PHYTOPLANKTON COMMUNITY AND WATER QUALITY DURING PRE AND POST MONSOON IN THE OMAN SEA (PART OF IRANIAN WATERS)

by

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LIST OF ABBREVIATIONS

DO	Dissolved Oxygen
TEM	Temperature
chl-*a*	Chlorophyll-*a*
Si	Silicate
Sal	Salinity
Bacilla	Bacillariophyceae
Dino	Dinophyceae
Cyano	Cyanophyceae
Totalphyto	Total phytoplankton
H	Hormozgan
SIS	Sistan and Baluchestan
psu	Practical salinity unit
GPS	Global Positioning System
CTD	Conductivity, Temperature, Depth
CCA	Canonical Correspondence Analysis
ANOVA	Analysis of Variance
SD	Standard Deviation
SPSS	Statistical Package for the Social Sciences
ANOSIM	Analysis of Similarity
PRIMER	Playmouth Routine In Multivariate Ecological Research
HAB_S	Harmful Algae Blooms

LIST OF SYMBOLS

°C	Degree Celsius
E	East
N	North
g	Gram
m^3	Cubic meter
mL	Milliliter
µg	Microgram
%	Percentage
mg	Milligram
L	Liter
mg/L	Milligram per Liter
cells/L	Cells per Liter
nm	Nanometer

KOMUNITI FITOPLANKTON DAN KUALITI AIR SEMASA PRA DAN PASCA MONSUN DI LAUT OMAN (SEBAHAGIAN DARIPADA PERAIRAN IRAN)

ABSTRAK

Kajian ini dijalankan di sepanjang perairan pesisir pantai Iran di Laut Oman, dalam tahun 2008 dan 2010, semasa pra- dan pasca musim monsun. Sampel dikutip di 10 transek dari zon pesisir pantai hingga lepas pantai dan dari permukaan hingga lapisan yang lebih dalam. Kajian ini bertujuan menentukan variasi ruang dan masa komuniti fitoplankton dan kualiti air. Sejumlah 204 spesies fitoplankton dikenal pasti, yang terdiri daripada Dinophyceae (105), Bacillariophyceae (89), Cyanophyceae (6), Dictyochophyceae (2), Euglenophyceae (1) dan silicoflagellate (1). Indeks kepelbagaian Shannon-Wiener mencirikan kualiti air daripada sederhana sehingga sedikit tercemar. Dinophyceae adalah dominan berbanding kelas lain dari segi kepelbagaian dan kelimpahannya, diikuti kelas Bacillariophyceae. Kelimpahan Bacillariophyceae didapati lebih tinggi semasa pasca- monsun berbanding dengan pra-monsun. Ketumpatan fitoplankton adalah lebih tinggi semasa pasca- monsun, tetapi, jumlah spesies adalah tinggi semasa pra- monsoon. Kelimpahan spesies fitoplankton yang tinggi dan kepelbagaiannya yang rendah ditemui di pesisir pantai berbanding dengan lepas pantai. Spesies yang dominan adalah *Nitzschia seriata*, *Chaetoceros dichaeta*, *Leptocylindrus danicus*, *Coscinodiscus radiatus*, *Lauderia annulata*, *Rhizosolenia alata*, *Lioloma elongatum*, *Chaetoceros atlanticus*, *Cochlodinium polykrikoides*, *Gymnodinium mikimotoi*, *Prorocentrum belizeanum*, *Prorocentrum lima*, *Prorocentrum gracile*, *Oscillatoria thiebautii* dan *Phormidium* sp. Analisis ANOSIM menunjukkan suatu perbezaan komposisi species yang

signifikan di antara dua musim. Parameter alam sekitar juga menunjukkan perbezaan yang signifikan di antara dua musim dan dua tempoh kajian. Kelimpahan fitoplankton yang tinggi dan kepekatan klorofil-*a* dicatat semasa pasca- monsun. Kepekatan klorofil-*a* dan kelimpahan fitoplankton semakin berkurangan dengan kedalaman air, dan juga daripada pesisir sehingga lepas pantai. Kemasinan dan suhu beransur berkurang dari bahagian barat ke timur kawasan kajian, sebaliknya, kepekatan nutrien semakin bertambah. Nutrien didapati bertambah dengan kedalaman laut dan di zon pesisir pantai. Nutrien menunjukkan variasi bermusim dan tahunan. Kepekatan nutrien adalah paling tinggi semasa musim pasca- monsun. Kawasan kajian menunjukkan N dan P yang terhad. Monsun memainkan peranan penting dalam mempengaruhi kelimpahan dan taburan fitoplankton, dan kepekatan nutrien di kawasan kajian. *Cochlodinium polykrikoides* pertama kali diperhatikan semasa pra-monsun daripada 2008 di bahagian timur dan kemudiannya tersebar ke kawasan barat. *Lioloma elongatum* dicatatkan dalam kelimpahan yang tinggi pada tahun 2010 semasa pasca-monsun, dan yang pertama kali direkodkan di kawasan kajian. Dinoflagelat yang toksik seperti *Pyrodinium bahamense*, *Lingulodinium polyedrum*, *Gymnodinium mikimotoi*, *Gymnodinium catenatum* dan *Gonyaulax polygramma*, ditemui dalam ketumpatan sel yang rendah, yang berpotensi menghasilkan blum alga memudaratkan di kawasan pesisir pantai perairan Iran di utara Laut Oman.

