Chapter 5
Algal Blooms

5.1 Introduction

The enormous proliferation of planktonic microalgae into millions of cells per litre when sufficient light and nutrients are present is termed as algal blooms. Algal blooms are usually natural phenomena and most of the blooms are beneficial to the marine ecosystem.

In some situations algal blooms can have a negative effect. As per the International Council for the Exploration of Seas (1984), algal blooms are defined 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'.

The negative impacts of algal bloom events appear to have increased in frequency, intensity and geographic distribution in the past two decades...
Harmful Algal Blooms (HABs) are becoming a potent threat all over the world by affecting human health, natural and cultured resources, tourism and ecosystems, and the economy. Whereas a normal algal bloom preferably supports the fishery resources, the fishes avoid the area having harmful algal blooms due to the increased proliferation or the presence of toxic substance which are harmful to it.

Usually blooms have very high population density but its potential harmful effect is influenced by seasonal, regional and species-specific characteristics. Thus, a low and high biomass of the bloom can cause harmful effect (Smayda, 1997). However, it is very difficult to define the cell count that cause potential harmful effect, as some species are so toxic that their presence even in relatively low numbers may impart high level of lethal effect (IOC, 2001).

There are two primary factors that are attributed to algal blooms: natural processes such as circulation, upwelling relaxation, and river flow; and anthropogenic loadings leading to eutrophication. The latter is generally assumed to be the primary cause of all algal blooms (Anderson et al., 2002). The occurrences of algal bloom are increasing throughout the world’s oceans. The reasons for this obvious increase remain unclear, which include not only eutrophication but increased observation efforts in coastal zones of the world.

Of around 5000 known species of microalgae around the world, only about 300 species are known to have the harmful algal bloom-forming effect, particularly of water discolouration, of which only about 80 species produce potent toxins (Hallegraeff, 2003).
Based on the problems caused by the algal blooms, they can be classified into four major groups, the 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 which produce potent toxins that can affect humans through seafood (Hallegraeff, 1995).

Basically, the species which cause water discolouration and those which are non-toxic to human but cause harmful effects in the fauna comprised non-toxic species. But under some conditions, due to huge growth that generates anoxic conditions, these blooms also may lead to the death of the fishes and invertebrates.

‘Toxins’ produced by the microalgae are commonly secondary metabolites and are primarily involved in bioluminescence, nitrogen storage, nucleic acid biosynthesis, bacterial endosymbiosis and pheromones.

Important human illnesses caused by toxic algae are Paralytic Shellfish Poisoning (PSP), Ciguatera Fish Poisoning (CFP), Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NSP), Amnesic Shellfish Poisoning (ASP) and Azaspiracid Poisoning (AZP).

Generally the toxin producing algal blooms may cause haemolytic, hepatotoxic and osmoregulatory and many other toxic effect on fauna that ingest these species. The toxicity and other negative effects caused by harmful algae are not limited to a particular genera but are distributed among several taxonomic groups, and the high taxonomical diversity of the harmful algae result in the variety of toxins (Anderson, 1997).
Among the HAB producing microalgae, species belonging to the group dinoflagellates are potent toxin producers. About one hundred and eighty five species are harmful in nature of which sixty species are able to produce toxins. *Amphidinium, Alexandrium, Ceratium, Cochlodinium, Dinophysis, Gymnodinium, Gyrodinium, Heterocapsa, Peridinium, Pfiesteria, Prorocentrum, Protoperidinium,* and *Pyrodinium* are the major harmful genera. Among these, many species can produce potent toxins that cause severe illnesses in humans. *Alexandrium* sp., *Gymnodinium catenatum,* and *Pyrodinium bahamense* are the causative microalgae of Paralytic Shellfish Poisoning (PSP). PSP induces muscular paralysis and in severe cases can lead to the death through paralysis of respiratory system. PSP is caused by ‘PSP toxins’, which is a combination of eighteen different toxins mainly saxitoxins, neosaxitoxins and gonyautoxins.

*Gambierdiscus toxicus, Prorocentrum lima, Ostreopsis siamensis, Coolia monitis, Thecadinium* sp. and *Amphidinium carterae* are the causative organisms of Ciguatera Fish Poisoning (CFP) in which the major toxins are Ciguatoxins and Maitotoxin. Ciguatoxins are very potent neurotoxins. Ciguatera fish poisoning (CFP) generate gastrointestinal, neurological and cardiovascular disorders in humans.

*Dinophysis* sp., *Prorocentrum lima, Protoceratium maculosum, Protoceratium reticulatum* and *Coolia* sp. cause Diarrhetic Shellfish Poisoning (DSP), by producing the toxins Okadaic acid, Dinophysis toxins, Yessotoxins and Pectenotoxins. Major symptoms of DSP are stomach pain, nausea, vomiting and diarrhoea.

*Karenia brevis* (formerly known as *Gymnodinium breve*) is the causative organism of Neurotoxic Shellfish Poisoning (NSP), which produces a potent
toxin called brevetoxin. NSP produces intoxication leading to gastrointestinal and neurological problems. Garthwaite (2000) reported the burning of the eyes and nasal passages, leading to cough and asthma like symptoms.

Major harmful algal genera under the class Prymnesiophyceae are *Chrysochromulina*, *Prymnesium* and *Phaeocystis*. The toxins produced by these have a wide range of biological effects, including ictyotoxicity, neurotoxicity, cytotoxicity, hepatotoxicity, haemolytic, allelopathic and antibacterial activity.

*Chatonella* and *Heterosigma* are the major harmful algae under the class Raphidophyceae, which produces neurotoxins and free fatty acids, whose reactive oxygen species are involved in tissue injury and mucus production.

Usually diatoms cause harmful effects either by physical stress or by oxygen depletion. However, some diatoms like *Pseudo-nitzschia pungens f. multiseries*, *P. australis*, *P. pseudodelicatissima*, *P. seriata*, *Nitzschia actydrophila* and *Amphora coffeaeformis* are able to cause Amnesic Shellfish Poisoning (ASP) in humans by producing a potent neurotoxin called domoic acid. Symptoms mainly include gastroenteritis, but in severe cases neurological symptoms along with dizziness, headache, disorientation, short term memory loss, respiratory difficulty and coma have also been observed (Perl *et al.*, 1990).

Among cyanobacteria, major harmful genera comprises *Anabaena*, *Aphanizomenon*, *Calothrix*, *Cylindrospermopsis*, *Lyngbya*, *Microcystis*, *Nodularia*, *Nostoc*, *Oscillatoria*, *Planktothrix*, *Scytonema* and *Trichodesmium*, of which the species of *Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Microcystis*,
Nodularia, Nostoc and Oscillatoria have toxic strains which are responsible for cyanophycean toxins.

In recent decades, the frequency, intensity and spreading of toxic and non-toxic planktonic algae and the HAB events have increased worldwide. (Hallegraeff et al., 1995; Lewitus et al., 2012). There are five possible reasons for increase in frequency and geographical extent of HAB events (Hallegraeff, 1993) (1) improved methods for detection and monitoring methods of blooms that would previously have gone unreported, (2) species dispersal through currents, storms or other natural mechanisms, (3) introduction of new algal species into inshore areas through ship ballast water exchange or aquaculture, (4) long-term climatic changes and (5) cultural eutrophication. These reasons may vary from one bio-region to the other with regional environmental settings. Bio-invasion is considered as one of the vectors for global expansion of HABs in other parts of the world (Blackburn et al., 2001; Marangoni et al., 2001).

