# Chapter 5
# Phytoplankton Ecology in Indian Coastal Lagoons: A Review

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**Abstract** Phytoplankton composition, diversity, and distribution pattern serve as efficient bioindicators in determining a lagoon's health. In this regard, this review was carried out to understand the phytoplankton ecology vis-à-vis environmental factors (biotic and abiotic) that regulate phytoplankton biomass and diversity in Indian coastal lagoons. Indian subcontinent houses eight coastal lagoons on the eastern seaboard and nine on the western seaboard. Phytoplankton ecology in Indian lagoons is principally determined by nutrient availability and light penetration, that promote phytoplankton biomass gain and factors that contribute to biomass loss, such as tidal flushing and zooplankton grazing. The phytoplankton floral spectra of Indian lagoons are represented by diverse algal divisions such as Bacillariophyta, Dinophyta, Cyanophyta, Chlorophyta, Euglenophyta, Chrysophyta, Cryptophyta, and Xanthophyta. This review revealed that the phytoplankton ecology of Chilika Lagoon is relatively well investigated compared to the other Indian lagoons. A total of 739 phytoplankton species have been reported from Chilika, followed by 141 from Muthukadu, 101 from Muthupet, and 53 from Pulicat, on the eastern seaboard. While on the western seaboard, 181 genera from Vembanad, 53 genera from Veli, and 53 species of phytoplankton from Ashtamudi Lagoon have been documented. Bacillariophyta is the most diverse and abundant phytoplankton group in coastal lagoons of both Indian east and west coast, which may be attributed to their high growth rates and positive correlation with regulating environmental factors. Indian coastal lagoons, which are hubs of fisheries and tourist attractions, are undergoing rapid changes due to natural and anthropogenic forcing such as littoral drift, climate change, agricultural runoff, industrial waste discharge, and

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domestic sewage. Hence, long-term but rapid analysis of phytoplankton communities across the broad spatial scales of lagoons are needed to decipher how these factors potentially influence lagoon phytoplankton ecology. This review recommends adoption of rapid and more robust pigment chemotaxonomy and remote sensing techniques to study phytoplankton ecology in Indian coastal lagoons, in addition to conventional microscopy.

**Keywords** Phytoplankton · Coastal lagoon · Anthropogenic influence · Pollution

## 1 Introduction

Coastal lagoons are shallow water bodies that run along a shoreline but remain separated from the ocean by sand bars/spits, coral reefs, or barrier islands (Kjerfve 1994; Duarte et al. 2002). They are widely distributed from the arctic to the tropics (Nichols and Boon 1994) constituting about 13% of the world's coastline (Kjerfve 1994). These shallow, nutrient-rich, turbulent, and light-attenuated ecosystems are particularly common along the east coasts of continents where tidal ranges are moderate to low (<2 m). Three distinct physical features characterize costal lagoons; first, continuous mixing of the shallow water column coupled with bottom friction that favor vertical homogeneity and sediment-water exchange; second, periodic tidal motion that facilitates material transfer with the adjacent continental shelf water; and third, water circulation is regulated primarily by tide in the mouth and wind in the interior part of the lagoon. Coastal lagoons are also subjected to rapid salinity changes year-round due to precipitation, evaporation, and wind action. Geomorphologic evolution of costal lagoons is driven by the balance between the rate of sedimentation and relative sea-level rise. Based on the degree of connectivity to the adjoining ocean, coastal lagoons are classified as choked (narrow inlet prevents tidal mixing with the sea), restricted (multiple channels and wind allow limited tidal exchange), and leaky (featuring the highest tidal mixing due to wider channels and faster water currents) (Kjerfve 1994). Coastal lagoons are among the most productive ecosystems globally because of their shallowness, relative isolation from the sea, and strong physicochemical gradients. Many of them support rich fisheries and act as a wintering ground for migratory birds. They extend a myriad of ecological services such as hydro-chemical maintenance, water treatment, oxygen production, recreation, climate regulation, flood protection, and ecotourism (Newton et al. 2018). Coastal lagoons are undergoing frequent environmental disturbances, fluctuations, habitat loss and modification, physical alteration, pollution, and overexploitation (Borja et al. 2010).

The lagoon's variable hydrological conditions due to floods fresh water runoff and marine intrusion cause spatiotemporal variations in Phytoplankton community composition and their production in a lagoon vary spatially and temporally due to dynamic hydrological conditions and marine intrusion through tide. Phytoplankton are microscopic algae primarily found in the upper sunlit layer of the aquatic ecosystem occupying about 1% of the global biomass. Phytoplankton are incredibly diverse and are majorly grouped into Bacillariophyta, Dinophyta, Cyanophyta, Chlorophyta, Euglenophyta, Chrysophyta, Cryptophyta, and Xanthophyta. They constitute base of all aquatic food webs, play an essential role in nutrient cycling, and contribute to the climatic processes by regulating the carbon cycle. They are also excellent indicators of health and productivity of aquatic environment (Brutemark et al. 2006; Goebel et al. 2013). Similar to other aquatic ecosystems, phytoplankton distribution in a lagoon is controlled by various physicochemical and biological processes which can be broadly grouped into abiotic (physical, chemical, geological, and climatic) and biotic (zooplankton grazing, photo adaptation, sinking rate) factors. In the lagoon environment, biogeochemical processes are interlinked with each other; for example, the impact of nutrients on phytoplankton communities in lagoon is dependent on other factors like light availability (Bledsoe and Phlips 2000), sedimentation, death and decomposition, hydraulic flushing (Richardson and Jørgensen 1996), and grazing (Frost 1980) of phytoplankton biomass. The challenge of declining the phytoplankton diversity remains a global problem in aquatic ecosystems (Cloern and Dufford 2005). Coastal lagoons in India, dotted across 7500 km-long coastline, are increasingly being subjected to anthropogenic influences that can affect phytoplankton and other biota up in the food chain. Several surveys in the past have been conducted to decipher diversity and environmental factors affecting phytoplankton in Indian costal lagoon, but no comprehensive synthesis of the existing literature has been conducted so far. This chapter summarizes the phytoplankton literature conducted on Indian coastal lagoons and points out future research directions.