PHYTOPLANKTON COMMUNITY AND WATER QUALITY DURING PRE AND POST MONSOON IN THE OMAN SEA (PART OF IRANIAN WATERS)

ABSTRACT

This study was carried out along the Iranian coastal waters of the Oman Sea in 2008 and 2010 during the pre-monsoon and post-monsoon seasons. Samples were collected at 10 transects from coastal to offshore zones and from surface to deep layers. The aims of this study were to determine the spatial and temporal variation of phytoplankton community and water quality. A total of 204 species of phytoplankton were identified which comprised of Dinophyceae (105), Bacillariophyceae (89) Cyanophyceae (6), Dictyochophyceae, (2) Euglenophyceae (1) and silicoflagellate (1). The Shannon-Wiener diversity index characterized the water quality as moderate to slightly polluted. Dinophyceae was dominant to other classes in terms of diversity and abundance, followed by Bacillariophyceae. Bacillariophyceae in the post-monsoon was more abundant compared to the pre-monsoon season. Phytoplankton density was higher in the post- monsoon season. On the other hand, the total number of species was more in the pre-monsoon season. Higher phytoplankton abundance and lower diversity of phytoplankton species were observed in the coastal waters as compared to offshore waters. The dominant species were *Nitzschia seriata*, *Chaetoceros dichaeta*, *Leptocylindrus danicus*, *Coscinodiscus radiatus*, *Lauderia annulata*, *Rhizosolenia alata*, *Lioloma elongatum*, *Chaetoceros atlanticus*, *Cochlodinium polykrikoides*, *Gymnodinium mikimotoi*, *Prorocentrum belizeanum*, *Prorocentrum lima*, *Prorocentrum gracile*, *Oscillatoria thiebautii* and *Phormidium* sp. The ANOSIM revealed a significant difference in species composition between the two seasons. Environmental parameters also showed significant differences between the two seasons and two periods of the study. High abundance of phytoplankton and chlorophyll-*a* concentration were recorded in the post-monsoon season. Chlorophyll -*a* and phytoplankton abundance decreased from surface to deeper layers and coastal to offshore waters. A gradual decrease of salinity and temperature were observed from west to east part of the study area, but nutrients concentration increased. Nutrients increased with depth and in coastal zone. Nutrients showed seasonal and annual variation. Concentrations of nutrients were the highest in the post-monsoon season. The study area showed N and P limitation. Monsoon played an important role in affecting the abundance and distribution of phytoplankton, and concentration of nutrients in the study area. *Cochlodinium polykrikoides* was firstly observed in the pre-monsoon season 2008 in the eastern part and then diffused to the west area. *Lioloma elongatum* was recorded in high abundance in 2010 during the post-monsoon season and it was the first record in the study area. Toxic dinoflagellate such as *Pyrodinium bahamense, Lingulodinium polyedrum*, *Gymnodinium mikimotoi*, *Gymnodinium catenatum* and *Gonyaulax polygramma*, were observed in low cell densities, indicating the possibility of having potential threat of harmful algae blooms in the coastal area of Iranian waters in the north of Oman Sea.

CHAPTER ONE: INTRODUCTION

Marine ecosystems that form the marine environment are the largest habitats on Earth for a diverse group of organisms. The biotic community of the marine environment is dominated by phytoplankton (Rajkumar and Yaakob, 2013). Phytoplankton are microscopic, autotrophic, unicellular plants that are responsible for 95% of the primary productivity of the sea (Holliday et al., 2006; Prabhahar et al., 2011). Phytoplankton are microorganisms that consist of single-celled and colonial aquatic photosynthetic organisms that drift with currents. Phytoplankton can photosynthesize because they have chlorophyll (Falkowski and Raven, 1997).

As primary producers in the sea, phytoplankton form the base of the marine food chain. The ocean ecosystem is entirely dependent on phytoplankton, which are prime components of the marine ecosystems because they are responsible for approximately half of the global primary production (Field et al., 1998). Phytoplankton are the most important sources of energy in the marine environment. They initiate the marine food chain by serving as food to primary consumers. Phytoplankton have various groups, namely, Bacillariophyceae, Dinophyceae Cyanophyceae, Euglenophyceae, Dictyochophyceae, and Chlorophyceae (Saravanakumar et al., 2008; Rajkumar and Yaakob, 2013).

Biodiversity and community structure are important determinants of ecosystem function (Bhadja, 2010). Diversity indices, such as Shannon–Wiener index, evenness or equitability index, and Margalef's index, are used for biodiversity evaluation. The Shannon–Wiener index is a sensitive indicator of pollution, and its values do not fluctuate widely (Bhandarkar and Bhandarkar, 2013). High diversity suggests a healthy ecosystem; the converse indicates a degraded environment (Ghosh et al., 2012).

A benefit of using phytoplankton is that they indicate water quality because they respond to chemical and physical changes in the habitat. Phytoplankton species can be found in different environments or ecosystems, some species grow in high-nutrient water, whereas other species grow in low-nutrient water. The presence of a particular phytoplankton species indicates water quality (Pongswat, 2002).