Arising from growing concerns of such an increase in the occurrence of HABs, a number of national, regional and international programmes viz. 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 been implemented to understand the features and mechanisms underlying the population dynamics of HABs and to improve and develop management and amelioration strategies.

India, being one of the major maritime countries, is endowed with a coastline of approximately 7,500 km which is embraced by two important
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seas, the Arabian Sea on the west coast and the Bay of Bengal on the east coast. Studies on algal blooms in Indian waters indicated that the west coast is a more bloom prone area compared to the east, since it is one of the most biologically productive areas among the World Oceans. Most blooms occurring in Indian waters are naturally driven due to physical forcing such as monsoonal influence, riverine discharge and seasonal upwelling. Besides these factors, variations in temperature, salinity, irradiance, water stability and nutrient enriched waters are important conditions that influence bloom formation. Some species-specific blooms of diatoms, raphidophytes and cyanophytes which followed a seasonal pattern are common in Indian waters, whereas the non-seasonal dinoflagellates blooms respond to short-term events such as sunny, calm weather (D’Silva et al., 2012). However, the algal bloom outbreaks are sporadic and unpredictable. Regular monitoring of bloom-prone areas will provide significant insights into bloom dynamics and its impact on the ecosystem and human community.

A national coordinated multi-institutional research programme for monitoring of “HABs in the Indian EEZ” and monitoring of phytoplankton under the Indian Expendable Bathythermographic (XBT) programme has been initiated by the Ministry of Earth Sciences, Government of India. Ballast Water Management Programme-India (BAMPI) and Port Baseline Biological Survey (PBBS) by the Council of Scientific and Industrial Research and the Ministry of Shipping, Government of India, and Moderate Resolution Imaging Spectroradiometer (MODIS)/Aqua data of remote sensing by INCOIS are the other programmes actively involved in the surveillance of HABs along the Indian coast.
In view of this, as part of the Ministry of Earth Sciences, Government of India sponsored project on ‘Monitoring and Surveillance of Algal Blooms’, funded by Centre for Marine Living Resources and Ecology, Ministry of Earth Sciences, Government of India, regular monitoring and surveillance of planktonic algal blooms along the southwest coast of India from the coastal/estuarine stations has been carried out. During the present investigation, occurrences of three blooms *Prymnesium parvum* N. Carter, *Proboscia alata* (Brightwell) Sandström and *Chattonella marina* (Subrahmanyan) Hara et Chihara have been observed from the northern Kerala coast.

5.2 Review of Literature

5.2.1 Algal Blooms: International status

The first written reference regarding the harmful algal bloom was (back in 1000 years B.C.) in the Bible, “... 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” (Exodus 7: 20-21). One of the first recorded fatal cases of human poisoning after eating shellfish contaminated with dinoflagellate toxins was in 1793. Captain George Vancouver and his crew, when landed in British Columbia, noticed that the local Indian tribes were intoxicated with contaminated shellfish when sea water became phosphorescent due to dinoflagellate blooms (Dale and Yentsch, 1978). However, there is fossil evidence that HABs have occurred long before this. The main constrain in the study of algal blooms is the lack of historical data and the restricted number of good long-term data series.

With the emergence of HAB studies, a series of conferences were held in Boston, Massachusetts, in November 1974 (LoCicero, 1974), at Miami, Florida,
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Smayda (1997) reported that in order to define algal blooms, subjective difference and arbitrary criteria are essential. Zingone and Enevoldsen (2000) reported that HABs show high diversity with regard to causative organisms, bloom dynamics and type of impact. Bio-invasion is considered as one of the vectors for global expansion of HABs (Marangoni et al., 2001). The intoxication of shellfish, fish fauna and avian community (Shumway et al., 2003) and ultimately of humans due to toxic bloom events have increased worldwide (Okolodkov, 2005). Paralytic Shellfish Poisoning (PSP) (Dale and Yentsch, 1978; Usup et al., 2002; Nguyen-Ngoc, 2004; Vila et al., 2005), Diarrhetic Shellfish Poisoning (DSP) (Kat, 1979, 1985; Kumagai et al., 1986; Lassus et al., 1985; Dahl and Yndestad, 1985; Cembella, 1989; Marasigan et al., 2001, Madigan et al., 2005), Amnesic Shellfish Poisoning (ASP) (Jeffery et al., 2004), Neurotoxic Shellfish Poisoning (NSP) (Magana et al., 2003; Kirkpatrick et al., 2004) and the outbreak with the toxicity of Prymnesium sp. (Holdway et al., 1978; Kaartvedt et al., 1991; Guo et al., 1996; Edvardsen and Paasche, 1998; Amsinck et al., 2005; Lundholm and Moestrup, 2006; Graneli et al., 2008; Baker et al., 2007, 2009) have been reported.
5.2.2 Algal Bloom events along the Indian waters

In the Indian EEZ, occurrence of algal blooms is more prevalent along the west coast than on the east coast. Hornell (1908) made the first observations on algal blooms that caused massive fish mortality while cruising along the Malabar Coast to the Laccadive Islands.

Diatom blooms have been reported from the west coast of India and the causative organisms were *Ditylum* sp. and *Thalassiosira* sp. (Hornell and Nayudu, 1923), *Fragilariopsis oceanica* (Devassy, 1974), *Nitzschia sigma* (Devassy and Bhattachir, 1974), *Skeletonema costatum* (Devassy and Bhattachir, 1974; Tiwari and Nair, 1998) and *Coscinodiscus asteromphalus* (Padmakumar et al., 2007). Diatom blooms by *Fragilariopsis oceanica* and *Skeletonema costatum* have been reported as a recurring annual feature (Gopinathan, 1974; Devassy, 1983; Devassy and Goes, 1988; Tiwari and Nair, 1998; Mitbavkar and Anil, 2002; Patil and Anil, 2008).

Dinoflagellate blooms along the west coast were mainly caused by *Glenodinium* sp. (Hornell and Nayudu, 1923), *Gymnodinium* spp. (Hornell and Nayudu, 1923; Bhimachar and George, 1950; Karunasagar, 1993), *Prorocentrum* spp. (Hornell and Nayudu, 1923), *Cochlodinium* spp. (Hornell and Nayudu, 1923; O’Herald, 2001), *Noctiluca* spp. (Bhimachar and George, 1950; Venugopal et al., 1979; Devassy et al., 1979; Devassy and Nair, 1987; Katti et al., 1988; Nayak and Karunasagar, 2000; Naqvi et al., 1998; Sahayak et al., 2005; Padmakumar et al., 2008; Sanilkumar et al., 2009; Padmakumar et al., 2010), *Dinophysis* sp. (Bhimachar and George, 1950), *Gonyaulax* sp. (Prakash and Sarma, 1964), *Karenia* sp. (Iyer et al., 2008; Madhu et al., 2011).
and *Protoperidinium* sp. (Sanilkumar *et al*., 2009). Among these, blooms of *Noctiluca* spp. were observed to be predominant.

Cyanobacterial blooms especially of *Trichodesmium* sp. are predominant in the Indian waters (Prabhu *et al*., 1965; Nagabhushanam, 1967; Qasim, 1970; Ramamurthy *et al*., 1972; Devassy *et al*., 1978; Verlancar, 1978; Sarangi *et al*., 2004; Anoop *et al*., 2007). Blooms of raphidophycean *Chatonella marina* (formerly *Hornellia marina*) was reported by various workers (Subrahmanyan, 1954; Jugnu and Kripa, 2009; Sanilkumar *et al*., 2012).

