographic atlas of the International Indian Ocean Expedition, National Science Foundation, Washington, DC.

Yamaguchi, M., I. Imai and T. Honjo (1991). Effects of temperature, salinity and irradiance on the growth rate of the noxious red tide flagellate *Chattonella antique* and *C. marina* (Raphidophyceae). *Nippon Suisan Gakkaishi,* 57: 1277-1284.

Yasumoto, T., Y. Oshima and W. Sugaware (1978). Identification of *Dinophysis fortii* as the causative organism of diarrhetic shellfish poisoning. *Bulletin of the Japanese Society for Scientific Fisheries*, 46: 1405-1411.

Zehr, J. P., J. B. Waterbury, P. J. Turner, J. P. Montoya, E. Omoregie, G. F. Steward, A. Hansen and D. M. Karl (2001). Unicellular cyanobacteria fix $N_2$ in the subtropical North Pacific Ocean. *Nature*, 412: 635-638.

# Acronyms and Abbreviations

| | |
|---|---|
| **ANOVA** | Analysis of variance |
| **ASP** | Amnesic shellfish poisoning |
| **AWS** | Automated Weather Station |
| **AZP** | Azaspiracid poisoning |
| **CFP** | Ciguatera fish poisoning |
| **CTD** | Conductivity - Temperature - Depth |
| **CMLRE** | Centre for Marine Living Resources and Ecology |
| **d** | Margalef's species richness |
| **DA** | Domoic Acid |
| **DOD** | Department of Ocean Development |
| **DO** | Dissolved Oxygen |
| **DSP** | Diarrhoeic shell fish poisoning |
| **E** | East |
| **e.g.** | exempli gratia (Latin word meaning `for the sake of example') |
| **EEZ** | Exclusive Economic Zone of India |
| ***et. al.*** | et alii (Latin word meaning `and others') |
| **etc** | et cetera (Latin word meaning `and other similar things; and so on') |
| **FORV** | Fishery & Oceanographic Research Vessel |
| **GF/F** | Glass Fibre/ Filter |
| **H'** | Shannon- Wiener's diversity index |
| **HABs** | Harmful Algal Blooms |
| **ICES** | International Council for the Exploration of Seas |
| **IOBC** | Indian Ocean Biological Centre |

| | |
|---|---|
| **IOC** | Intergovernmental Oceanographic Commission |
| **JGOFS** | Joint Global Ocean Flux Studies |
| **M** | Monsoon |
| **MLD** | Mixed Layer Depth |
| **MPN** | Multiple Plankton Net |
| **MR-LR** | Marine Research - Living Resources |
| **N** | North |
| **NEAS** | North eastern Arabian Sea |
| **NSP** | Neurotoxic shell fish poisoning |
| **$NO_2$-N** | Nitrite - Nitrogen |
| **$NO_3$-N** | Nitrate – Nitrogen |
| **NWC** | North West Coast |
| **OMZ** | Oxygen Minimum Zone |
| **$PO_4$-P** | Phosphate – Phosphorus |
| **POM** | Postmonsoon |
| **PP** | Primary Productivity |
| **PRM** | Premonsoon |
| **PRIMER** | Plymouth Routines in Multivariate Ecological Research |
| **PSP** | Paralytic shell fish poisoning |
| **Psu** | Practical Salinity Unit |
| **PUAs** | Poly unsaturated aldehydes |
| **SEAS** | South Eastern Arabian Sea |
| **$SiO_4$- Si** | Silicate – Silicon |
| **SST** | Sea Surface Temperature |
| **SWC** | Southwest coast |
| **WHO** | World Health Organization |