Variations in phytoplankton distribution could result from the differences in local environmental conditions, and the composition, abundance, and distribution of phytoplankton could be influenced by water quality. Different hydrological parameters, such as pH, temperature, salinity, nutrient concentration, and solar radiation, determine the species composition, succession, and abundance of phytoplankton. Differences in physical and chemical processes are the main factors that determine variation in communities both in time and space. Physical, chemical, hydrological, and biological characteristics are determinants of water quality (Redekar and Wangh, 2000).

Many of these fluctuations, which are called seasonal successions, could result from the life activities of previously existing phytoplankton and zooplankton, fishes, as well as other organisms. The seasonal succession of phytoplankton is a problem that has long attracted the attention of algologists; the majority of studies on periodicity are restricted to limited areas (Wagey, 2002).

Microalgae exhibit seasonal fluctuations: many species are found at certain periods of the year, whereas others are present for most of the time, although their numbers may fluctuate, with massive abundance interspersed by periods of relative scarcity. Planktonic species are seasonal, and their seasons may last only a week or two each year, with a succession of species waning throughout the year (Joseph, 1989). Phytoplankton distribution is useful for the general monitoring of certain aspects of the environment, such as hydrographic events, eutrophication, water pollution, and their complex and delicate relations (Moss, 1998).

Phytoplankton are indicators of water quality and pollution in the aquatic environment (Chellappa et al., 2009; Herrera-Silveira and Morales-Ojeda, 2009). Their population and composition are good indicators of the health of the water that they inhabit. Phytoplankton are direct indicators of human interference in the marine environment. Any alarming changes in their population or composition can be considered an alarm signal to check the source of pollution in the system. Studies on phytoplankton diversity have contributed to the understanding of system dynamics (Hillebrand and Sommer, 2000). The dynamic rapid increase or decrease in plankton populations is an important issue in marine plankton ecology (Sarkar and Chattopadhayay, 2003).

Phytoplankton can also be used to determine climatic changes in different geological periods and are used as live-feed for zooplankton and for the larvae of aquatic invertebrates and vertebrates in hatcheries. Phytoplankton distribution and productivity depend on various physico–chemical factors, such as temperature, salinity, dissolved oxygen, pH, and nutrients (e.g., nitrite, nitrate, phosphate, and silicate) (Nedumaran and Ashok, 2009). Thus, plankton in a water body should be studied. Each water body showed different species composition and distribution of phytoplankton. Some species are cosmopolitan and generally distributed over the entire area (Tomas et al., 1996). Adesalu (2010) identified phytoplankton as useful indicators of aquatic environmental quality because they act as early warning signals.

Water quality is used to describe the condition or environmental health of a water body (Meybeck et al., 2006). Physical and chemical standards are set for maximum adequate concentrations of pollutants, acceptable ranges for physical variables, as well as minimum and maximum values of other water quality parameters. A numeric biological test, which describes available community attributes, can be established on the basis of measures such as species richness, the presence or absence species, and the distribution of classes of organisms. A water body can be characterized by physicochemical and biological assessment. Environmental features such as temperature, salinity, dissolved oxygen, nutrients, chlorophyll-*a*, and monsoon play vital roles in production.

Phytoplankton survive in the upper layers known as the euphotic zone, which varies widely depending on water clarity, latitude, and season (Ghosh et al., 2000). Variations in some physical and chemical parameters, such as rainfall, temperature, salinity, nitrate, nitrite, and phosphates, influence phytoplankton abundance (Adesalu and Kunrunmi, 2012). According to Dogiparti et al. (2013) reported that the major limiting nutrients for phytoplankton are nitrogen in the form of nitrate (NO_3^-) and phosphate (PO_4^-). Nitrogen tends to be the limiting nutrient in marine systems. These two nutrients are needed for cell membranes and proteins, such as enzymes.

The relationship between biodiversity and stability has been studied to elucidate the damaging effects of the increased stress and extinction rates of the ecosystem function (Diaz and Cabido, 2001). Species invasions illustrate how an increase in species richness may drastically change ecosystem processes, including the water, nutrient, and trophic transfer (Chapin, 2003).

Monsoon

The word “monsoon” is derived from the Arabic word “mausim,” which means “season.” The monsoon period is divided into pre-monsoon and post-monsoon seasons (Wilson, 2000). Monsoons are believed to result from the differential heating of land and ocean. In dry climates, monsoons serve as an important replenishment for life because water is supplied back into drought-stricken areas of the world. Moreover, monsoons play a critical role in triggering environmental features, such as seawater temperature, salinity, dissolved oxygen content, and nutrient generation, which in turn are responsible for phytoplankton production. Monsoons are important for phytoplankton abundance, distribution, and species composition (Boonyapiwat, 1997).

The study areas are connected to the Indian Ocean. Therefore, the Indian Ocean monsoon winds have noticeable effects on this area. The pre-monsoon season is between April and June, whereas the post-monsoon season is from October to December. During monsoon season, the sea becomes stormy and nutrients go up from the bottom to the surface layers, thus providing favorable conditions for phytoplankton growth. Circulation in the Oman Sea is dominated by clockwise gyres in the west and counterclockwise gyres in the east (Reynolds, 1993).