Diatom blooms in the east coast were mainly caused by *Rhizosolenia* sp. (Raghu Prasad, 1956), *Asterionellopsis* spp. (Subba Rao, 1969; Mani *et al*., 1986; Choudhury and Panigrahy, 1989; Panigrahy and Gouda, 1990; Mishra and Panigrahy, 1995; Satpathy and Nair, 1996; Sasamal *et al*., 2005), *Thalassiothrix* sp. and *Coscinodiscus* spp. (Mishra and Panigrahy, 1995).

Dinoflagellate blooms were mainly caused by *Noctiluca miliaris* (Aiyar, 1936; Raghu Prasad, 1953, 1958; Santha, 1975) and *Noctiluca scintillans* (Silas *et al*., 1982; Sargunam and Rao, 1989; Eashwar *et al*., 2001; Dharani *et al*., 2004; Mohanty *et al*., 2007; Gopakumar *et al*., 2009).

*Trichodesmium erythraeum* was the predominant bloom forming cyanobacteria on the east coast (Chacko, 1942; Chidambaram and Unny, 1944; Ramamurthy, 1968, 1970a and b, 1973; Chellam and Alagarswami, 1978; Jyothisabu *et al*., 2003; Satpathy *et al*., 2007; Anantharaman *et al*., 2010). *Microcystis aeruginosa* bloom was reported by Santhosh *et al*. (2010).
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 have been reviewed by Karunasagar and Karunasagar (1990). D’Silva et al. (2012) made the pioneer review regarding the occurrence of algal blooms from 1908 to 2009, and showed that there has been an exponential increase in algal bloom events along the Indian coasts, which have direct or indirect effects on coastal waters, fisheries, other marine organisms and humans.

However, the intoxication of humans by algal bloom is comparatively less in Indian waters (D’Silva et al., 2012). Paralytic Shellfish Poisoning by an unidentified toxic species, due to the consumption of bloom infected Meretrix casta resulted in casualties in Tamil Nadu in 1981 and in Mangalore (Karnataka) in 1983 (Bhat, 1981; Silas et al., 1982; Karunasagar et al., 1984; Devassy and Bhat, 1991). Low levels of PSP were recorded in shellfish from surrounding estuaries near Mangalore on two occasions during 1985 and 1986 (Segar et al., 1989). Planktonic and cyst forms of Gymnodinium catenatum, a PSP-producing dinoflagellate were recorded from Mangalore (Godhe et al., 1996). In 1997 at Vizhinjam (Kerala), shell fish poisoning by Gymnodinium resulted in causalities and hospitalisation of people inhabiting the coastal belt (Karunasagar et al., 1998). In 2004, a bloom event that occurred along the coasts of Kollam and Trivandrum due to species belonging to the genera Gonyaulax, Cochlodinium and Karenia caused massive fish kill and hospitalization of people, especially children, due to the consumption of intoxicated sea food (Sahayak et al., 2005, Iyer et al., 2008). Subsequent to this event, an unidentified holococcolithophore (Ramaiah et al., 2005) was reported from southern Malabar Coast.
5.2.3 Factors influencing algal blooms

The formation of algal blooms is influenced by physical processes such as upwelling, cyclones and eddies (Vinayachandran and Mathew, 2003; GEOHAB, 2005; McGillicuddy et al., 2007), chemical processes such as increased nutrient conditions (Anderson et al., 2002; Smayda, 2005), biological processes like competition, grazing and allelopathy (Smayda, 1998; Graneli and Johansson, 2003) in combination with local meteorological conditions of the geographical region (Naik et al., 2011).

Algal blooms along the west coast of India, one of the highly productive regions of the world’s oceans (Smith et al., 1991; Banse, 1994) were mainly influenced by upwelling during the monsoon period (Venugopal et al., 1979; Mathew et al., 1988; Banse et al., 1996; Madhupratap et al., 2001) which leads to high nutrient conditions triggering high primary production and bloom events (De Sousa et al., 1996; Raghukumar and Anil, 2003; Patil and Anil, 2008; D’Silva et al., 2012).

The break in monsoon can cause sudden changes of salinity and water temperatures, and might induce the blooming of certain species that prefer a particular range of salinity and temperature in the presence of sufficient nutrients in the coastal waters (Subrahmanyan, 1959; Gopinathan, 1974; Patil, 2003; Patil and Anil, 2008; Wang et al., 2011). Nutrient availability together with light and temperature are primary determinants of phytoplankton growth and biomass accumulation (Kooistra et al., 2007; Patil and Anil, 2008) which in turn is linked to anthropogenic eutrophication (Glibert et al., 2005).
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The most important nutrients that limit the microalgal growth in the coastal waters are silicate, an important nutrient for diatoms (Tilstone et al., 1994; Kristiansen and Hoell, 2002; Kudela, 2008) and nitrogen (Wilkerson and Dugdale, 2008).

5.2.4 Monitoring of algal blooms in Indian EEZ

Since, Indian fisheries economy depends heavily upon the coastal zone for marine products, keen attention has been taken regarding the occurrence of toxic microalgae and its proliferation even on a low scale, because such harmful or toxic blooms cause substantial impacts on the growth, recruitment and mortality of fish population. This causes direct and severe damage to coastal fishing industries, and thus emphasizes the need for efficient monitoring systems to minimize damage to fisheries and to reduce public health risks (D’Silva et al., 2012).

5.3 *Prymnesium parvum* N. Carter bloom

*Prymnesium parvum* N. Carter, commonly referred as “golden alga”, is a microscopic haptophyte. Blooming of *P. parvum* is common in brackish and coastal waters, especially in nutrient rich condition (Edverdsen and Paasche, 1998). This species can produce exotoxins called prymnesins under certain conditions and have wide range of biological activities, including icthyotoxic, neurotoxic, cytotoxic, hepatotoxic and haemolytic activity towards a wide range of marine organisms including fish and shellfish (Yariv and Hestrin, 1961; Manning and LaClaire, 2010). Blooms of *Prymnesium* sp. may cause serious economic losses (Moestrup, 1994).
A monospecific bloom of *Prymnesium parvum* was observed off Azheekode (Lat. 10° 11’ 02” N & Long. 76° 09’ 22” E) in the southwest coast of India, during the monsoon 2009 (Fig.40). The surface water colour was turned into pale brownish, which extended up to 8-10 nautical miles from the coast. However, there was no foam production and fish mortality during the bloom event. The bloom lasted only for one day as heavy rain dissipated the cells. This is the first report of *Prymnesium parvum* bloom from Indian waters.

**Fig. 40** Phase contrast images of *Prymnesium parvum*
5.3.1 Result
5.3.1.1 Standing crop and pigment composition

At the time of bloom observation, a monospecific standing crop of the *P. parvum* was observed with the cell density of $8 \times 10^7$ cellsL$^{-1}$. Chlorophyll *a* concentration was higher, 13.54 µgL$^{-1}$, whereas on the previous and successive years of the same season at the same station chlorophyll *a* was found to be only of 3.82 µgL$^{-1}$ and 2.61 µgL$^{-1}$, respectively. Chlorophyll *c* and carotenoid values were 3.44 µgL$^{-1}$ and 1.91 µgL$^{-1}$ at the time of bloom event, whereas comparatively lower concentration of chlorophyll *c* and carotenoid was observed during the previous and successive years (Fig.41).