## 2 Coastal Lagoons of India

The lagoons are highly productive and valuable aquatic ecosystem with an abundance of flora and fauna including migratory birds, thus acting as blue economy hub by supporting fisheries and coastal tourism. The Indian lagoons are shallow with an average depth of 2 m (Mahapatro et al. 2013) and remain well mixed by waves and currents. Their primary production is between ~50 and >500 g C/m$^2$/year and hence grouped into eutrophic (300–500 g C/m$^2$/year), mesotrophic (100–300 g C/m$^2$/year), and oligotrophic (<100 g C/m$^2$/year) lagoons (Nixon 1995). Broadly there are 17 lagoons present along the Indian coast, out of which 8 are on the eastern coast (Chilika Lagoon, Pulicat Lagoon, Pennar Lagoon, Bendi Lagoon, Nizampatnam Lagoon, Muttukadu Lagoon, Muthupet Lagoon, Lagoon of Gulf of Mannar) and 9 are in the western coast (Vembanad Lagoon, Ashtamudi Lagoon, Paravur Lagoon, Ettikulam Lagoon, Murukumpuzha Lagoon, Veli Lagoon, Talapady Lagoon, Lagoons of Mumbai, and Lagoons of Lakshadweep) (Ingole 2005; Mahapatro et al. 2013). The Indian lagoon ecosystems face challenges from two different sources:

natural stressors and anthropogenic stressors that potentially affect phytoplankton assemblage and dynamics. Ecological processes of the Indian coastal lagoons are significantly less understood due to the lack of extensive studies. A combination of the keywords ‘Coastal lagoon’ AND ‘India’ and ‘Coastal lagoon’ AND ‘Phytoplankton’ and ‘Specific name of the coastal lagoon present in east and west coast’ AND ‘India’ was used to extract the Google Scholar database’s bibliographic information till February 1, 2021. A total of 103 numbers of research articles were found. Out of India’s total 17 coastal lagoons, we were able to get the information related to phytoplankton ecology only in 8 lagoons (four in the east coast and four in west coast). There are still 9 coastal lagoons, in which phytoplankton diversity-related information are yet to be explored. A brief description of the climatic and geomorphological features of Indian coastal lagoons has been provided in Table 5.1. Their location along the India’s coastline has been shown in Fig. 5.1.

## 3 Phytoplankton Diversity and Seasonal Dynamics in Indian Lagoons

Some of the most important phytoplankton groups found in Indian coastal lagoons include Bacillariophyta, Dinophyta, Cyanophyta, Chlorophyta, Euglenophyta, Chrysophyta, and Xanthophyta. A brief description of them can be found in Table 5.2. A brief account of dominant phytoplankton groups, their relative abundance, and major controlling factors from Indian coastal lagoons have been shown in Table 5.3 and Fig. 5.2 and are discussed briefly below.

The seasonal abundance of phytoplankton has been described as per the prevailing monsoon wind system in Indian subcontinent where pre-monsoon (hot summer months comprising of Mar - May), monsoon (rainy season comprising June - September) and post-monsoon (relatively cooler months October to February) offers distinct temperature, humidity and rainfall pattern.

This is also to be noted that this chapter describes phytoplankton dynamics only in the coastal lagoon attached to the mainland. Atolls and lagoons in the islands have been excluded from this literature synthesis.

### *3.1 East Coast of India*

There are eight coastal lagoons present on India’s east coast, and among them, Chilika is the largest lagoon with brackish water environment supporting a rich diversity of phytoplankton. A total of 739 species have been reported from the groups Bacillariophyta (270) > Chlorophyta (178) >Cyanophyta (103) > Euglenophyta (92) > Dinophyta (88) > Chrysophyta (5), and > Xanthophyta (3)

**Table 5.1** Climate and geomorphological features of the lagoons

| Lagoon (state) | Lat/Long | Area (km2) | Depth (m) | Climate | Geological setting | Ecological Significance if any | Anthropogenic setting and threat | References |
|---|---|---|---|---|---|---|---|---|
| Chilika Lagoon (Odisha) | 19°28'–19°54' N to 85°6'–85°35'S | 906–1165 | 0.3–4.2 | Temperature range: 14°C–39.9 °C Average annual rainfall 1238.8 mm (driven by SW monsoon from July to September) | • Shallow bar-built estuary<br>• Pear shaped having length 64.3 km and width of 20.1 km<br>• Narrow channels connect the lagoon with the Bay of Bengal | • Largest brackish water lagoon in Asia<br>• Designated Ramsar site (Ramsar Convention of Wetlands in 1981)<br>• Largest wintering ground for migratory birds | • Siltation<br>• Shrinkage of water surface area<br>• Choking of the inlet channel leading to decrease in salinity<br>• Proliferation of freshwater invasive species<br>• Overfishing and illegal prawn farming | Panigrahi et al. (2009) |
| Pullicat Lagoon (Andhra Pradesh 96%, Tamil Nadu 3%) | 13.33°–13.66° N to 80.23°–80.25° E | 250–450 | 1.8 | Air temperature (15 °C to 45 °C) | • A barrier island separates the lagoon from the Bay of Bengal<br>• Hypersaline (salinity can reach up to 55 psu) | • Second largest brackish water lagoon in India<br>• Harbors Pulicat Lake Bird Sanctuary | • Siltation and periodic closure of the mouth<br>• Thermal pollution, oil spill from mechanized boats, pollution from municipal sewage, agricultural chemicals and industrial effluents<br>• Unsustainable fishing practice | Basuri et al. (2020), Basha et al. (2012) |
| Muthukadu Lagoon (Tamil Nadu) | 12°49′N, 80°15′E | 0.87 | 1–2 | North east monsoon | • Connected to the sea by a bar-built mouth<br>• Remain cut off from the sea during May-September | NA | • Fishing and boating activities<br>• Oil spill from mechanized boat<br>• Aquaculture | Prasath et al. (2019) |

(continued)

**Table 5.1** (continued)

| Lagoon (state) | Lat/Long | Area (km2) | Depth (m) | Climate | Geological setting | Ecological Significance if any | Anthropogenic setting and threat | References |
|---|---|---|---|---|---|---|---|---|
| Muthupet Lagoon (Tamil Nadu) | 10.33°N, 79.55°E | 68 | 1 | North east monsoon | • Semi enclosed coastal lagoon<br>• The bottom of the lagoon is formed of silt clay substratum | • This lagoon is known for oyster population and acts as a nursery ground for marine fishes | • Aquaculture<br>• Agricultural runoff | Gupta et al. (2006) |
| Vembanad Lagoon (Kerala) | 9.5968°N, 76.3958°E | 2114 | 1–9 | Rainfall varies from 250 to 400 cm (southwest and northeast monsoon) | • Separated from the Lakshadweep Sea by a narrow barrier island<br>• Connected to the Arabian sea by two permanent inlets | • Designated Ramsar site<br>• Home to more than 20,000 waterfowls<br>• Wintering ground for the migratory birds | • Plastic littering<br>• Oil spill from motorized boat<br>• Discharge from the sea food processing units<br>• Receive heavy load of organic material and sewage<br>• Tourism activity | Asha et al. (2016) |
| Asthamudi Lagoon (Kerala) | 8.98°N, 76.6°E | 1700 | Max 6.4 | Max temp (27.5 °C), Min temp (25.5 °C) Average annual rainfall 2400 mm | • It is a palm-shaped extensive water body with eight prominent arms | • Designated Ramsar site<br>• Hosts many migratory birds | • Solid waste dumping<br>• Oil spills from thousands of fishing boats<br>• Disposal of large quantities of untreated effluents from industries | |
| Talapady Lagoon (Karnataka) | 12.78°N, 74.85°E | 0.2 | 1 | Southwest monsoon | • It is a blind lagoon<br>• Seawater seeps into the lagoon across the sand bar or during the high tide | • Support rich fish and bird biodiversity | • Fishing and boating activities<br>• Sewage discharge | Nayar (2006) |
| Veli Lagoon (Kerala) | 8.46°N, 76.95°E | 135 | 2–3 | | • It has no permanent connection with the sea, remains separated by a narrow strip of sandy beach | NA | Pollution from agricultural runoff, industrial effluents, and domestic sewage | Sajinkumar et al. (2017) |

