Donat-P. Häder
E. Walter Helbling
Virginia E. Villafañe *Editors*

Anthropogenic Pollution of Aquatic Ecosystems

Springer

Anthropogenic Pollution of Aquatic Ecosystems

Donat-P. Häder · E. Walter Helbling ·
Virginia E. Villafañe
Editors

Anthropogenic Pollution of Aquatic Ecosystems

Springer

Editors
Donat-P. Häder
University of Erlangen-Nürnberg
Erlangen, Germany

E. Walter Helbling
Estación de Fotobiología Playa Unión
Rawson, Argentina

Virginia E. Villafañe
Estación de Fotobiología Playa Unión
Rawson, Argentina

ISBN 978-3-030-75601-7 ISBN 978-3-030-75602-4 (eBook)
https://doi.org/10.1007/978-3-030-75602-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Aquatic ecosystems exceed terrestrial ones in size and rival them in productivity. In addition to offering food to a rapidly growing human population, they render a wide array of services. The oceans take up most of the anthropogenically produced heat and a large share of the emitted trace gases such as CO_2 from human activities. The productivity of the oceans is affected by a plethora of environmental stress factors such as rising temperatures, ocean acidification and deoxygenation. Of growing importance is the increasing pollution of aquatic habitats. Because of the enormous size of the oceans, humans have always used them to get rid of their wastes. With the explosion of the human race, this behavior is becoming a burning problem because in addition to biodegradable material, toxic and long-lived wastes are being dumped into aquatic ecosystems. Terrestrial runoff transports fertilizers into coastal ecosystems which increase eutrophication. In addition, pesticides, drugs and pharmaceuticals accumulate in the water. The growing industry and lacking or inadequate cleaning strategies result in heavy metals concentrating in the rivers which transport these toxic materials into the oceans. Accidental and deliberate oil spills are found both in coastal areas and in open ocean waters affecting the biota from microorganisms to vertebrates. After their invention, plastic materials were celebrated as cheap, non-toxic and versatile blessings for human life. But, the accidental or deliberate disposal in the landscape, coastal zones and the oceans has accumulated the debris to enormous waste piles. Solar UV radiation and mechanical forces of wind and waves result in the fragmentation of larger wastes into mico- and nanoplastics which are a threat for most marine organisms which ingest the particles which subsequently bioconcentrate in the food web. All these growing polluting materials threaten our race, and fast and efficient solutions have to be developed to stop the attacks on human health.

Erlangen, Germany — Donat-P. Häder
Rawson, Argentina — E. Walter Helbling
Rawson, Argentina — Virginia E. Villafañe
Spring 2021

Contents

Contributors

Anthony Andrady Department of Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC, USA

Marina Arcagni Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, Bariloche, Argentina

Azizullah Azizullah Department of Biology, The University of Haripur, Haripur, Pakistan

Anastazia T. Banaszak Integrative Reef Conservation Research Laboratory, Unidad Académica de Sistemas Arrecifales, Instituto de Ciencias Del Mar Y Limnología, Universidad Nacional Autónoma de México, Puerto Morelos, Mexico

José Bonomi Baruffi Phycology Laboratory, Botany Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil;
Center of Physical and Mathematical Sciences, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Eduardo Bastos Phycology Laboratory, Botany Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Göran Björk Dept. Marine Sciences, University of Gothenburg, Gothenburg, Sweden

Marco J. Cabrerizo Centro de Investigación Mariña da Universidade de Vigo (CIM-UVigo), Vigo, Spain;
Departamento de Ecología y Biología Animal, Universidade de Vigo, Facultad de Ciencias del Mar, Vigo, Spain

Verena A. Campodonico Centro de Investigaciones en Ciencias de la Tierra, Consejo Nacional de Investigaciones Científicas y Técnicas y Universidad Nacional de Córdoba, Córdoba, Argentina