![Fig.41](image_url) Comparison of standing crop and pigment concentrations of *P. parvum* bloom (MON 2009) with those during MON 2008 and 2010 off Azheekode.

5.3.1.2 Physico-chemical parameters

At the time of boom event, the sea surface temperature was 28°C, salinity 34 psu and pH 8. When compared with the previous and successive years of the same season at the same station (temperature 26°C, salinity 35 psu, pH 7.8 and temperature 26°C, salinity 30 psu, pH 8.1, respectively) no drastic change in physical parameters was noticed (Fig.42).
During the *P. parvum* bloom event, nitrate concentration was 5.6 µmolL⁻¹, phosphate was 1.9 µmolL⁻¹ and silicate was 62 µmolL⁻¹. However, in the previous and successive years of the same season, higher level of nitrate concentration was recorded, whereas phosphate concentration was lowest in the 2008 monsoon season (0.36 µmolL⁻¹) but highest at 2010 monsoon season.

**Fig. 42** Comparison of physical variables at the time of *P. parvum* bloom (MON 2009) with those during MON 2008 and 2010 off Azheekode.

**Fig. 43** Comparison of nutrient concentrations, DO and Net PP of *P. parvum* bloom (MON 2009) with those during MON 2008 and 2010 off Azheekode.
In the bloom event, dissolved oxygen was found to be lower (1.41 mgL\(^{-1}\)), whereas net primary production was higher (3.5 gC/m\(^3\)/day) when compared with the previous and successive years of the same season at Azheekode (Fig.43).

**5.3.2 Discussion**

**5.3.2.1 Standing crop and pigment composition**

*Prymnesium parvum* is a common member of the marine phytoplankton (Lee, 1980; Bold and Wynne, 1983; Larsen, 1999). It is a uninucleate, unicellular flagellate with an ellipsoid or narrowly oval cell shape (Prescott, 1968; Lee, 1980). *P. parvum* cell has two equal flagella and a well-developed haptonema. The flagella are used for motility and the haptonema may be involved in attachment and/or phagotrophy (McLaughlin, 1958; Prescott, 1968). Bold and Wynne (1983) described *P. parvum* as photosynthetic with possible heterotrophic growth (phagotrophy) when cells sink below the euphotic zone which enable them to sustain under nutrient deficient condition. It is a euryhaline and eurythermal organism tolerating a broad range of salinities and temperatures.

*P. parvum* was first identified as the culprit of mass fish mortalities in the brackish waters of Denmark and Holland (Shilo and Aschner, 1953; McLaughlin, 1958) in the Ketting Nor off the coast of Jutland and again in 1939 in the Selso So located on a peninsula of Sjalland Island (Reichenbach-Klinke, 1973). Shilo and Shilo (1953) reported *P. parvum* bloom occurrence in 1947 with large fish mortality in Israel waters. Bales *et al.* (1993) noted multiple fish mortalities associated with *P. parvum* in England starting in 1969 and becoming less severe until 1975, this bloom event was supposed to be stimulated by gull-guano from the large number
of black-headed gulls nesting in the area. In Norway, from 1989-1996, mixed blooms of *P. parvum* have occurred every summer in the Sandsfjord system (Larsen and Bryant, 1998). Hallegraeff (1992) also noted that since the 1970’s, *P. parvum* blooms have been related to recurrent fish kills in Vasse-Wonnerup estuary of Australia. Harmful blooms of *P. parvum* associated with fish kills have been reported from China (Guo *et al.*, 1996), Europe and Australia (Edvardsen and Paasche, 1998; Lindholm *et al.*, 1999), Morocco (Sabour *et al.*, 2000), Israel (Gordon and Colorni, 2008) and North America (Roelke *et al.*, 2007). Usually, blooming of *P. parvum* with faunal mortalities is quite common in temporal waters when compared with tropical waters. Even a cell density of $5 \times 10^7 \text{ cellsL}^{-1}$ could bring about faunal mortality (Lindholm and Virtanen, 1992). However, in the present bloom event, even though the cell density was $8 \times 10^7 \text{ cellsL}^{-1}$ no faunal mortality was observed. The toxic effect of different strains will vary depending up-on the strain and the physico-chemical factors. The same species which cause blooming and faunal mortality in one area were not supposed to have the same effect on everywhere because both physico-chemical variables and the biogeography of the area play a significant role in the metabolic activity of algal strains. This was quite true in the case of blooming of *P. parvum*. The factors that are responsible for the formation of toxic *P. parvum* blooms have yet to be determined. Apart from these, the environmental conditions conducive to blooms and the factors that lead to the formation and termination of harmful algal blooms in general are complex (Paerl, 1988; Roelke and Buyukates, 2001).
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However, the factors that are likely to contribute to *P. parvum* bloom formation include the production of chemicals toxic to grazers (Graneli and Johansson, 2003; Tillmann, 2003; Barreiro *et al*., 2005; Michaloudi *et al*., 2009; Brooks *et al*., 2010), use of alternative energy and nutrient sources through mixotrophy and saprophytic nourishment (Nygaard and Tobiesen, 1993; Skovgaard and Hansen, 2003; Lindehoff *et al*., 2009), suppression of competitors through allelopathy (Fistarol *et al*., 2003, 2005; Graneli and Johansson, 2003; Roelke *et al*., 2007; Errera *et al*., 2008) and resistance to the allelopathic effects of other algae (Suikkanen *et al*., 2004; Tillmann *et al*., 2007). In the present bloom event, no other microalgae were enumerated other than *P. parvum*. The monospecific nature of the present bloom event could be substantiated by the alleopathic effect of the *P. parvum* because, by producing allelopathic chemicals *P. parvum* can immobilize plankton and suppress competitors, thereby fuelling bloom development and persistence (Fistarol *et al*., 2003, 2005; Graneli and Johansson, 2003; Uronen *et al*., 2005; Roelke *et al*., 2010).

Chlorophyll *a, c* and carotenoid concentrations during the bloom were much higher than the values obtained during the previous and subsequent years. The chlorophyll *a* was found to be 13.54 µgL⁻¹, with a standing crop of 8×10⁷ cellsL⁻¹. Lindholm and Virtanen (1992) reported a bloom of *P. parvum* with toxicity and fish mortality in Finland waters during June 1990, where chlorophyll *a* was below 10 µgL⁻¹ and standing crop was 5×10⁷ cellsL⁻¹. A significant hike in the chlorophyll *c* and carotenoids were present in the bloom event. This is because chlorophyll *c* and carotenoid (fucoxanthin) are the major accessory pigment of the haptophycean members. *P. parvum* cells have large amounts of fucoxanthin, a carotenoid pigment that gives its characteristic golden colour (Moestrup and Thomsen, 2003).
5.3.2.2 Physico-chemical parameters

Shilo and Aschner (1953) observed that temperatures greater than 30°C were inhibitory to the growth of *P. parvum*, and 35°C resulted in cell lysis, however, the cells could survive at 2°C for many days. McLaughlin (1958) noted erratic growth of *P. parvum* above 32°C with death occurring at 34°C. Larsen *et al.* (1993) found that *P. parvum* has a growth temperature optimum of 26°C and growth was found to be severely limited at 10°C. However, different strains of *P. parvum* tested by Larsen and Bryant (1998) exhibited maximum growth rate at 15°C and tolerated wide temperature range of 5°C to 30°C. An outbreak of *P. parvum* occurred in Morocco waters where the temperature was between 15°C - 23.5°C (Sabour *et al.*, 2000). All these investigations suggest that *P. parvum* is a eurythermal organism. In the present *P. parvum* bloom event also the sea surface temperature was 28°C, which is well within the optimal range of growth temperature of *P. parvum*.