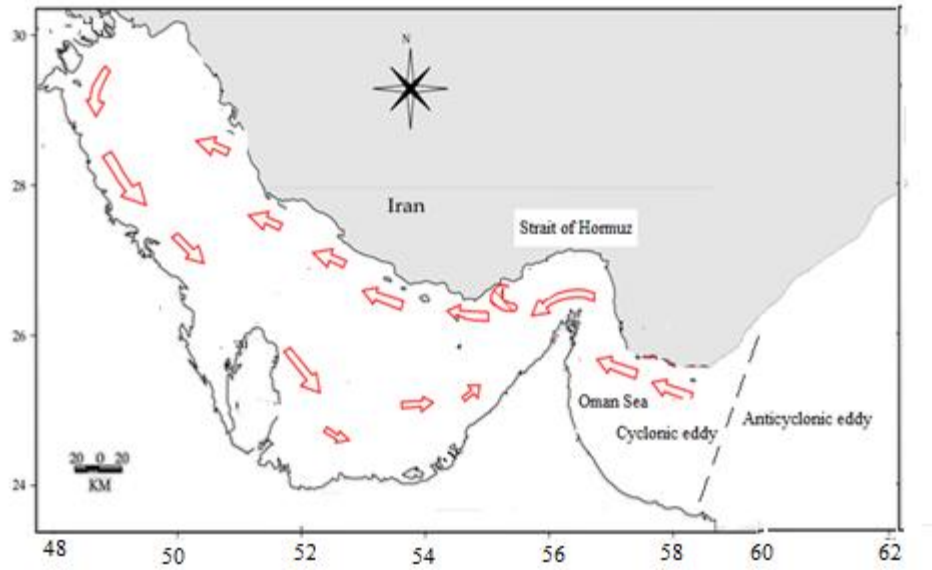

Figure 1.1 Schematic diagram of surface currents and circulation processes in the Persian Gulf and the Oman Sea (Reynolds, 1993)

Favorable environmental conditions can increase these microalgae into high concentrations (millions of cells per liter) and often lead to a discoloration of the sea surface when red tide occurs. Red tide is a natural phenomenon caused by the dense accumulation of plankton; densities become excessively high, such that the sea becomes discolored. Phytoplankton act as primary producers in all aquatic habitats; however, when their population is abundant, other forms of aquatic life are affected. In addition, environmental and economic impacts are likely to occur and are prevalent in coastal waters. An increase in their population or bloom formation generally changes the color of surface water to red, pink, brown and olive, depending on which groups of algae dominate the affected area. Red surface water discoloration resulting from algal blooms is also known as red tide or popularly called harmful algal blooms (Tett and Edwards, 2002).

Bloom formation is a natural process that although enhances biological productivity, can be harmful after long durations or be caused by toxic species and consequently lead to massive fish mortality. Blooms can spread in a matter of days and disappear just as rapidly (Bhat et al., 2006). Algal blooms are completely natural phenomena, and in the past two decades, the public health and economic impacts of such events have increased in terms of frequency, intensity, and geographic distribution (Daranas et al., 2001). Only a small number of the several thousand planktonic algal species known to exist are potentially harmful. These species can cause fish kills, contaminate seafood with toxins, pose a direct risk to human health, and affect the ecosystem. Harmful blooms all over the world have required marine biologists to periodically investigate the community structure, growth pattern, and succession in phytoplankton.

General description of the study area

1.1.1 Oman Sea

The Oman Sea is one of the most important waterways and one of the most important marine ecosystems in the world. The Oman Sea is located between Iran, Oman, Pakistan, and the United Arab Emirates (Figure 1.2). It is the entrance to the Persian Gulf in the west through the Strait of Hormuz and is connected to the Arabian Sea and the Indian Ocean in the east and the northeast, respectively. The Oman Sea is 3398 depth m, and its maximum width ranges from approximately 370 km to 545 km and increases from west to east. Its location is between latitudes 22° and 27° N and between longitudes 56° and 62° E. The Oman Sea is at the northern edge of the tropical weather systems in the Arabian Sea and the Indian Ocean, which are mainly affected by extra-tropical weather systems. The Oman Sea is deep and is greatly affected by monsoon conditions in the Indian Ocean (Robenson and Brink, 2006).

The Persian Gulf and the Oman Sea are two different ecosystems from several ecological viewpoints (particularly in terms of depth, temperature, salinity, and nutrients), water exchanges between them through the Strait of Hormuz. The highly saline water of the Persian Gulf flows out to the Oman Sea at depth, whereas the low-saline water of the Oman Sea flows into the Persian Gulf in the surface layers. Both types of water extend a significant distance from the Strait of Hormuz. The high evaporation rate over the Persian Gulf forms warm and salty water masses, which flow into the Oman Sea through the Strait of Hormuz (Reynolds, 1993).

The Iranian waters of the Oman Sea start from the Strait of Hormuz to Gwadar, covering two areas, the Hormozgan province (half in the Persian Gulf and half in the Oman Sea) as well as the Sistan and Baluchestan province.

Figure 1.2 Map of the Oman Sea located between Iran, Oman, Pakistan, and United Arab Emirates (Worldatlas, 2010)

1.1.1.1 Iran: Hormozgan and Sistan and Baluchestan Provinces

Iran is located in Southwest Asia and is bordered by Iraq, Turkey, Azerbaijan, Turkmenistan, Afghanistan, and Pakistan. Iran has a 2440 km coastline along the Persian Gulf and the Oman Sea. Hormozgan, Sistan and Baluchestan are located in the south of Iran along the Persian Gulf and the Oman Sea. Sistan and Baluchestan is located in the southeast of Iran, bordering Pakistan and Afghanistan in the northeast of the Oman Sea, whereas Hormozgan is bordered by the Persian Gulf and the Oman Sea (IPC, 2000).