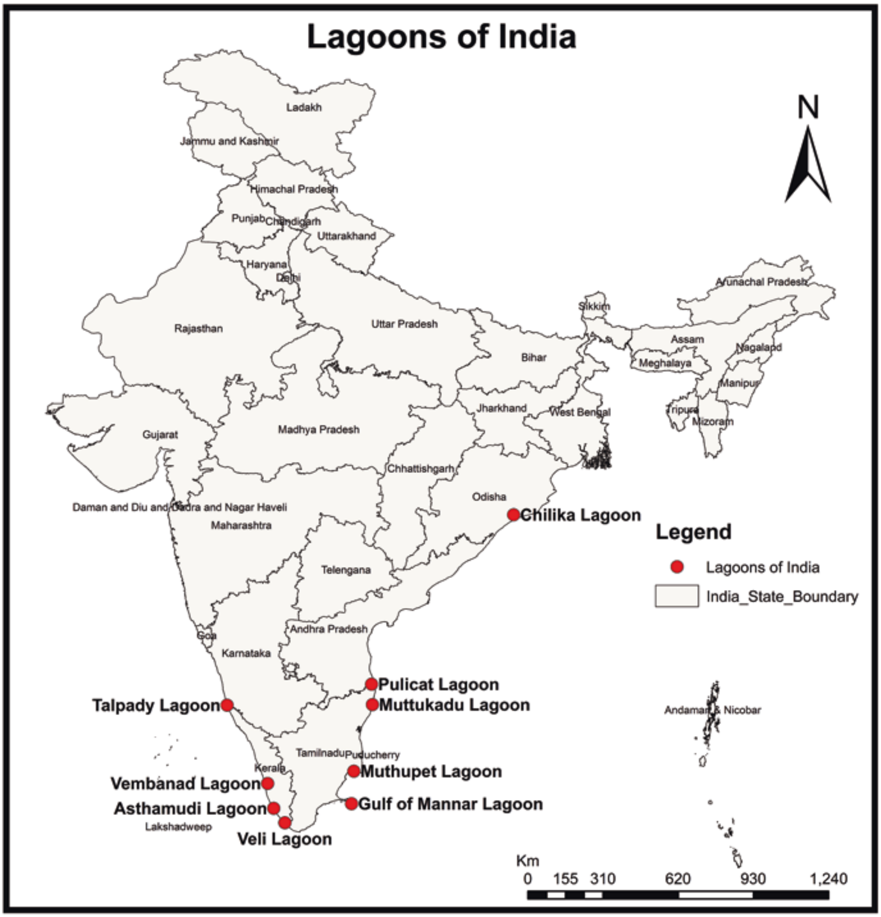


**Fig. 5.1** Costal lagoons of India

during 2000–2014 (Srichandan and Rastogi 2020). Among the recorded 270 species of Bacillariophyta, *Pleurosigma* sp., *P. normanii*, *Synedra* sp., *Thalassionema nitzschioides*, *Surirella* sp., *Chaetoceros* sp., *Coscinodiscus* sp., *Lithodesmium undulatum*, *Hemiaulus sinensis*, and *Paralia sulcata* dominate all over the lagoon (Srichandan et al. 2015a; Srichandan and Rastogi 2020). Phytoplankton population density varies between 2000 and 12,000 cells/L registering higher values during the pre-monsoon period (Srichandan and Rastogi 2020). Euglenophyta predominated among other phytoplankton at low salinity sectors, whereas Bacillariophyta predominated in high salinity sectors (i.e., southern sector, central sector, and outer

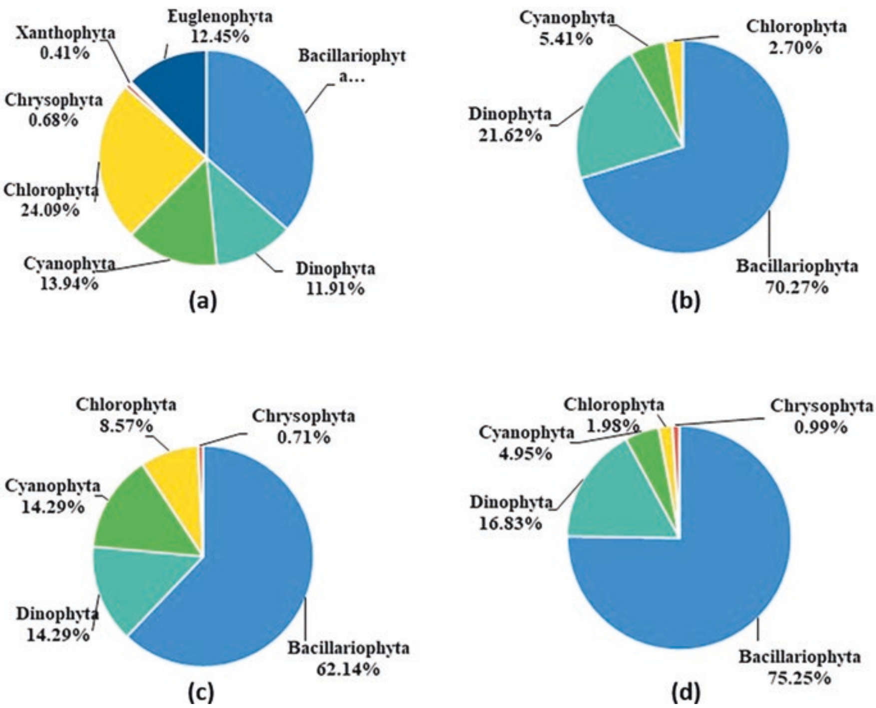


**Fig. 5.2** Relative Abundance of phytoplankton groups in Indian Lagoons [(**a**): Chilika Lagoon (**b**) Pulicat Lagoon (**c**) Mutthukadu Lagoon (**d**)Muthupet Lagoon]

channel) of Chilika Lagoon (Srichandan et al. 2015a). Bacillariophytes which are the most dominant group in Chilika become more abundant in monsoon (mean cell density 1879 cells/L), subsequently decreasing in post-monsoon (710 cells/L) and further increasing in pre-monsoon (1134 cells/L) (Srichandan et al. 2015a).

Pulicat is the second largest brackish water lagoon of India. Earlier, a total of 53 phytoplankton species were documented (Basha et al. 2012). Later, 37 species have been reported in 2016 (http://jscmwr.org/research-2/page/2/) constituted by Bacillariophyta (26), Dinophyta (8), Cyanophyta (2), and Chlorophyta (1). Maximum phytoplankton diversity is recorded during monsoon, followed by the post-monsoon period. Phytoplankton population density varies between $1.02 \times 10^5$ and $5.94 \times 10^5$ cells/L in monsoon and $6.79 \times 10^4$ and $6.28 \times 10^5$ cells/L in post-monsoon. Group abundance follows the order Bacillariophyta > Dinophyta > Cyanophyta > Chlorophyta. According to Basha et al. (2012), invasive phytoplankton species such as *Spirulina major*, *Oscillatoria* sp., and *Anabaena* sp. have been found in Pulicat. A bloom has been reported in this lagoon consisting of *Biddulphia pulchella*, *Biddulphia biddulphiana*, and *Biddulphia laevis*, which indicates Pulicat is experiencing pollution (Santhanam and Farooqui 2018).