Salinity may also play an important role in the blooming of *P. parvum* and its toxicity. Optimum salinity of bloom formation depends on the strains. Larsen *et al.* (1993) reported growth of *P. parvum* in the salinity range of 8-25 psu. Larsen and Bryant (1998) noted that different strains of *P. parvum* survived in salinities ranging from 3 to 30 psu. Sabour *et al.* (2000) reported that *P. parvum* bloom associated with the fish kill in Morocco was characterized by a salinity of 8.6 to 12.4 psu. In the present bloom observation, the salinity was 34 psu. A rapid change in physical variables especially of salinity and temperature in the bloom event as a result of heavy rain could be one reason that caused the *P. parvum* bloom deterioration on the very next day. Roelke
et al. (2011) observed that an increase in anthropogenic activity and change in the climate can influence the frequency and magnitude of *P. parvum* bloom. Usually an alkaline pH favoured the blooming of *P. parvum* (Lindholm et al., 1999; Prosser et al., 2012). Sabour et al. (2000) reported that the *P. parvum* outbreak in Morocco occurred in water with a pH of 7.67-9.04. In the present study, the pH was found to be 8 during the bloom which was favourable for the growth of this alga.

Usually, high nutrient supply can promote algal blooms by supporting rapid reproductive growth. After a population has grown, its ultimate abundance is often controlled by the supply of a critical nutrients, such as nitrogen or phosphorus, because conversion of nutrients to algal biomass occurs through the process of consumption and growth. Since *P. parvum* bloom occurs usually in the eutrophic waters, nitrogen and phosphorus can play a key role in the bloom dynamics and toxicity. In the present bloom event, nitrate concentration was 5.6 µmolL^{-1}, nitrite was 0.8 µmolL^{-1} and phosphate was 1.9 µmolL^{-1}. The low nitrate to phosphate ratio might be one reason for the blooming. Similarly, Michaloudi et al. (2009) reported that low nitrogen concentrations favoured the initiation of the *P. parvum* bloom in northern Greece. The present bloom station, off Azheekode was located near the northern end of the Cochin estuary, which carry large influx of rain water. Since the bloom event occurred in the monsoon season, it might have played a significant role in the bloom dynamics. However, the important point to be noted in connection with the planktonic microalgal blooms is not why they occur but rather what mechanisms control the species which occur at a given time and place (Richardson, 1997). The marine environment provides different niches that can be exploited by different microalgal
species and each species has its own specific combination of necessities such as light, micro and macro nutrients. The triggering of a particular microalga to its bloom stage is not only dependent on a particular factor but also on a combination of all the favourable factors like physico-chemical, geographical, biological as well as the occurrence of the target species at that time.

The toxicity of *P. parvum* increased markedly under nitrogen or phosphorus deficient conditions compared to nutrient sufficient conditions (Johansson and Graneli, 1999) suggesting that the production of toxins is a chemical response to low nutrient levels. However, the presence of blooms of *P. parvum* did not necessarily mean that the algae will produce and secrete toxins into the water, and in fact studies suggested that bloom density and toxicity are not strongly correlated (Shilo, 1981) which was quite evident in the present bloom event also. Even though *P. parvum* cell density was high, there was no faunal mortality or foam production; this might be due to the sufficiency in nitrogen and phosphorus concentration at the present bloom event. So, it could be clear that apart from the geographical variation, which provide a species-specific privilege, nutrients played a significant role in the harmless effect at the time of the present *P. parvum* bloom. A low concentration of dissolved oxygen was recorded at the time of bloom observation, since the bloom was in the decline stage. Ramaiah et al. (2005) noted a very low level of dissolved oxygen concentration as a consequence of excessive organic loading due to crash of the bloom in southern coast of Kerala. So, it could be inferred that, rather as a specific factor, the multiple resources like temperature, salinity, pH, nutrients, other environmental factors and geographical adaptations, in a favourable range for a particular species,
commonly referred to as ‘species-specific’, played a significant role in the present bloom dynamics.

5.4 **Proboscia alata** (Brightwell) Sandström bloom

*Proboscia alata* (Brightwell) Sandström is widespread in boreal, tropical and subtropical realms of the World Ocean and the seas of the middle latitudes. It substantially contributes to the abundance and biomass of the total phytoplankton and carbon fluxes in pelagic ecosystems (Jordan *et al*., 1991; Takahashi *et al*., 1994). *Proboscia* sp. are quite important in the aspect of diatom–diazotrophic cyanobacterial association and its episodic, monospecific bloom formation, since it can contribute high rate of carbon and nitrogen fixation in the marine ecosystem. *Proboscia alata* can dominate phytoplankton biomass in highly productive areas (Garate-Lizarraga *et al*., 2003).

The coastal sea off Bekal (Lat. 12° 38’ 02” N & Long. 75° 04’ 31” E), experienced a bloom of centric diatom *Proboscia alata* (Brightwell) Sandström; (formerly *Rhizosolenia alata*) during 10th to 12th October 2009, in the early post-monsoon (Fig.44). During the bloom, there was a pale brown discolouration of sea surface water, which extended around 3 nautical miles along the coastal area. There was no fish mortality and foam production. For a comparative analysis, sampling was also done from two reference stations, Off Thykadapuram (St.1) (Lat. 12° 22’ 84” N & Long. 75° 10’ 94” E) and Off Puthur (St.2) (Lat. 12° 55’ 18” N & Long. 74° 95’ 18” E), one before and one after the bloom station in the same latitude.
Fig. 44 *Proboscia alata*. (A) A complete cell, (Phase contrast microscopy). (B) Apical part of valve, (ESEM). (C) Proboscis structure, varied spinules (ESEM). (D) Girdle segments, (ESEM). (E) Details of clasper and contiguous area, (ESEM).
Chapter 5

5.4.1 Result
5.4.1.1 Standing crop and pigment composition

Table 18 Abundance of standing crop during *Proboscia alata* bloom

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Class</th>
<th>Off Bekal 10-10-2009</th>
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<th>Off Puthur Reference st.1</th>
<th>Off Puthur Reference st.2</th>
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</tr>
<tr>
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Dinophyceae

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<th>Off Puthur Reference st.1</th>
<th>Off Puthur Reference st.2</th>
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<tr>
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<td><em>Ceratium fusus</em></td>
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<td><em>Ceratium trichoceras</em></td>
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<td><em>Dinophysis acuminata</em></td>
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<td><em>Pyrophacus steinii</em></td>
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<td><strong>166</strong></td>
<td></td>
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</tr>
</tbody>
</table>

*Grand total 80000 28792 583 364
*cellsL\(^{-1}\)
The abundance of standing crop during the bloom is presented in Table 18. On 10th October, the total standing crop comprised only *P. alata*, with $8 \times 10^4$ cells$L^{-1}$. On 12th October, the abundance of *P. alata* decreased to $2.8 \times 10^3$ cells$L^{-1}$ and a few species of other diatoms and dinoflagellates were also observed. Both the reference stations showed the predominance of diatoms.