Problem statement

Phytoplankton are the most important primary producers and biological indicators in aquatic ecosystems. Studies related to the dynamics of phytoplankton population have achieved importance because of global increases in harmful algae. Various factors such as climate change, human activity, and eutrophication result in increased blooms, changes in water quality, changes of species, and the arrival of invasive and new species in the area. In the waters of the Oman Sea, particularly in Iranian waters, sufficient information is lacking concerning phytoplankton community and water quality. In view of these conditions, data should be collected to detect any natural changes or unexpected circumstances that have occurred in the sea that coincide with negative effects on the ecosystem. Accessible data help in the assessment of damage to the ecosystem.

Planktonic succession has changed, thus affecting the environment and the food chain. As a result, the seasonal and annual variability of phytoplankton communities should be comprehensively studied. Thus, this study aimed to determine the phytoplankton community and distribution in relation to water quality characteristics.

This study aimed to assess the phytoplankton community and the water quality in the Oman Sea (Iranian waters). The study provides significant insight into phytoplankton and physico–chemical parameters in the study area. The results of this investigation will be useful for studies on marine life ecology, red tide, and marine fisheries in Iran and neighboring countries.

Objectives

The study was conducted to achieve the following objectives:

1. To determine the phytoplankton species composition, distribution, and water quality in the Iranian waters of the Oman Sea
2. To study the seasonal variations of phytoplankton with respect monsoon seasons.
3. To determine the vertical distribution of phytoplankton assemblage.
4. To determine the distribution of phytoplankton from coastal to offshore waters.
5. To determine the species red tide or new species in the study area.

CHAPTER TWO: LITERATURE REVIEW

Phytoplankton definition and taxonomic group

"Plankton" means "wanderer" in the Greek. Plankton are organisms that cannot move against water current and are thus transported by it. All organisms that drift with water currents in the water body are classified as plankton (Patterson and Glavovice, 2008). Colonial, filamentous, and free-floating phytoplankton represents the fundamental elements in the marine food chain (Millman et al., 2005). They produce food sources directly for other animals in the marine environments (Khuantrairong and Traichaiyaporn, 2008). They also forcefully constitute the base of aquatic food chains in marine ecosystems around the world (Achary et al., 2010). Phytoplankton compounds determine water fertility (Qasim and Kureishy, 1986). Each phytoplankton species inhabits different environments. Some phytoplankton species can thus be used as water quality indicators because most plankton organisms have short life cycles and can quickly respond to changing environments such as water pollution (Primrose et al., 2008).

Phytoplankton are divided into various groups: Dinophyceae (dinoflagellates), Bacillariophyceae (diatoms), Cyanophyceae (blue-green algae), Euglenophyceae, Dictyochophyceae, Chlorophyceae (green algae), Coccolithophora, and Silicoflagellata (Liu, 2008). Phytoplankton have several cell arrangements, such as single-cell, colony, and filamentous arrangements (Lee, 2008).

Bacillariophyceae and Dinophyceae represent the common characteristics of plankton in marine systems and are distributed in different environments with various temperatures and salinities, such as rivers, estuaries, lakes, and seas. They are also the main elements of photosynthetic organisms in the marine food chain (Al-Kandari et al., 2009). Diatoms are one of the most important groups of primary producers in the aquatic ecosystem, and dinoflagellates are the second most abundant forms of autotrophic life in the marine ecosystem (Perry, 2003).

Bacillariophyceae or diatoms are tiny single cells of algae in freshwater, brackish water, and marine water (Hoppenrath et al., 2009). Their cell walls consist of two parts: a lower hypotheca and an upper epitheca. The cell walls are frequently formed with a compound structure with small indented edges, which are applied for classification (Chandy et al., 1992). Diatoms are mostly identified by their valve morphology (Round, 1990).

Dinophyceae are unicellular with two flagella. One flagellum is approximately longitudinal, and the other one is almost transversal. The theca, which is their cell covering structure, differentiates them from other algal groups. Cells are either armored or unarmored. Armored cells have thecae divided into plates composed of cellulose or polysaccharides. The cell covering unarmored species comprises a member complex. The theca may be smooth and simple or may have spines, pores, or grooves and may be variously ornamented (Tomas et al., 1996).

Class Cyanophyceae contains approximately 150 genera and 2000 species found in different environments (in freshwater, in the sea, and in damp soil) and in a broad range of temperatures, particularly in hot summer. *Oscillatoria* can often form extensive blooms in tropical oceans and are visible as with the discoloration surface of water (Sanilkumar, 2009). Sourina et al. (1991) and Khuantrairong and Traichaiyaporn (2008) found that approximately 500 genera and 4000 species of phytoplankton exist in a huge range of water environments.