Giulia Burle Costa Phycology Laboratory, Botany Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil;
Center of Physical and Mathematical Sciences, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Enrique Crespo Centro para el Estudio de Sistemas Marinos (CESIMAR)—Centro Nacional Patagónico—CONICET, Puerto Madryn, Chubut, Argentina

Lineu del Ciampo Program in Health and Environment, University of Joinville Region Univille, Joinville, SC, Brazil

Pedro J. Depetris Academia Nacional de Ciencias, Córdoba, Argentina

Giovanna Destri Phycology Laboratory, Botany Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil;
Center of Physical and Mathematical Sciences, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Cristian Durante Centro para el Estudio de Sistemas Marinos (CESIMAR)—Centro Nacional Patagónico—CONICET, Puerto Madryn, Chubut, Argentina

Gilmar S. Erzinger Postgraduate Program in Health and Environment, University of the Region of Joinville—UNIVILLE, Joinville, Santa Catarina, Brazil

Mauricio Faleschini Laboratorio de Oceanografía Química y Contaminación de Aguas, CESIMAR, CCT CONICET-CENPAT, Puerto Madryn, Chubut, Argentina

Ana Fazio Centro Para El Estudio de Sistemas Marinos (CESIMAR-CONICET, CCT CONICET-CENPAT), Puerto Madryn, Chubut, Argentina

Alessandra Larissa Fonseca Center of Physical and Mathematical Sciences, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil;
Marine Biogeochemistry Laboratory, Oceanography Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Monique Fröhlich Program in Health and Environment, University of Joinville Region Univille, Joinville, SC, Brazil

Kunshan Gao State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences, Xiamen University, Xiamen, China

Raúl González Escuela Superior de Ciencias Marinas, Universidad Nacional del Comahue and CONICET (CIM Almirante Storni), San Antonio Oeste, Río Negro, Argentina

Donat-P. Häder Department of Biology, Friedrich-Alexander Universität, Erlangen, Germany

E. Walter Helbling Estación de Fotobiología Playa Unión, Chubut and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rawson, Chubut, Argentina;
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

Paulo Antunes Horta Phycology Laboratory, Botany Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil;
Center of Physical and Mathematical Sciences, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Peng Jin School of Environmental Science and Engineering, Guangzhou University, Guangzhou, China

Romina Juncos Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, Bariloche, Argentina

Sarzamin Khan Department of Chemistry, University of Swabi, Swabi, Pakistan

Neha Kumari Laboratory of Photobiology and Molecular Microbiology, Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Carla Keite Machado Program in Health and Environment, University of Joinville Region Univille, Joinville, SC, Brazil

Sonal Mishra Laboratory of Photobiology and Molecular Microbiology, Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Maite Narvarte Escuela Superior de Ciencias Marinas, Universidad Nacional del Comahue and CONICET (CIM Almirante Storni), San Antonio Oeste, Río Negro, Argentina

Luis F. H. Niencheski Instituto de Oceanografia, Fundação Universidade Federal do Rio Grande, Rio Grande, RS, Brazil

Marina L. Nievas El Makte Centro Para El Estudio de Sistemas Marinos (CESIMAR-CONICET, CCT CONICET-CENPAT), Puerto Madryn, Chubut, Argentina;
Facultad Regional Chubut, Universidad Tecnológica Nacional, Puerto Madryn, Chubut, Argentina

Abha Pandey Laboratory of Photobiology and Molecular Microbiology, Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Andrea I. Pasquini Centro de Investigaciones en Ciencias de la Tierra, Consejo Nacional de Investigaciones Científicas y Técnicas y Universidad Nacional de Córdoba, Córdoba, Argentina

Rosana Polifroni Centro Para El Estudio de Sistemas Marinos (CESIMAR-CONICET, CCT CONICET-CENPAT), Puerto Madryn, Chubut, Argentina