**Table 5.2** Identifying characters of major phytoplankton groups in lagoon

| Phytoplankton groups | Characters |
|---|---|
| Bacillariophyta | • Unicellular but often found to form chains/colony; size range 15–400 mm<br>• Spectrum of shape varies from pennate (bilateral symmetry) to centric (radial symmetry)<br>• The cell wall, called frustule, has three parts: base (hypotheca), cap (epitheca), and belt (singulum). Frustule is composed of silicon and is often ornamented<br>• Key pigments found: chlorophyll *a* and *c*, beta carotene, and fucoxanthin. Autotrophs<br>• Specialized vegetative cell division<br>• Ubiquitous; found across all salinity ranges; fresh > brackish > marine. Both benthic and pelagic forms are found |
| Dinophyta | • Mainly (90%) marine<br>• Size range 15–40 μm<br>• Can swim by means of two flagella<br>• Key pigment: Peridinin; Autotrophs and heterotrophs; some are mixotrophs<br>• Most common sources of bioluminescence and toxic algal bloom |
| Cyanophyta (blue green algae) | • Cyanophyta are unicellular and filamentous organisms that are ubiquitous in all the aquatic medium<br>• Key pigment: chlorophyll *a*, phycobilin, carotenoids, phycocyanin, and zeaxanthin; Autotrophs<br>• Chlorophyll is scattered throughout the protoplasm but not contained within the chloroplasts<br>• Prokaryotes; cell wall contains pectin, hemicellulose, and cellulose sometimes in the form of mucus |
| Chlorophyta (green algae) | • Largest among the eight algal divisions<br>• Unicellular or multicellular in nature<br>• Green-colored phytoplankton with chlorophyll and xanthophyll and carotenes as the dominant photosynthetic pigment<br>• Photosynthetic pigments localized in chloroplasts in which usually pyrenoids are present<br>• These are common inhabitants of marine, freshwater, and terrestrial environments |
| Euglenophyta | • Unicellular flagellates found in freshwater and marine environment<br>• Possess definite nucleus<br>• Chlorophyll localized in chromatophores giving grass green color; few species lack chromatophores and are colorless<br>• One, two, or rarely three flagella being attached to the anterior end of the cell<br>• Reproduction is by cell division along the long axis |
| Chrysophyta (golden-brown algae) | • Often unicellular pigmented heterokonts and have a flagellum, allowing them to be mobile in the water<br>• Commonly referred to as due to their coloration from specific photosynthetic pigments; Autotrophs<br>• Major component of coastal and estuarine water |
| Xanthophyta (yellow green algae) | • Non-motile, unicellular, or colonial eukaryotic algae<br>• These are commonly found in freshwater and most of them are free floating<br>• The cell wall is often absent, but when present it contains more pectic compounds<br>• The motile forms usually bear two flagella but rarely one. They are unequal and inserted at the anterior end<br>• The chromatophores are discoid in shape and are numerous in each cell<br>• The photosynthetic pigments are chlorophyll a, P-carotene, diadinoxanthin, violaxanthin, and lutein |

**Table 5.3** Dominant phytoplankton groups and their controlling factors in Indian lagoons

| Location | Name of the lagoon | Phytoplankton relative abundance | Phytoplankton Total # of sp. | Major controlling factors |
|---|---|---|---|---|
| East Coast | Chilika | Bacillariophyta>Chlorophyta>Cyanophyta>Euglenophyta>Dinophyta>Chrysophyta>Xanthophyta | 739 | • Salinity<br>• Turbidity<br>• Nutrient stoichiometry<br>• Zooplankton grazing |
| | Pullicat | Bacillariophyta>Dinophyta>Cyanophyta>Chlorophyta | 37 | • Nutrient<br>• Water temperature |
| | Muttukadu | Bacillariophyta>Cyanophyta> Dinophyta>Chlorophyta>Chrysophyta | 141 | • Salinity<br>• Solar radiation<br>• Zooplankton grazing |
| | Muthupet | Bacillariophyta>Dinophyta>Cyanophyta>Chlorophyta>Chrysophyta | 101 | • Salinity<br>• Nutrient stoichiometry |
| West Coast | Vembanad | Bacillariophyta>Chlorophyta>Cyanophyta>Dinophyta>Euglenophyta>Eusstigmatophyta>Rhodophyta>Haptophyceae>Chrysophyceae>Cryptophyceae>Dictyochophyceae | 181(Genera) | • Nutrient<br>• Water temperature<br>• Salinity<br>• Organic matter |
| | Asthamudi | Cyanophyta> Chlorophyta>Bacillariophyta>Dinophyta | 53 | • Salinity<br>• Nutrient<br>• Organic matter<br>• Turbidity |
| | Talapady | Chlorophyta>Bacillariophyta>Cyanophyta>Dinophyta | | • Salinity<br>• Nutrient |
| | Veli | Bacillariophyta>Chlorophyta>Cyanophyta>Dinophyta>Euglenophyta | 53 (Genera) | • Turbidity<br>• Salinity |

In Muttukadu, 141 phytoplankton species have been recorded, including Bacillariophyta (87), Cyanophyta (21), Dinophyta (20), Chlorophyta (12), and Chrysophyta (1) during 2010–2012 (Prasath et al. 2019). Phytoplankton population density ranges between $1.78 \times 10^4$ and $3.26 \times 10^7$ cells/L (Prasath et al. 2019), with maximum population density recorded during pre-monsoon and minimum during post-monsoon. The following abundance order Bacillariophyta > Cyanophyta > Dinophyta > Chlorophyta > Cryptophyta has been documented. Muttukadu witnessed bloom of *Microcystis aeruginosa* in January–April 2014 due to the high concentration of nutrient input from the catchment area (Vasudevan et al. 2015).

One hundred one (101) species of phytoplankton have been recorded in the Muthupet lagoon. The species comprised Bacillariophyta (76), Dinophyta (17), Cyanophyta (5), Chlorophyta (2), and Chrysophyta (1) as per the survey conducted in 2009–2010 (Babu et al. 2013). The most abundant species were *Nitzschia seriata*, *Coscinodiscus centralis*, *Thalassiothrix frauenfeldii*, and *Ceratium furca* (Babu et al. 2013). Diatoms (*Nitzschia seriata*, *Thalassiothrix frauenfeldii*, *Odontella sinensis*) dominated during the pre-monsoon, and freshwater algae (*Anabaena* sp., *Oscillatoria* sp., *Chlorella* sp., *Nostoc* sp., *Lyngbya* sp., *Spirogyra* sp.) dominated in the monsoon. Phytoplankton population density ranged between $5.91 \times 10^3$ and $7.63 \times 10^5$ cells/L. Following relative abundance was recorded; Bacillariophyta > Dinophyta > Cyanophyta > Chlorophyta > Chrysophyta. A bloom of *Trichodesmium erythraeum*, a filamentous cyanobacteria capable of fixing atmospheric nitrogen, was reported by Santhanam et al. (2013) in May 2011 from Muthupet.