Biological indices

Diversity is an essential ecological issue directly related to the regulation and performance of the aquatic ecosystem. Several parameters are related to variations in phytoplankton diversity in the marine ecosystem. Seasonal displacements of phytoplankton assemblages are strongly related to seasonal variations in temperature as well as the amount of light and nutrients. Other factors change daily and weekly, such as meteorological events, wind, precipitation, cloudiness, and hydrological features (e.g., water, hydrological extraction, inputs, and fluctuations of water level). Variations in the rate and intensity of these factors affect species diversity and the equilibrium dynamics in the ecosystem (Chalar, 2009).

The effects of pollution and disturbances on marine ecosystems have been assessed by using biological indices (Junshum et al., 2008). In addition to number of species, diversity also includes richness and evenness, which are respectively related to the abundance and distribution of the species. Diversity indices, such as Margalef's index, Shannon–Wiener index, and evenness index, are very important (Bhandarkar and Bhandarkar, 2013). A Shannon–Wiener index greater than 3 showed that the water is clean, a value between 1 and 3 indicated that the environment is relatively polluted; and an index less than 1 suggests seriously polluted water (Wu, 1984; Ali et al., 2003). Variations limiting parameters and other environmental factors affect species diversity and characterize the species community (Washington, 1984).

TRIX index

Vollenweider et al. (1998) introduced the trophic index (TRIX) to characterize eutrophic levels. The scale of the index is between 0 and 8 (Table 2.1). A value of 8 indicates high eutrophication (high level of chl-*a* and nutrients), and a value of 0 indicates oligotrophic status (Nasrollahzadeh et al., 2008; Krivokapić et al., 2011; Balkis et al., 2012). TRIX values are sensitive: a slight change in oxygen, chlorophyll-*a* (chl-*a*), inorganic nitrogen, and phosphorus concentrations changes index values (Boikova et al., 2008). The index is suitable for monitoring coastal water environments, and it contains useful biological and physicochemical parameters that describe the trophic level of an environment (Giovanadi and Vollenweider, 2004).

Table 2.1 Trophic index and water quality classified adopted from Vollenweider et al. (1998)

Trophic index TRIX	Condition	Trophic status
<2	Water very poorly productive Very low trophic status	Excellent (Ultra oligotrophic)
2-4	Water poorly productive Lower trophic status	High (Oligotrophic)
4-5	Water moderator productive Medium trophic status	Good (Mesotrophic)
5-6	Water moderate to high productive High trophic status	Moderate (Mesotrophic to eutrophic)
6-8	Water light productive Higher trophic status	Poor Eutrophic

Phytoplankton ecology

Phytoplankton ecology refers to the relationship of plankton with the physical and chemical parameters that control their growth and distribution. In other words, the relations between organisms and their environment are defined in ecology (Lenntech, 2013).

2.1.1 Factors affecting phytoplankton growth

Environmental conditions affect phytoplankton, and various species of plankton react to different chemical or organic materials. Phytoplankton is sensitive to a broad range of environmental factors, such as seasonal and regional variability, temperature, salinity, nutrient concentration, and light. The community structure of phytoplankton is affected by several physicochemical factors (Bhadja, 2010; Ghosh et al., 2012). Physical conditions include parameters such as temperature and turbulence, whereas salinity and nutrients are classified as chemical conditions (Reynolds, 1984). Temporal variations of temperature, salinity, and nutrients have major contributions to phytoplankton species succession (Hallegraeff and Jeffrey, 1993).

2.1.1.1 Temperature

Temperature is a significant factor that affects chemical and biological interaction and thus regulates the photosynthesis rate in the aquatic ecosystem (Achary et al., 2010). Phytoplankton reproduction rates are related to temperature. For example, the rate of cell division increases two times for each 10 °C increase in temperature; the upper limit of growth is therefore related to temperature. Temperature is essential for any increase and decrease in the rate of the growth and reproduction of algae (Harris, 1986; Reynolds, 1984). Different algae prefer various temperatures for growing; for example, diatoms grow well at 20 °C to 28 °C, green algae exhibit maximum abundance at 30 °C to 35 °C, and blue-green algae prefer 34 °C to 35 °C. Water temperature is an important factor in determining the dominance of an algal group in a water body. Blue-green algae tend to be dominant in warm water temperatures (Renaud et al., 2002). Phytoplankton species have different responses to temperature, which result in seasonal changes in species composition and biomass (Karentz and Smayda, 1984). *Skeletonema costatum* is often recorded in marine coastal waters during winter. Dinophyceae, such as *Gymnodinium* sp., can grow well in high-temperature water (Pongswat, 2002).

2.1.1.2 pH

pH affects the chemical and biological characterization of liquids. pH is one of the most significant factors in water chemistry and is calculated as the concentration of acidity or alkalinity on a scale from 0 to 14. Changes in temperature, salinity, and biological activity alter pH. Biological respiration decreases and increases concentrations of oxygen and carbon dioxide, respectively, thus naturally decrease pH (Crawford et al., 2007). Optimum pH (6–8) is suitable for living organisms (Jaworski et al., 1981). pH is important for the variables of each species and the quantity of phytoplankton. The pH of seawater routinely varies by 1 pH unit from approximately 7 to 8.5. pH values outside this range can prevent the growth of a number of species (Hinga, 2002).