On 10th October, the chlorophyll *a* concentration was found to be highest, 10.8 $\mu$gL$^{-1}$, whereas it receded to 6.48 $\mu$gL$^{-1}$ on 12th October with an average of 8.64 $\mu$gL$^{-1}$. Lower concentration of chlorophyll *b* was detected from the bloom event. Chlorophyll *c* concentration was highest on the first day with 4.62 $\mu$gL$^{-1}$, and on 12th October, it was 3.97 $\mu$gL$^{-1}$ with an average of 4.29 $\mu$gL$^{-1}$. On 10th October, carotenoid concentration was 2.39 $\mu$gL$^{-1}$, while on 12th October it receded to 2.01 $\mu$gL$^{-1}$ with an average value of 2.20 $\mu$gL$^{-1}$. In the reference stations, the average chlorophyll *a* concentration (4.34 $\mu$gL$^{-1}$) was lower than the bloom event. Both chlorophyll *c* and carotenoid average values (2.39 $\mu$gL$^{-1}$ and 1.13 $\mu$gL$^{-1}$ respectively) were also found to be in a lower range than the *P. alata* bloom event (Fig.45).

![Fig.45 Concentration of pigments during Proboscia alata bloom](image-url)
5.4.1.2 Physico-chemical parameters

In the bloom event, the sea surface temperature was 27°C on the first day while on 12th October it was 28°C. Salinity was stable at 35 psu in the entire bloom event, whereas the pH showed a gradual decrease from 8.4 on the first day to 8.2 on 12th October, when the bloom almost crashed. The pH observed in the reference stations were comparatively lower (7.6 and 7.8 in Ref. stations 1 and 2 respectively) (Fig.46).

**Fig.46** Variation in temperature, salinity and pH during *Proboscia alata* bloom

During the bloom event, on the first day, concentration of silicate was high (38.31 µmolL⁻¹) which receded to 14.2 µmolL⁻¹ on the last day. Concentration of nitrate ranged from 2.11 µmolL⁻¹ to 1.4 µmolL⁻¹, whereas nitrite was below the detectable range. Phosphate concentration was found to be ranged from 1.40 µmolL⁻¹ to 1.20 µmolL⁻¹ during the bloom event. Dissolved oxygen concentration was 5.42 mgL⁻¹ on the first day, whereas at the end of bloom event, it was 4.09 mgL⁻¹. Primary production was found to be highest (1.87 gC/m³/day) on first day of bloom event, whereas the lowest
(1.05 gC/m³/day) was recorded on the last day of the bloom. In the reference stations (st.1 and st.2), concentration of silicate was 1.86 μmolL⁻¹ and 2.46 μmolL⁻¹, and nitrate was 3.03 μmolL⁻¹ and 2.65 μmolL⁻¹, respectively. Phosphate concentration was found to be very low. Dissolved oxygen value was 6.25 mgL⁻¹ and 5.24 mgL⁻¹ and net primary production was 0.76 gC/m³/day and 1.41 gC/m³/day, respectively in reference stations 1 and 2 (Fig.47).

Fig.47 Chemical variables during *Proboscia alata* bloom

### 5.4.2 Discussion

The west coast of India is one of the most biologically productive areas of the World Oceans (Smith *et al.*., 1991; Banse, 1994) mainly influenced by the seasonally reversing monsoon systems, southwest monsoon (June-September) and northeast monsoon (November-February), leading to upwelling. The microalgal blooms triggered by upwelling influenced eutrophication is common in this area. Hence the occurrence of the present *P. alata* bloom soon after the monsoon can be coupled with upwelling which leads to high nutrient conditions, triggering high primary production (De Sousa *et al*., 1996).
Chapter 5

5.4.2.1 Standing crop and pigment composition

On the first day of the bloom event, *Proboscia alata* was seemingly in a monospecific condition with a cell count of $8 \times 10^4$ cells L$^{-1}$. There was no significant difference in the cell abundance on the 2nd day of the bloom event. However, on the 3rd day (12th October 2009), the surface water discolouration nearly faded and the cell abundance reduced to $2.8 \times 10^3$ cells L$^{-1}$. Along with *P. alata* a number of other diatom and dinoflagellate species like *Chaetoceros decipiens* Cleve; *Coscinodiscus asteromphalus* Ehrenberg; *Cylindrotheca closterium* (Ehrenberg) Reimann & J.C. Lewin; *Ceratium fusus* (Ehrenberg) Dujardin; *Ceratium trichoceros* (Ehrenberg) Kofoid and *Pyrophacus steinii* (Schiller) Wall & Dale, were enumerated from the sample on the third day, which apparently indicated that the bloom was in a stage of decline. In the reference stations also diatoms were found to be the predominant flora with 11 species, but the cell numbers were considerably less. The dinoflagellates (4species) which were prominent in the reference stations were also found in the bloom station when the bloom was at the decline stage. *Proboscia alata* was found in lower cell density of 59 cells L$^{-1}$ and 66 cells L$^{-1}$ respectively, in the reference stations. So it could be inferred that during the algal bloom as the number of blooming species increases the diversity of microalgae decreases. At the end of the bloom event, the diversity further increased and the abundance of *P. alata* decreased.

The magnitude and the composition of the algal bloom were indicated by the concentration of the pigments, especially of chlorophyll *a*, *c* and carotenoid. On the first day of the bloom event, the chlorophyll *a* was found to be high, which gradually receded in the last day of the bloom event. A hike in
concentration of chlorophyll $c$ and carotenoids were also found on the first day which substantiated the diatom bloom event, since these are the major accessory pigments of diatoms, and showed a gradual decrease on the last day of the bloom. The concentration of pigments particularly of chlorophyll $a$, $c$ and carotenoids in the reference stations were comparatively much lower. The occurrence of chlorophyll $b$ especially in the initial stages of the bloom sample might be due to the presence of prochlorophytes / euglenophytes / chlorophytes, which could not be enumerated by Sedgewick-Rafter counting cell.

5.4.2.2 Physico-chemical parameters

In the present bloom event, the pH was found to be high (8.4) on the first day, when the bloom was monospecific and a gradual decrease in pH was observed by the third day when the bloom was in the decline stage. The hydrogen ion concentration in the coastal environment is probably altered through nutrient enrichment. Upon the availability of more nutrients the phytoplankton proliferates into bloom condition which may progressively drive the pH higher (Kenneth, 2002). However, in the reference stations the hydrogen ion concentration did not show much variation. Both the salinity and temperature did not change drastically during the bloom event, which were found to be almost similar to the reference stations.

During the bloom event, the concentration of silicate was much higher compared to the reference stations and its concentration reduced gradually in the second and third day. Since silicate is utilised for the formation of siliceous frustules of the diatoms, it is considered as the most important nutrient regulating the growth and proliferation and ultimately the blooming of diatoms (Kristiansen and Hoell, 2002). *Proboscia* species are weakly silicified and
they can adjust their buoyancy and migrate to deeper levels below the euphotic zone to obtain nutrients. In seasonal upwelling regions, this migration often enables them to reach nutrient rich water layers before the mixing of photic zone, resulting in a high contribution to the primary production by these diatoms. Therefore, remnants of *Proboscia* species may serve as biomarkers for upwelling conditions (Tilstone *et al.*, 1994). Southwest coast of India is a known area of upwelling during southwest monsoon period and since *Proboscia* is a common species, comparatively high silicate value probably due to the coastal upwelling might have influenced the formation of this bloom. Usually, the diatom growth in marine waters is likely to be limited by dissolved silica when Si: N ratios are less than 1 (Piehler *et al.*, 2004). On the first day of the bloom event, the Si: N ratio was 17:1, whereas on the third day, when the bloom almost crashed, it receded to 9:1. This depletion in Si: N ratio was found to be positively correlated with variations of chlorophyll *a* and standing crop in the bloom event. However, no such remarkable variation in the individual concentration of nutrients especially of silicate and Si: N ratio was observed in the reference stations. Hence, it could be inferred that high Si: N ratio played a significant role in the formation of the *P. alata* bloom. Dissolved oxygen and primary production were high in the initial stages of the bloom, whereas it gradually decreased as the bloom crashed. As a consequence of excessive organic loading, during the crash of the bloom, the dissolved oxygen concentration might decrease (Ramaiah *et al.*, 2005). So it may be inferred that, an increased Si: N ratio with alkaline pH favoured the *P. alata* bloom and lowering of Si: N ratio with decreasing pH might have caused the bloom declination.
5.5 *Chattonella marina* (Subrahmanyan) Hara et Chihara bloom