### *3.2 West Coast of India*

There are nine coastal lagoons present on the western coast of India. Fifty-three genera of phytoplankton have been reported from Veli with the following distribution order: Bacillariophyta (22), Chlorophyta (17), Cyanophyta (9), Dinophyta (2), and Euglenophyta (1). Bacillariophyta showed preference to pre-monsoon months but were barely present during peak monsoon (Mathew and Nair 1981). Chlorophyta such as *Oedogonium*, *Spirogyra*, and Desmidiales dominated in monsoon. Among Cyanophyta, *Oscillatoria* sp. occurred almost throughout the year.

Fifty-three (53) species of phytoplankton belonging to 38 genera have been documented from Ashtamudi during summer month of 2017 (Badusha and Santhosh 2018). Following relative dominance has been reported: Cyanophyta > Chlorophyta > Bacillariophyta> Dinophyta (Badusha and Santhosh 2018). Blue-green algal members such as *Oscillatoria* dominated the lagoon's phytoplankton community (Badusha and Santhosh 2018; Mathew and Nair 1980).

One-hundred and eighty-one genera of phytoplankton belonging to 11 classes have been documented from Vembanad during 2010–2012 (Vidya et al. 2020). Abundance order is Bacillariophyta > Chlorophyta > Cyanophyta > Dinophyta > Euglenophyta > Eustigmatophyta > Rhodophyta > Haptophyta > Chrysophyta > Cryptophyta > Dictyochophyta (Nandan and Sajeevan 2018; Vidya et al. 2020).

Phytoplankton density varied from 0.01 to $65.55 \times 10^5$ cells/L in Talapady Lagoon during 1996–1997 (Nayar 2006). Bacillariophyta dominated the assemblage during pre-monsoon, while Cyanophyta dominated during monsoon and post-monsoon season. High temperature, salinity, and organic waste promote cyanophytes' growth in Vembanad (Babu et al. 2013). Seasonal variation showed Bacillariophyta (*Thalassiosira subtilis*, *Nitzschia closterium*, *Navicula henneydii*, *Coscinodiscus marginatus*, *Chaetoceros indicus*, and *Campylodiscus cribrosus*) dominating the assemblage during pre-monsoon while Cyanophyta (*Oscillatoria limosa*, *Gomphosphaeria aponia*, and *Agomenellum quadruplicatum*) dominating during monsoon and post-monsoon season.

## 4 Factors Controlling Phytoplankton Distribution and Dynamics in Indian Lagoons

The phytoplankton abundance, distribution, and diversity are mostly influenced by the habitat heterogeneity in lagoons (Clegg et al. 2007). The coastal lagoon's heterogeneity is due to freshwater input coming from river discharge and monsoon rainfall and tidal influx that affect the lagoon's water chemistry. We have grouped various controlling factors that regulate phytoplankton distribution in Indian coastal lagoons under (1) physical factors, (2) chemical factors, (3) geological factors, (4) biological factors, (5) anthropogenic factors, and (6) meteorological factors which are discussed below. Range values of various physicochemical parameters have been given in Table 5.4.

**Table 5.4** Range of various parameters in Indian Coastal lagoons (from published literature)

| East coast | | | | | |
|---|---|---|---|---|---|
| | Parameters | Chilika lagoon | Pullicat lagoon | Muttukadu lagoon | Muthupet lagoon |
| 1 | Water Temperature (˚C) | 18.9–35.9 | 25.2–32.8 | 22–34 | 22–31 |
| 2 | Salinity (psu) | 0–37 | 12.6–61.1 | 0–36 | 1–34 |
| 3 | pH | 6.1–10.35 | 7.9–8.8 | 7.23–8.95 | 7.6–8.2 |
| 4 | DO (mg/L) | 0.3–14 | 2.7–7.8 | 2.1–6.93 | 2.87–8.64 |
| 5 | $NO_2$ (µmol/L) | 0.01–2.01 | 0.0–0.7 | 0.23–1.57 | 0.16–3.33 |
| 6 | $NO_3$ (µmol/L) | 0.12–19.88 | 0.1–4.9 | 16.21–42.6 | 1.42–6.15 |
| 7 | $PO_4$ (µmol/L) | 0.01–2.85 | 0.2–2 | 10.4–24.58 | 0.16–1.6 |
| 8 | $SiO_2$ (µmol/L) | 0.1–363 | | 22–188 | |
| **West coast** | | | | | |
| | | **Vembanad lagoon** | **Asthamudi lagoon** | **Veli lagoon** | **Talapady lagoon** |
| 1 | Water Temperature (˚C) | 28–33 | 27.40–31.80 | 27.1–32.3 | 26.18–34.50 |
| 2 | Salinity (psu) | 0.1–33 | 7.9–32.5 | 0.2–4.5 | 0.2–18.5 |
| 3 | pH | 6.25–10.2 | 6.70–8.20 | 7.5–8.15 | |
| 4 | DO (mg/L) | 4–9.6 | 3.16–8.86 | 4.29–6.37 | 5.07–8.06 |
| 5 | $NO_2$ (µmol/L) | | | 0.13–1.2 | 0.1–9.8 |
| 6 | $NO_3$ (µmol/L) | 74.0–95.80 | 0.69–3.99 | 6.0–12.3 | 2.5–16.1 |
| 7 | $PO_4$ (µmol/L) | 18.67–25.80 | 0.09–0.78 | 0.66–2.41 | 3.4–6.5 |
| 8 | $SiO_2$ (µg-at/L) | | | 46.3–121.5 | 15.3–132.9 |

## *4.1 Physical Factors*

Coastal lagoons being shallow water bodies are subjected to physical forcing like air and water temperature, water level, photic depth, water currents, turbidity and transparency, precipitation, and evaporation that affects lagoon ecosystem directly or indirectly.