Goldman (1999) found that *Stephanopyxis palmeriana*, *Coscinodiscus* sp., and *Ditylum brightwellii* have constant growth rates from 8.1 to 8.45, 8.51, and 8.31, respectively. Above these values, the growth rates decreased. Dinoflagellate abundance was high with high pH. A correlation between Dinophyceae abundance and high pH in marine water was reported by Hinga (1992). At a pH lower than 4.5, blue-green algae could not be found, although some species of green algae were present. The ability to reproduce during summer blooms in eutrophic waters shows the ability of blue-green algae to grow at high pH. Competitive interactions between phytoplankton may form blooms, and the better capability of Cyanophyceae at high pH is their advantage over other groups (De Souza Santos et al., 2011). pH is one of the main water quality parameters and strong indicators of seawater quality.

2.1.1.3 Dissolved oxygen

Dissolved oxygen is the amount of molecular oxygen in the water body that supports life and is represented in milligrams per liter (mg/L). Dissolved oxygen has a major role in water analysis and is an indicator of physico–chemical and biological activities within the water body. Dissolved oxygen is necessary for the metabolism of all aquatic organisms with aerobic respiratory biochemistry (Goldman and Horne, 1983). Furthermore, the amount of dissolved oxygen can be used as an indication of the quality of water resources.

Diffusion from the air and photosynthetic activity is an important source of dissolved oxygen. Temperature and salinity affect dissolved oxygen levels (Saravanakumar et al., 2008). With increasing salinity, the concentration of dissolved gas decreases in water. The concentration of dissolved oxygen in salt water is estimated to be 20% lower than that in water with low salinity. Phytoplankton use different concentrations of oxygen to live; for instance, *Achnanthes minutissima* needs high oxygen levels for survival, whereas *Navicula seminulum* and *Nitzschia amphibian* can grow in low oxygen levels (Pongswat, 2002).

2.1.1.4 Salinity

Salinity is the amount of salts dissolved in water and is reported in parts per thousand. One of the most important properties of seawater, salinity determines the growth and survival of ambient life. The abundance and distribution of phytoplankton are determined by the level of salinity. Marine phytoplankton species often have a wide salinity-tolerance range. Many species can grow within a broad range of salinity (Brand, 1984). Marine diatoms, such as *Thalassiosira* sp., *Skeletonema costatum*, and *Ditylum brightwellii*, grow in 10 psu and higher levels of salinity (Lionard et al., 2005). The phytoplankton succession along the salinity gradient is normally attributed to the fact that most phytoplankton species are stenohaline, suggesting that they suffer from osmotic stress upon exposure to salinity changes (Flameling and Kromkamp, 1994).

2.1.1.5 Nutrients

Nutrients are functionally involved in the processes of living organisms. In chemical oceanography, this term usually refers to silicate, phosphate, and nitrate, which support the ocean food chains (Prommas et al., 2008).

Nutrients are generally present in seawater in low concentrations; however, only small amounts of them are necessary for living organisms. For their growth, phytoplankton need nutrients, which are taken up by phytoplankton cells and used as atoms in amino acids, proteins, nucleic acids, and fats. Diatoms need silicate to build up their skeletons (Baretta-Becker et al., 1998). Marine bacteria decompose dead phytoplankton, zooplankton, or higher-order organisms and then convert them to dissolved form, which phytoplankton can use easily. The distribution of nutrients is used to predict phytoplankton abundance and assemblages. Furthermore, such distribution is a marker for the status of nutrient loading or productivity (De-Pauw and Naessens, 1991). Nutrients control the phytoplankton community structure and biomass (Raymont, 1980; Tilman, 1982). The greatest influence of nutrients on phytoplankton abundance is obvious from the strong negative correlation between phytoplankton abundance and nutrients such as nitrate, silicate, and phosphate. When phytoplankton become abundant the concentration of nutrients in the water is low or undetectable (Paul et al., 2007).

Nitrogen compounds: The nitrogen cycle is important in all ecosystems, and the specific importance of nitrogen cycle in the marine environment is related to its function of controlling the primary productivity rate (Ward, 1996). Furthermore, nitrogen is the necessary component of proteins and genetic material. Inorganic nitrogen is changed to organic forms by plants and microorganisms. Nitrogen with a range of oxidation forms, including nitrate (NO_3^-) and nitrite (NO_2^-), exists in the environment (Chapman, 1996). In surface waters, igneous rocks, land drainage, as well as plant and animal debris are the main sources of nitrite ions. Nitrite has an important role for aquatic plants, and environmental factors such as plant growth and decay cause seasonal fluctuations in nitrate concentration. Nitrite ions rapidly oxidize to nitrate (Robertson and Groffman, 2007).

Phosphate (PO_4^-): Phosphorus is an important component of the biological cycle and a vital nutrient for living organisms. Phosphorus has both dissolved and particulate forms in ecosystems. Natural sources of phosphorus mainly include the weathering of phosphorus-bearing rocks and the decomposition of organic matter. Basic water quality surveys or background monitoring programs usually use phosphorus as an indicator (Genevieve et al., 2008). Phytoplankton need dissolved inorganic nutrients for their growth. The free orthophosphate ion component is a vital nutrient for supporting marine productivity (Codispoti, 1980; Tyrrell, 1999) and is the limiting nutrient for primary productivity in marine systems. Available phosphorus for marine primary producers can result from the regeneration of phosphorus from both the particulate and dissolved forms of organic phosphorus (Ammerman and Azam, 1985; Monaghan and Ruttenberg, 1999). Phytoplankton can use only soluble phosphate for growth (Goldman and Horne, 1983).