Marine raphidophycean algae, especially *Chattonella* sp. have been implicated in major fish kills in various parts of the world (Tiffany *et al*., 2001). Blooms of *Chattonella marina* have been linked to mass mortality of marine life along the southwest coast of India [reported as *Hornellia marina* by Subrahmanyan (1954); Jugnu and Kripa, 2009; Padmakumar *et al*., 2011; Sanilkumar *et al*., 2012).

A conspicuous brown discolouration of surface water was observed in the coastal sea off Mahe (Lat. 11° 42’ 18” N & Long. 75° 32’ 36” E), along the northern part of Kerala from October 27th to November 1st 2011. This was due to the massive bloom of marine raphidophyte, *Chattonella marina* (Subrahmanyan) Hara et Chihara (Fig.48) which extended up to about two kilometres inside the Mahe (Mayyazhi) estuary during high tide. The spreading of visible water discolouration (about 1 km in width) extended from the bar mouth to both the northern and southern sides. The bloom event lasted for a period of one week.
5.5.1 Result

5.5.1.1 Standing crop and pigment composition

The abundance of standing crop during the bloom is presented in Table 19. The bloom was in a monospecific condition on the first day of investigation (27th October) with the cell abundance of $4.5 \times 10^6$ cells$L^{-1}$. There was a gradual

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*cells$L^{-1}$
decrease in the cell numbers on the 29th of October, with $4 \times 10^6$ cells$L^{-1}$. On the 3rd day of observation, 1st November, a steady decrease in cell abundance was observed with $3.8 \times 10^5$ cells$L^{-1}$.

On the first day of observation the chlorophyll $a$ concentration was 10.89 $\mu$g$L^{-1}$, which receded gradually, and on the last day of observation it was 6.69 $\mu$g$L^{-1}$. The highest concentration of chlorophyll $b$ was 0.69 $\mu$g$L^{-1}$ on the first day and the lowest being 0.49 $\mu$g$L^{-1}$ on the final day. Concentration of chlorophyll $c$ varied from 2.44 $\mu$g$L^{-1}$ to 1.75 $\mu$g$L^{-1}$, while concentration of carotenoid pigment varied from 3.19 $\mu$g$L^{-1}$ to 2.29 $\mu$g$L^{-1}$ by the last day of bloom event (Fig.50).

![Fig.50 Concentration of pigments during *Chattonella marina* bloom](image)

### 5.5.1.2 Physico-chemical parameters

During the bloom event temperature varied from 25°C to 27°C. Salinity was 30 psu on the first day of bloom, whereas it receded to 28 psu on the last day of bloom event. pH was 7.9 on the first day of investigation and on the last day it was 7.7 (Fig.51).
The concentration of nitrate ranged from 12.54 µmolL⁻¹ on 27th October, to 6.99 µmolL⁻¹ on 1st November. Silicate concentration varied from 3.47 µmolL⁻¹ to 2.38 µmolL⁻¹, whereas the phosphate concentration varied from 0.56 µmolL⁻¹ to 0.49 µmolL⁻¹. The concentration of nitrite was below detectable range. Dissolved oxygen concentration varied from 5.2 mgL⁻¹ to 4.4 mgL⁻¹, whereas net primary production ranged from 4.2 gC/m³/day to 1.2 gC/m³/day in the bloom event (Fig.52).
5.5.2 Discussion

Blooms of marine raphidophyte *Chattonella marina* (Subrahmanyan) Hara et Chihara are known to have deleterious effects on the marine fauna by having potent ability to produce haemolytic, haemoagglutinating compounds and reactive oxygen species (ROS) including superoxide anion radicals (O$_2^-$), hydrogen peroxide and hydroxyl radicals (OH) (Onoue and Nozawa, 1989; Oda *et al.*, 1994). The toxic effects of *Chattonella marina* have been attributed to the production of brevetoxins and potent neurotoxins similar to those of dinoflagellate, *Gymnodinium breve* (Ahmed *et al.*, 1995; Khan *et al.*, 1995). Even in a nanomolecular concentration, these polyether compounds can act as an ichthyotoxin and the gills become highly susceptible absorptive area for these brevetoxins from the water column. Hence, exposure of fish to *C. marina* causes gill epithelium to become swollen with massive mucous production (Endo *et al.*, 1985, 1992) and fish appear to smother even in well-oxygenated waters. The bloom of the same species had been reported as to have appeared in different colours like green (Subrahmanyan, 1954; Jugnu and Kripa, 2009) and brownish-red (Padmakumar *et al.*, 2011). Usually, *C. marina* had numerous bright green, disc-shaped chromatophores, uniformly distributed all over the body around its peripheral region (Subrahmanyan, 1954). Here, the chromatophores appeared in golden brown colour instead of the normal green, which might be the reason for the brown discolouration of the surface water during the bloom.

5.5.2.1 Standing crop and pigment composition

In the present study, on the first day of investigation, *Chattonella marina* bloom was found to be monospecific with a standing crop of $4.5 \times 10^6$ cellsL$^{-1}$. 
On the second day, the standing crop of *Chattonella marina* decreased to $4 \times 10^6$ cellsL$^{-1}$ and a few species of diatoms like *Coscinodiscus asteromphalus* Ehrenberg, *Coscinodiscus radiatus* H.L.Smith and *Odontella aurita* (Lyngbye) C.Agardh were also observed. On the last day of observation the standing crop of *Chattonella marina* receded to $3.8 \times 10^5$ cellsL$^{-1}$. The abundance of diatoms (9 species) and dinoflagellates (2 species) increased profoundly. *Chattonella marina* bloom had been reported in Kerala coast earlier. A bloom of the same species occurred during September 2002 and 2003 with a standing crop of $28 \times 10^7$ and $135 \times 10^5$ cellsL$^{-1}$ respectively, along the Calicut coast (Jugnu and Kripa, 2009) and it was associated with huge fish mortality. In the case of this bloom event also the bloom was monospecific initially; however, the species diversity increased gradually during the crash of the bloom. A species succession could be noted during algal bloom and its crash.