### 4.1.1 Water Temperature

Water temperature is a crucial component of coastal lagoons, influenced mainly by solar radiation, heat transfer from the atmosphere, stream confluence, thermal pollution, and turbidity. Each phytoplankton species can only survive within a specific temperature range. 25 °C is the optimal temperature range where the species grows best, and it grows less at lower and higher temperatures. The optimum growth temperature for a given species is different at different light regime or $PCO_2$ (Partial pressure of carbon dioxide in water) conditions. Some phytoplankton grows faster during warmer conditions, but high growth rates are not always a good indicator of cell health. Usually, phytoplankton cells grow very fast only during the stressed condition, which only continues for a short period. Based on the published literature, the water temperature lies between 18 and 36 °C in eastern coastal lagoons and 26 and 35 °C in India's western coastal lagoons. The highest water temperature usually is observed in the pre-monsoon period with an increase in solar energy and resulting stable water column (Saravanakumar et al. 2008). Low water temperature is recorded during monsoon, possibly due to prevailing sea breeze, rainfall, and cloudy sky (Rajkumar et al. 2009). Water temperature influences the phytoplankton's metabolic rates and photosynthetic production (US Environmental Protection Agency 2012). For example, Cyanophyta dominates due to its growth preference in the higher temperature range (Kosten et al. 2012). However, the effect of temperature is not uniform across phytoplankton groups. For example, in Chilika, Bacillariophyta can tolerate an extensive range of water temperature (Sasamal et al. 2005), whereas growth of benthic Cyanobacteria occurs only at favorable temperature (Srichandan and Rastogi 2020). Basha et al. (2012) reported the adverse effect of thermal pollution on the phytoplankton population in Pulicat Lagoon. Muthupet and Muttukadu's phytoplankton abundance was lowest during monsoon months because of decreased water temperature due to overcast sky and cool conditions (Babu et al. 2013). The effect of water temperature on phytoplankton distribution was not very prominent in Veli (Mathew and Nair 1981).

### 4.1.2 Photic Depth and Turbidity

Ninety percent of the aquatic lives live in the photic zone due to the availability of abundant solar energy. Photic depth is the uppermost layer of the water body, which allows phytoplankton to photosynthesize. In this zone, the photosynthesis rate exceeds the respiration rate. The high intensity of solar radiation may damage the algae's light-harvesting system, so they develop photoprotective compounds. Phytoplankton diversity, abundance, and spatial variation change according to photic depth (Flöder et al. 2002). Photic depth in coastal lagoons is a function of solar radiation intensity, water turbidity, presence of submerged aquatic vegetation, and pollution. Turbidity, which inversely varies with the photic depth, is the amount of cloudiness in water (Gallegos 1992). A high amount of suspended matter occurs due to flooding and intense rainfall, common during monsoon seasons. Turbidity is the key controlling factor which regulates the photic depth of the lagoon and affects the phytoplankton production in Chilika (Srichandan et al. 2015a, b). According to Srichandan et al. (2015b), phytoplankton bloom could not happen in Chilika for high turbidity even though a large amount of dissolved nutrient was brought inside the lagoon during cyclone Phailin. Badusha and Santhosh (2018) observed that in Ashtamudi lagoon, phytoplankton species diversity reached its maximum (41 species) when turbidity was minimum. According to Mathew and Nair (1981), high turbidity during monsoon resulted in fewer phytoplankton counts in Veli. Similar trend was also noticed in both Muttukadu and Muthupet in the east coast, where the phytoplankton abundance was the lowest during monsoon months due to high turbidity caused by river runoff and phytoplankton abundance was highest during summer/pre-monsoon season due to low turbidity (Babu et al. 2013; Prasath et al. 2019).

### 4.1.3 Water Current

The water current is the rate of movement of the water. It plays very important role for its influence in transportation of sediment, pollutant, phytoplankton species, and nutrient (Mohanty and Panda 2009). Water current inside the coastal lagoon is mainly controlled by freshwater runoff, tidal effect, strong winds, water density difference, and difference in temperature and salinity. Water current has significant importance in driving the phytoplankton from one place to another in an aquatic ecosystem (Phlips et al. 2002). The southwest and northeast monsoons influence the current pattern by playing a key role in determining the phytoplankton species diversity inside the lagoon (Murty and Varma 1964; Rao et al. 2011; Jyothibabu et al. 2013). According to Mohanty and Panda (2009), wind, tide, and freshwater input regulate the circulation and mixing pattern in Chilika.

## 4.2 Chemical Factor

The critical chemical factors responsible for phytoplankton distribution in coastal lagoons are pH, total alkalinity, salinity, dissolved oxygen, biochemical oxygen demand, and nutrients which are discussed below.

### 4.2.1 Nutrients

Nutrient concentrations and stoichiometry, specifically of silicate, nitrate, nitrite, phosphate, and ammonia, act as one of the most significant determinants of phytoplankton biomass and distribution in a lagoon environment. Any shortage of nutrients causes a decrease in the photosynthetic rate in phytoplankton. The source of nutrients in coastal lagoons can be both autochthonous (decomposition of organic matter, upwelling, wind-driven resuspension) and allochthonous (river discharge, weathering, atmospheric deposition). Concentration of nitrate and phosphate was recorded maximum during the pre-monsoon season due to the higher residence time of water and low-flow period in Chilika Lagoon (Muduli et al. 2013). In Chilika concentration of silicate was higher throughout the monsoon period due to high land runoff which went down in the pre-monsoon period for low freshwater influx and consumption by the Bacillariophyta (Srichandan et al. 2015a, b). In Chilika, nitrate and phosphate greatly influence phytoplankton abundance and diversity, especially of Dinophyta (Srichandan et al. 2015a). Coastal lagoons highly loaded with sewage (organic matter) may manifest algal blooms or sometimes toxic algal blooms, as shown in Pulicat Lagoon (Santhanam and Farooqui 2018). In Muthukadu, a high nutrient input concentration leads to a very high phytoplankton population density dominated by blue-green algae *Microcystis aeruginosa*. Vembanad receives enough nutrients from Kuttanad paddy fields that cause bacillariophytes and chlorophytes' dominance. In Veli, a clear inverse relationship of phosphate concentration with Chlorophyta has been established. Bacillariophyta shows silicate dependence as it has been observed that there was a decrease in silicate concentration with increased Bacillariophyta population (Mathew and Nair 1981).

### 4.2.2 Salinity

Salinity is an important determining factor for phytoplankton diversity and abundance that decreases with an increase in salinity. Salinity in a coastal lagoon is mainly controlled by freshwater influx through riverine water, local rainfall, tidal amplitude, high solar radiation, and water residence time. In coastal lagoons, phytoplankton are generally euryhaline (able to sustain in an array of salinity) in nature. Salinity fluctuation causes osmotic stress in phytoplankton cells. In Chilika, salinity plays a critical role by controlling the phytoplankton abundance and distribution (Panigrahi et al. 2009; Srichandan et al. 2015a, b). Raman et al. (1990) and

Srichandan et al. (2015a) observed that southern sector (i.e., stable salinity region) is dominated by the phytoplankton groups of Dinophyta and Chrysophyta, whereas northern sector (i.e., low salinity region) is mostly dominated by the group of Euglenophyta. Bacillariophyta were prevalent all over the high salinity regimes (southern sector, central sector, and outer channel) in Chilika. The outer channel (i.e., high salinity zone) is dominated by marine phytoplankton species because of its direct connection with the Bay of Bengal. Due to high freshwater influx from rivers and land runoff, the northern sector is usually dominated by freshwater forms of phytoplankton. Siltation caused the complete closing of mouths of Pulicat leading to salinity fluctuation and water level changes of the lagoon, which had noticeable effect on the phytoplankton abundance (Basha et al. 2012). In Muttukadu, the minimum population density was recorded during low salinity months, whereas the maximum population was recorded during high salinity months (Prasath et al. 2019). Widely changing salinity at the Muthupet is responsible for the predominance of bacillariophytas at the mouth (Mishra et al. 1993; Ramakrishnan et al. 1999; Senthilkumar et al. 2002). According to Nayar et al. (1999), in Talapady, Bacillariophyta counts were higher in the summer season and lower in monsoon and were moderate during the post-monsoon season.