Silicate (SiO_2^-): Silicon is the most important element in the Earth's crust and is primarily present as mineral silicate. Chemically weathering terrestrial rocks solubilizes silicon, which is then carried by river runoff into the ocean. Marine plankton that form siliceous hard parts are extraordinarily effective at removing dissolved silicon from seawater. The availability of dissolved silicon controls the growth of various phytoplankton classes (Libes, 2009). SiO_2^- is an essential nutrient in marine environments. Diatoms, radiolarian, and silicoflagellates use silicate for their growth. Silica plays an important role in the ecology of aquatic systems and is an essential element for diatoms (Bacillariophyceae), comprising 26%–69% of cellular dry weight (Demaster, 1981). When silicate is available in the surface layer, and other nutrients and light are sufficient to support photosynthesis, diatoms are usually the dominant phytoplankton.

N: P Ratio (nutrient limiting factor)

Nitrogen and phosphorus are the major limiting factors in aquatic ecosystems. The relative concentrations of N and P determine the limiting nutrient for algal growth in the ecosystem. In 1934, Alfred Redfield (Redfield, 1934) discovered that, for healthy ecosystems, the ratio of carbon to nitrogen to phosphors is 106 to16 to 1 (Table 2. 2).

Table 2.2 Redfield ratio reference

	C	N	P
Redfield ratio in (µM)	106	16	1
N: P =16		No limitation	
N: P<16		N limitation	
N: P>16		P limitation	

The stoichiometric relationship of inorganic nutrient concentrations is used to forecast phytoplankton dynamics and devise management strategies for coastal and estuarine waters (Piehler et al., 2004). The N: P ratio of Redfield Planktonic Microalgae (16:1) has been applied as an indicator of phytoplankton nutrient limitation in ecosystems for a long time.

Chlorophyll- *a*

Chlorophyll-*a* is a green pigment found in plants and is used as a water quality parameters. This pigment absorbs sunlight and converts it into sugar during photosynthesis. Chlorophyll-*a* concentrations are indicators of phytoplankton abundance and biomass in water bodies. Algae have three types of photosynthetic pigment: chlorophylls, carotenoids, and phycobilins. Chlorophylls are the basic pigments involved in light absorption and photochemistry in algae, plants, and photosynthetic bacteria. Algae have four types of chlorophyll: chlorophyll-*a*, -*b*, -*c*, and -*d* (Vymazal, 1995).

As the first trophic level in the primary production cycle, phytoplankton contain green pigment called chlorophyll-*a*. Chlorophyll concentration indicates phytoplankton biomass. Chlorophyll-*a* is a highly accepted index for phytoplankton abundance and the population of primary producers in an aquatic environment (Shaaban et al., 2008). Chlorophyll-*a* is a major pigment in phytoplankton cells. Thus, chlorophyll-*a* is commonly used as an indicator for the productivity of water resources (Korneva and Mineeva, 1996).

Chlorophyll-*a* is a photosynthetic pigment found in all photosynthetic organisms, including all algae, thereby making chlorophyll-*a* an excellent proxy for determining algal biomass (Wetzel, 2001). Chlorophyll-*a* is a highly reliable indicator of algal quantity because chlorophyll-*a* is a chemical extracted directly from the algal cells present in a water sample. The amount of chlorophyll-*a* in water determines the amount of phytoplankton, which is directly related to the nutrient level. The amount of chlorophyll-*a* in a collected water sample is generally used to measure phytoplankton concentration. Measuring chlorophyll-*a* concentration also facilitates the monitoring of nuisance algal blooms that may influence water sources. By gaining insight into phytoplankton population and its distribution, researchers could draw conclusions about the health, composition, and ecological status of a water body (Jone and Lee, 1982).

Physico-chemical assessment (water quality)

Studies on water quality have explored the physical, chemical, and biological parameters as well as their complex and delicate relations. The amount of oxygen in the water, the concentration of nutrients available to marine life, water temperature, and salinity are the main factors that are surveyed in water quality. Water quality varies with location and time (Nilsson and Malm Renöfält, 2008). Monitoring the water quality of marine water can be conducted for many purposes, such as characterizing water and identifying changes or trends in water quality over time, identifying specific existing and emerging water quality problems, gathering information to design specific pollution prevention or remediation programs, providing supplemental data for a research project, and directing public attention toward a pollution problem.

Monitoring may be conducted over a month, a season, or an ongoing effort, depending on the needs of the specific situation (Kelli et al., 2009). Water quality objectives can be important components of any format for water body. Marine water quality has become a serious concern because of its effects on human health and aquatic ecosystems, including a rich array of marine life. Reliable information on water quality requires regular monitoring programs. The resulting data are huge and complex, comprising a large number of physicochemical and biological parameters (Gupta et al., 2009).

The water sustainability in many regions around the world is changing. Both water quantity and water quality are becoming dominant issues in many countries. Water quality information is important to public safety, our environment, and the national economy. Monitoring water quality is also important for minimizing environmental hazards. By monitoring different aspects of water quality over time, changes in the aquatic environment can be detected and an understanding of ecosystem health can be developed. Measuring a combination of these parameters provides a complete picture of the status of a water resource. If only physical or chemical parameters are measured, their effects on the aquatic life would be difficult