The concentrations of pigments like chlorophyll $a$, $b$, $c$ and carotenoids were significantly related with the bloom event, since a gradual decrease in the pigment concentrations were observed from the first day to the last day of the bloom event. The pigment concentration changed with different phases of the bloom. On the first day, the pigment concentration and the standing crop revealed that the bloom was in an exponential phase. On the second day of observation, slight decrease in the standing crop and pigment concentration were noted which pointed out the transition of exponential phase to the stationary phase. On the last day of the bloom event, the decreased standing crop and the pigment concentration indicated the late stationary phase, which led to decline phase of the bloom. Significant hike in chlorophyll $c$ and carotenoids were admissible to *Chattonella marina* bloom since Chl $c_1+c_2$ and fucoxanthin dominated carotenoid were the major accessory pigments of...
marine/brackish water golden brown raphidophytes. The mean chlorophyll \( a \) concentration in the bloom event (9.14 ±2.18 µgL\(^{-1}\)) was found to be higher when compared with the five year mean value of the same at Mahe for the same season (3.48 ±3.10 µgL\(^{-1}\)). Similarly, the mean concentrations of chlorophyll \( c \) and carotenoid at the time of present bloom event (2.11 ±0.35 µgL\(^{-1}\) and 2.79 ±0.46 µgL\(^{-1}\) respectively) were also higher when compared with the five year mean concentrations at Mahe (1.57 ±0.71µgL\(^{-1}\) and 1.63 ±2.13 µgL\(^{-1}\) respectively). The chlorophyll \( b \) value indicated the presence of chlorophytes / prochlorophytes / euglenophytes which are very small and could not be counted by Sedgewick-Rafter counting cell.

### 5.5.2.2 Physico-chemical parameters

The surface water temperature showed a gradual increase from 25°C to 27°C from the first day to third day of observation. The optimum growth of \( C. marina \) in laboratory conditions was shown to be at 25°C (Marshall and Hallegraeff, 1999). The bloom condition observed here was found to be optimum for the maximum growth of \( C. marina \). The sea surface temperature range was 15°C to 35°C in the Salton Sea during the bloom of the same species (Tiffany et al., 2001). However, \( C. marina \) preferred an optimal temperature of 25°C and 18°C as the minimum for its survival (Wang et al., 2011). Here on 27\(^{th}\) October, the temperature was exactly 25°C and then increased to 27°C. Even though the variation was very minor, intense bloom appeared when temperature was at 25°C and the bloom receded with increasing surface water temperature during the following days. The temperature optima of \( C.marina \) from different geographical areas differ with seasons. \( C. marina \) blooms mostly occur in summer along the Japanese coast,
when water temperature was within a range of 20–25°C. The raphidophycean blooms commonly occur when the temperature varies from 20–32°C during spring and autumn in the southern Chinese coastal waters (Wang et al., 2006b).

On the first two days of bloom event, when the cell abundance was high, the salinity was 30 psu, which was optimum for the maximum growth of *C. marina* (Marshall and Hallegraeff, 1999). In accordance with the decrease in salinity (28 psu on the last day) the cell abundance of *C. marina* was also found to be decreased.

The nutrient concentrations did not show any marked variation during the bloom days except nitrate (12.54, 7.54 and 6.99 µmolL⁻¹). The mean nitrate concentration during the bloom period was 9.02 ±3.06 µmolL⁻¹ against the 2006-2010 mean of 6.59 ±1.90 µmolL⁻¹ (Fig.49). *C. marina* prefer nitrogen rich environment for their better growth and survival. Studies from the Chinese coasts also have shown that *Chattonella* blooms are nitrogen dependent. The increase of nitrogen, particularly nitrate, was thought to be the important cause of the bloom of *C. marina* in the Daya Bay, South China Sea (Wang et al., 2006b; Wang et al., 2011). Here also the increased nitrate concentrations, when compared to the five year mean value, might have influenced the development of bloom.

The mean phosphate level during the bloom event was 0.52 ±0.04 µmolL⁻¹, which was comparatively lesser than that of the five year mean concentration (1.92 ±1.90 µmolL⁻¹). *C. marina* could efficiently utilize all organic phosphate compounds as noted for several other harmful algal bloom species (Yamaguchi et al., 2008). It could maintain growth and survive in phosphate free conditions, which suggest that this species has the ability to store
phosphorus in an internal pool for sustaining population numbers (Yamaguchi et al., 2008; Wang et al., 2011).

The levels of silicate are usually higher during the early post-monsoon season at Mahe and the five year mean (2006-10) value was 12.48 ±10.73 µmolL⁻¹. Diatoms were the dominant group found here and they have an absolute requirement for silicon as they are the most important silicifying algal group (Kristiansen and Hoell, 2002). During the bloom event, the silicate concentration was comparatively very low, (2.38 to 3.47 µmolL⁻¹) hence it has limited the proliferation of diatoms. The diatom growth in marine waters is likely to be limited by dissolved silica when Si: N ratios are less than one (Piehler et al., 2004). In this bloom event, the Si: N ratios were less than one against the five year mean of 3:1. Since there was no competition from diatoms, C. marina could proliferate well and produced the bloom.

The N: P ratios showed highest value on 27th October with 26:1, while it decreased to 12:1 on 1st November. Five year mean of 4:1 ratio prevailed in the location since 2006. The high nitrate concentration might have played a major role in this bloom. Similar observations were made during the C.marina bloom along Chinese coast by Shen et al. (2006).

5.5.2.3 Fish mortality during *Chattonella marina* bloom

During the bloom event, mortality of a few fishes like Pearl Spot (*Etroplus suratensis*) and Mullets (*Mugil cephalus*) was observed on 27th October, in the region of one kilometre inside the estuary (Fig.49). It was found that the gills were fully choked with algal cells and the death might have been due to suffocation. No other faunal mortalities were observed. The
avoidance of fishes from the bloom areas along this coast was very much evident. Commercially important shoaling fishes shift from bloom waters to other favourable grounds during the *C. marina* bloom incidents (Subrahmanyan, 1954; Jugnu and Kripa, 2009). There are several reports on the production of ichthyotoxin during the bloom of *C. marina* (Endo *et al*., 1992; Jugnu and Kripa, 2009). Contrary to this, the fish killing activity of *C. marina* is attributed to the ROS (Reactive Oxygen Species) produced by these algae (Kim and Oda, 2010). However, the impact of harmful algal blooms depends on the concentration of the harmful species; even the most toxic species must have a minimum cell concentration to exert the harmful effect (Smayda, 1997). The present harmful algal bloom incident was not at all a prolonged one and no other faunal mortalities were observed. Hence, it is imperative to comment that even though mortality of a few fishes were observed during the bloom, it may not have been associated with the effect of toxins formed during the present *Chattonella marina* bloom event.

It could be inferred from the present bloom events that, most of the bloom formations are naturally driven by physical forcing such as monsoonal influence, riverine discharge and seasonal upwelling, which result in variations in temperature, salinity, irradiance, water stability, nutrient enrichment (eutrophication) etc. The optimum conditions for blooming will vary from species to species. Occurrence of *Chattonella marina* bloom, which is considered as a ‘species-specific bloom’, following a seasonal pattern (D’Silva *et al*., 2012) is mainly attributed to the presence of higher concentration of nitrate, since N: P ratio was found to be high during the initial stage of the bloom. Optimum temperature for this bloom was found to be 25°C.
The occurrence of *Proboscia alata* bloom soon after the monsoon was coupled with upwelling, which led to high nutrient conditions (eutrophication) especially of silicate which impart high Si: N ratio that played a significant role in the bloom initiation. Even though there was no specific factor that could be attributed to *Prymnesium parvum* bloom, the combination of eutrophic condition with the species-specific optimum favourable conditions of physical variables could have favoured the bloom event. The bloom was non-toxic in nature which might be due to the availability of sufficient nutrients, nitrogen and phosphorus in the medium. It can be concluded that algal blooming is not triggered by a single factor. A combination of species-specific, optimum favourable physico-chemical, geographical and biological factors can play a key role in the microalgal bloom dynamics.