Sabeela Rehman Department of Chemistry, University of Swabi, Swabi, Pakistan

Lyllyan Santos Rocha Phycology Laboratory, Botany Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil;
Center of Physical and Mathematical Sciences, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Leonardo Rubi Rörig Phycology Laboratory, Botany Department, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil;
Center of Physical and Mathematical Sciences, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Juan Seco Pon Instituto de Investigaciones Marinas y Costeras, IIMyC—Universidad Nacional de Mar del Plata—CONICET, Mar del Plata, Argentina

Marcela A. Sepúlveda Centro Para El Estudio de Sistemas Marinos (CESIMAR-CONICET, CCT CONICET-CENPAT), Puerto Madryn, Chubut, Argentina

Vidya Singh Laboratory of Photobiology and Molecular Microbiology, Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Rajeshwar P. Sinha Laboratory of Photobiology and Molecular Microbiology, Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Sebastian M. Strauch Postgraduate Program in Health and Environment, University of the Region of Joinville—UNIVILLE, Joinville, Santa Catarina, Brazil

Nadia Taimur Department of Botanical and Environmental Sciences, Kohat University of Science and Technology, Kohat, Pakistan

Américo I. Torres Laboratorio de Oceanografía Química y Contaminación de Aguas, CESIMAR, CCT CONICET-CENPAT, Puerto Madryn, Chubut, Argentina

Virginia E. Villafañe Estación de Fotobiología Playa Unión, Chubut and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rawson, Argentina;
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

Juan I. Vizzo Estación de Fotobiología Playa Unión, Rawson, Chubut, Argentina; Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

Sten-Åke Wängberg Dept. Marine Sciences, University of Gothenburg, Gothenburg, Sweden

Liping Zhu Center for Advanced Low-Dimension Materials, State Key Laboratory for Modification of Chemical Fibers and Polymer Materials, Donghua University, Shanghai, China

Chapter 1
Introduction

Donat-P. Häder, E. Walter Helbling, and Virginia E. Villafañe

Abstract Aquatic ecosystems cover more than 70% of our planet. They produce about the same amount of biomass as all terrestrial ecosystems taken together, and they absorb about 90% of the anthropogenically produced heat. They take up a large amount of the emitted CO_2 and transport it to the deep ocean, thus curbing global climate change. Aquatic producers and consumers are under the effect of multiple stressors such as rising temperature, acidification and UV radiation. Pollution is a major stress factor affecting all aquatic ecosystems including fresh, coastal and open ocean waters. The main pollutants are oil spills, persistant organic pollutants, fertilizers and pharmaceuticals which reach the hydrosphere by terrestrial runoff. Toxic chemicals and heavy metals have long been dumped into the oceans affecting marine life such as invertebrates and vertebrates. A more recent advent is the growing pollution by microplastics.

Keywords Aquatic productivity · Ocean acidification · Solar UV radiation · Climate change · Ocean warming · Interactive effects · Pollutants · Stress factors

Even though water is the second most abundant molecule in the universe, the Earth is the only planet in the solar system to hold a considerable amount of water. About 70.7% are covered by water which corresponds to 361.2 million sq. km. Most of the water is concentrated in the oceans with a mean depth of 3617 m. Less than 1% of the available water represents liquid freshwater plus between 1.75 and 2% frozen in glaciers, ice and snow (Khyade and Swaminathan 2016). The aquatic ecosystems fix about 50–60 Pg carbon per year in the form of CO_2 from the atmosphere. This amount is equal to the uptake by all terrestrial ecosystems combined (Falkowski

D.-P. Häder (✉)
Department of Biology, Friedrich-Alexander Universität, 91054 Erlangen, Germany
e-mail: donat@dphaeder.de

E. W. Helbling · V. E. Villafañe
Estación de Fotobiología Playa Unión, Chubut and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Casilla de Correos No 15, 9103 Rawson, Argentina

D.-P. Häder et al. (eds.), *Anthropogenic Pollution of Aquatic Ecosystems*,
https://doi.org/10.1007/978-3-030-75602-4_1

2013) even though the standing crop of aquatic ecosystems is only about 1% of that of their terrestrial counterparts.