### 4.2.3 pH

pH is the measurement of the hydrogen ion concentration in water. Coastal lagoons are prone to fluctuating pH concentrations due to regular intermixing of fresh and saline water, phytoplankton's photosynthetic activity, respiration, and decomposition of organic matters (Ganguly et al. 2015; Muduli et al. 2013). pH concentration in the aquatic medium can regulate the growth and diversity of phytoplankton and nutrient availability. It regulates the carbon cycle and has a crucial role in the growth and survival of phytoplankton (Sculthorpe 1967). Srichandan et al. (2015a) reported the pH variability in Chilika is due to the $CO_2$ assimilation by phytoplankton and macrophytes. Srichandan et al. (2015a) reported a strong positive correlation of pH with abundance of Cyanophyta in Chilika. Similarly, in Ashtamudi, phytoplankton abundance dropped in highly polluted water with a lower pH value (6.70) (Badusha and Santhosh 2018).

### 4.2.4 Dissolved Oxygen

Dissolved oxygen (DO) represents the total amount of oxygen present in dissolved form in water, and it is an essential determinant of the aquatic ecosystem's health. Oxygen is produced in the process of photosynthesis by the phytoplankton, macrophytes, and submerged vegetation. Wind flow drives the mixing of oxygen in the water from the atmosphere. According to Garnier et al. (1999), oxygenation in aquatic systems results from a variation between photosynthesis, organic matter degradation, re-aeration, and physicochemical characteristics of water. Changes in freshwater flow may have important effects on dissolved oxygen (Mallin et al. 1993). Respiration and denitrification of bacteria in the lagoon act as a sink of oxygen. According to Barik et al. (2017), water temperature and wind maintain a linear relation with dissolved oxygen in Chilika. Dissolved oxygen level 3 mg/L must be maintained to protect aquatic life (CPCB 1986). It was reported that DO concentration varied from 0.3 to 14 mg/L in the Chilika Lagoon, which is well saturated due to the large area of the lagoon, high rate of photosynthesis, and wind churning effect (Barik et al. 2017; Srichandan and Rastogi 2020), Dissolved oxygen varied from 2.7 to 7.8 mg/L in Pulicat Lagoon (Basuri et al. 2020). In lagoon ecosystems, concentration of DO decreases due to the rise in water temperature and organic matter decomposition. If the concentration of dissolved oxygen increases, it tends to increase the phytoplankton number.

#### 4.2.5 Biochemical Oxygen Demand (BOD)

BOD is defined as the amount of dissolved oxygen used by aerobic bacteria to oxidize organic matters. It is an important indicator of the microbial load and amount of organic pollution in aquatic ecosystems (Ndimele 2012). High concentration of BOD is an indicator of high demand of oxygen and low water quality and vice versa. According to Badusha and Santhosh, (2018), maximum phytoplankton species diversity occurred in less polluted areas, while the lowest number of species was observed at more polluted (high BOD) parts of the Ashtamudi Lagoon contributed by oil spills from tourist boats and fecal contamination.

### *4.3 Geological Factor*

The geological factors impact coastal lagoon through littoral drift, groundwater discharge, catchment influx, marine water intrusion, the coastal geomorphological process, inlet configuration and dimension, lagoon size, orientation to prevailing winds, and water depth (Mahapatro et al. 2013). Chilika characterizes a complex geological process involving the deposition of beach ridges and spits. The lagoon spreads from northeast to southwest in parallel to the Bay of Bengal, with a variable width of 20 km in the east coast of India. The lagoon gets its share of saline water through a narrow tidal inlet connected to the Bay of Bengal in the east and freshwater through various rivers and rivulets from the north, leading to various salinity regimes in the lagoon. This has created a diverse niche for inhabiting phytoplankton to exploit resources efficiently. Hence, marine phytoplankton dominates in the lagoon mouth than the northern sector, where mostly freshwater phytoplankton dominates (Srichandan et al. 2015a, b). The central sector is inhabited by freshwater and marine phytoplankton because of the mixing of freshwater and seawater. Maintaining connection between lagoon and sea is challenging as littoral drift, basin sedimentation, depletion in tidal prism, and tidal influence change water chemistry of a lagoon and also affect species migration pattern between sea and lagoon (Kumar and Pattnaik 2012).

The Pulicat has connection with the Bay of Bengal by an inlet channel at the north and outflow channel at its southern end. Muttukadu is a bar-built coastal lagoon where the effect of littoral drift is prominent. The Muttukadu is typically separated from the sea during May to September because of the flood stream's inundation from the upper reaches. Ashtamudi is a palm-shaped extensive water body and has eight prominent arms (Nagaraj 2014). Talapady is a semi-enclosed water body lying parallel with the Arabian Sea (Nayar et al. 1999). The lagoon opens into the Arabian Sea during southwest monsoon through an opening in the sand bar. During the rest of the year, seawater seeps into the lagoon across the sand bar, or the high tide water flows over the sand bar into the lagoon. During the southwest, the river's influx transports silt-laden freshwater into the lagoon. During summer, the river dries up and becomes an extension of the lagoon (Nayar et al. 1999, 2001; Nayar 2006). Due to the above geological features, the resulting water chemistry strongly influences the spatial distribution of phytoplankton.

## *4.4 Biological Factor*

Biological factors such as zooplankton grazing, heterotrophy, shading, community shift, community succession, parasitism, and microbial loop play an important role in spatiotemporal distribution of phytoplankton in the lagoon ecosystem. Grazing, deposition, and washout can effectively remove phytoplankton biomass from the water column (Underwood and Kromkamp 1999). Dube and Jayaraman (2008) and Dube et al. (2010), through modeling study, showed zooplankton grazing is a significant biotic regulating factor of phytoplankton abundance in Chilika. According to Jyothibabu et al. (2006), microzooplankton are responsible for the grazing rate of 43 ± 1% for the daily phytoplankton standing stock during the high saline condition (27.5). Eutrophication causes phytoplankton community shifts by changing their physiology. Studies related to biological control of phytoplankton on Indian coastal lagoons are generally lacking.