About 10% of the organic biomass produced in the process of photosynthesis sinks out of the photic zone into the deep sea in the form of dead organisms and fecal pellets which can be detected as marine snow (Laurenceau-Cornec et al. 2015). In addition, these pellets contain mineral forms of N and P as well as Ca, Mg and K. 99.5% of this organic material is mineralized by bacteria, and about 0.5% reaches the deep sea sediment. This removal of atmospheric carbon dioxide is called biological pump (Sigman and Haug 2006). The sinking velocity of the organic carbon is about 1 m per day, so that it may take more than 10 years to reach the ocean floor assuming an average depth of about 3600 m in the oceans. Formation of calcium carbonate shells of plankton such as coccolithophorids and foraminifera, animals such as worms and molluscs sequesters more CO_2 from the water column which also sediments to the deep seafloor; this process is called carbonate pump (Hain et al. 2014). The carbon which has reached the deep sea bottom will remain there for millions of years. With 36,000 million tons, this carbon reservoir is the largest on our planet.

1.1 The Aquatic Food Web

The main primary producers in aquatic habitats are phytoplankton which live in the photic zone. The lower limit is defined by the depth where 99% of the surface irradiance is absorbed. The top layer of the water column, that is in contact with the atmosphere, is called upper mixed layer (UML) in which most of the phytoplankton dwell. The lower boundary of the UML is the thermocline (pycnocline) below which the temperature abruptly drops and density increases. This stratification reduces the upwelling of nutrients from deeper layers into the UML (Fischer et al. 2017). Increasing temperatures fueled by global climate change augment the strength of the stratification and tend to diminish the depth of the UML. Organisms living in the UML are thus exposed to high solar visible and UV radiation. The global distribution of phytoplankton is not even, and the highest concentrations are found near the poles and coastal areas that hold the highest concentration of higher organisms in the food web such as fish and mammals. On the other hand, the central gyres of the oceans at mid-latitudes are deserts as can be visualized in pseudocolor images of the surface chlorophyll distribution (Fig. 1.1).

The growth of macroalgae is almost exclusively restricted to rocky shores of the oceans (with the notable exception of *Sargassum*) (Richmond and Stevens 2014). Algal beds and sea grass meadows are important habitats for larval invertebrates and vertebrates. Even though their productivity contributes only a fraction of that of phytoplankton, macroalgae provide a significant contribution of ecological and economic importance. Red, green and brown macroalgae can be either harvested in the wild or grown in aquaculture. They are used as food, fodder, fertilizer and biofuels (Seghetta et al. 2016; Mac Monagail et al. 2017). They are also a source of