## *4.5 Meteorological Factor*

Some important meteorological factors that control phytoplankton biomass, distribution, and abundance in Indian coastal lagoons are monsoon (discussed before in this chapter), regional climate change, and cyclones. It was reported that regional climate change leads to changes in the precipitation pattern in the Mahanadi River basin region which impacts salinity gradient in the Chilika Lagoon by altering freshwater flow (Kumar and Pattnaik 2012). Monsoon-driven rainfall appears to be an essential cyclic phenomenon, and the hydrographical parameter in the Indian lagoon system showed a distinct pattern of variations leading to predictable phytoplankton community succession. It was reported that in a lagoon ecosystem, abundance of phytoplankton remains high in the dry period (pre-monsoon) and low during the wet period (monsoon) (Perumal et al. 2009). Phytoplankton abundance during pre-monsoon increases due to the increased water temperature and penetration of high intensity solar irradiance and was lowest throughout the monsoon seasons due to heavy rainfall, high turbidity, decrease in temperature, an overcast sky, and cool conditions (Saravanakumar et al. 2008). The high density during the pre-monsoon might be ascribed to more stable hydrological conditions prevailing during the season (Babu et al. 2013). Based on the published literature, it appears that Bacillariophyta dominates in almost all coastal lagoons of India due to its ability to withstand wide ranges of salinity and temperature. Tropical cyclones frequently impact coastal lagoons in India's eastern peninsula, bringing rapid changes in salinity, turbidity, and nutrient stoichiometry (Srichandan et al. 2015b). Increased number of freshwater Cyanophyta, viz., *Cylindrospermum* sp., and toxic dinophyta species, viz., *Alexandrium* sp., *Gonyaulax* sp., *and Prorocentrum cordatum*, have been reported in the central and northern sectors of Chilika in the post-Phailin (an Extremely severe cyclonic storm that made landfall in the vicinity of Chilika lagoon) period (Srichandan et al. 2015b).

#### 4.5.1 Aerosol

Aerosol is the suspension of solid or liquid particles in air or other gases (Hinds 1999). It consists of volcanic ash, biological particles, and mineral dust, black carbon, and water vapor. Aerosols act as an essential source of nutrients and trace metal to the aquatic system and regulate climate system by influencing radiation budget. These particles regulate earth's temperature by attenuating solar radiation through absorption, scattering and cloud droplet formation (Goosse et al. 2010). So, aerosol particles are directly or indirectly responsible for the growth and diversity of phytoplankton in India's coastal lagoons. But there is a lack of research regarding aerosol particles' impact on phytoplankton diversity in Indian coastal lagoon.

### *4.6 Anthropogenic Factor*

Marine pollution has long been a problem in the world's coastal zones, and there is ever-increasing pressure on coastal ecosystems. Lagoons are important areas of economic activity. Population growth and industrial developments alongside the lagoons have greatly influenced pollution loads into the lagoon environment. Pollutants enter into lagoons through various point and non point sources, such as industrial effluents, untreated municipal effluents sediment from catchment, agricultural runoff. Fertilizers and pesticides from agricultural runoff, tourism waste, urban and industrial waste, and aquaculture act as direct sources of contaminants while leaching from antifouling boat paints act as an indirect source of pollutants (Ahner et al. 1997). It has been reported that Chilika Lagoon is receiving heavy silt load because of the changes in land use pattern within the Chilika basin. Fragmentation of floodplains, and aggraded channels lead to loss of water holding capacity of the lagoon thus directly affecting the phytoplankton diversity (Kumar and Pattnaik 2012). Increasing tourist pressure and fishing boats in Chilika can add to the pollution burden leading to stress on the ecosystem. Malpracticed aquaculture activity leads to organic pollution in the lagoons like Chilika, which has an adverse effect on the phytoplankton community. Amir et al. (2019) have reported that the northern sector of Chilika Lagoon is heavily affected by urban and industrial wastewater input. The contaminants pose severe threat to the coastal lagoon ecosystems stimulating eutrophication, algal bloom occurrence, increased mortality of fishery resources and decreased fishery production, and significant economic loss (Gao et al. 2014). Heavy loading of organic matter in tropical coastal lagoons (Balasubramanian et al. 2004) can potentially disrupt the Redfield ratio in the lagoon environment. For example, Pulicat receives industrial effluents from the Arani and Kalangi rivers, which dump high concentrations of nutrients into the lagoon (Basha et al. 2012). Hence toxic phytoplankton blooms are not uncommon in Pulicat (Santhanam and Farooqui 2018). Pulicat also experiences thermal pollution due to the release of hot coolant water and discharge of toxic fly ash in the form of a slurry from the nearby thermal power plant, which causes a rise of water temperature by 5 °C resulting in a decline in phytoplankton species. It has been reported that phytoplankton in Pulicat may have reduced to just half from the original level due to pollution (Basha et al. 2012). Badusha and Santhosh (2018) observed that, in Ashtamudi Lagoon, phytoplankton species diversity reached its minimum, where oil pollution from tourist boats and fecal contamination is more, while maximum diversity reached up to 41 species, where pollution and turbidity were minimum. The Vembanad receives an excess amount of nutrients from adjacent Kuttanad paddy fields leading to accelerated growth of bacillariophytes and chlorophytes. It is important to note that cyanophytes are favored in organic wastes, potentially replacing Dinophyta and bacillariophytes (Nandan and Sajeevan 2018; Vidya et al. 2020). High BOD designates unhealthy and poor water quality of an aquatic system and high microbial load.

## 5 Conclusion and Future Research Directions

Few trends are apparent from this literature review on phytoplankton in the Indian coastal lagoon. First, Indian coastal lagoons are not as intensively studied as other coastal estuarine systems, although coastal lagoons are crucial for providing various ecosystem services. Most of the studies relied on either one-time sampling or seasonal sampling. No long-term (more than 5 years) studies on phytoplankton biomass and productivity pattern change over the year have been established. Second, investigation and publication frequency from Indian coastal lagoons are disproportionately skewed than others, Chilika in the East Coast, for example has the highest number of scientific publication. Third, when it comes to studying phytoplankton in Indian lagoons, all are focused on microscopic studies. Microscopy has the distinct advantage of identifying phytoplankton at the species level, but it is time-consuming, prone to subjective error and needs trained man power. Fourth, the impact of monsoon-driven rainfall is distinct in shallow coastal aquatic systems such as lagoons. Monsoon brings freshwater, sediments, and nutrients in the system from the catchment, but it does not coincide with the maximum phytoplankton growth and biomass accumulation, which instead happens a few months later after water column gets stabilized. Fifth, anthropogenic impact such as thermal pollution and organic and inorganic matter loading in the Indian coastal lagoons is on the rise, leading to cascading effects on the food web. Sixth, for sustainable management of lagoon ecosystem, it is needed to understand the ecological components (physical form, lagoon soils, physicochemical characteristic of water biota, climate, geomorphology, hydrobiology, energy-nutrient dynamics), ecological processes (the process that maintains animal and plant population, species interaction, physical processes), and ecological services (provisioning services and cultural services) in a long-term basis. Increased frequency of monitoring can ensure sustainable management of these vulnerable ecosystems in Indian coastal waters. Remote sensing observation for case-2 waters, remote sensing algorithms for observation and detection of multiple phytoplankton types from satellite data, ecological algorithm, and modeling (primary productivity, carbon budget, nutrient budget, trophic status indexing), now-casting, and forecasting water quality parameters are possible future research scopes. The importance of deploying high-frequency remote sensors for cost-effective, long-term monitoring of large lagoons is gaining attention. Besides, HPLC to characterize pigment as a chemical marker for the determination of phytoplankton size classes and functional types can also give valuable information to study phytoplankton at the interface of biogeochemistry and management. More such studies need to be undertaken in the future.

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