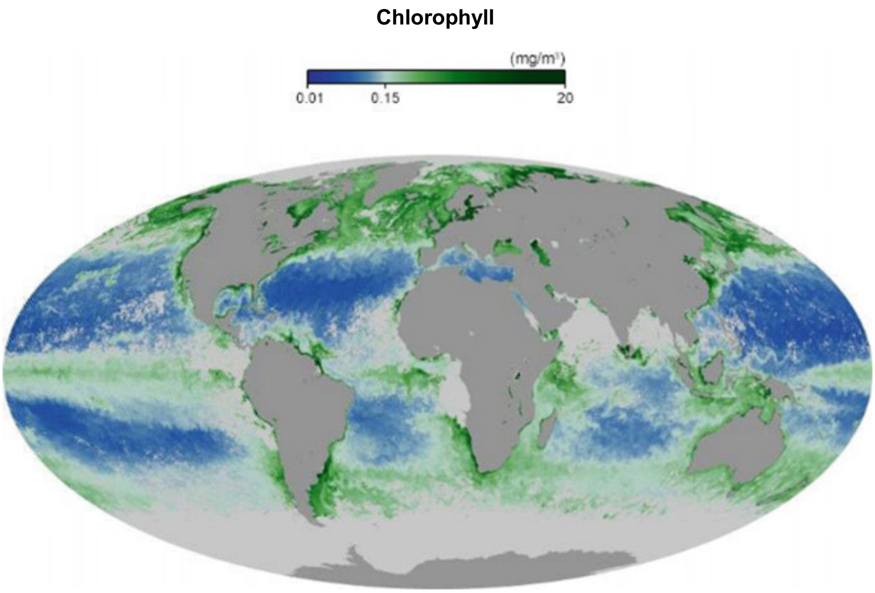

Fig. 1.1 Chlorophyll concentrations in the oceans as measured by satellite imaging in August 2020. Imagery produced by the Earth Observatory Group in coordination with Gene Feldman and Norman Kuring, NASA Goddard Ocean Color Group

polysaccharides, phycobiliproteins, mycosporine-like amino acids (Torres et al. 2019) and natural bioactive compounds for therapeutic uses (Ismail et al. 2020). Millions of tons are harvested every year for many technological applications (Konda et al. 2015; Garcia-Vaquero and Hayes 2016). Stress factors such as temperature and ocean acidification affect the algal communities and their interaction with grazers (Harley 2014; Sampaio et al. 2017). Terrestrial runoff carries dissolved organic matter (DOM) into coastal areas (Clark et al. 2016), changing the transparency and thus affecting the growth of macroalgae. In addition, increasing pollution by heavy metals, microplastics, fertilizers, fossil oil products as well as drugs and pharmaceuticals affect macroalgal species composition (Pinto 2015; Gubelit et al. 2016).

Prokaryotic and eukaryotic phytoplanktons as well as macroalgae and sea grasses form the basis of the branched marine food webs and feed the primary and secondary consumers (Hussey et al. 2014). These food webs are very dynamic and rapidly altered in response to changing environmental conditions and stress factors (Quillien et al. 2016; Ullah et al. 2018). Small changes in the assemblages of the primary producers can have considerable effects on the consumers. Increasing solar UV, higher temperatures and ocean acidification affect all elements in the marine food webs (Feister and Häder 2019; Gao et al. 2019).

1.2 Environmental Stress Factors

Since 1970, the atmospheric global temperatures have risen by 0.27 °C per decade, while the ocean surface temperatures have increased by 0.13 °C in the same time interval (Larson et al. 2020). This anthropogenic forcing has significant effects on the marine biota as evidenced, e.g., by massive coral bleaching (Sully et al. 2019) and increases in tropical cyclones and hurricanes (Halpern et al. 2008; Kossin et al. 2020). In addition, rising temperatures affect habitat selection and species composition of marine taxa (Thomas et al. 2012), such as diatoms and copepods (Jenkins and Black 2019), dinoflagellates (Brosnahan et al. 2020), coccolithophorids (Gafar et al. 2019) and cyanobacteria (Harada et al. 2019). Habitats defined by thermal niches will move toward the poles (Oziel et al. 2020); e.g., tropical radiolaria have been found in Arctic waters (http://earth.columbia.edu; Bjørklund et al. 2012), and in tropical phytoplankton species diversity declines (Thomas et al. 2012).

While the availability of CO_2 is essential for photosynthetic organisms, excessive concentrations are harmful and can be considered anthropogenic pollutants. Over the last millenium, the atmospheric CO_2 concentration has been relatively constant at about 270 ppm, but since the beginning of the Industrial Revolution around 1880, it steadily increased. Today, the carbon dioxide concentration in the atmosphere has risen to above 410 ppm (Boretti 2020). An increase to 650 ppm is considered as a red line, and passing it will increase the global temperature above the target of 2 °C (Knutti et al. 2016). Following a business-as-usual scenario in fossil fuel utilization will drive the atmospheric CO_2 concentration beyond 750 ppm by the end of the century (Santos et al. 2017).

The atmosphere and the water surface are in close equilibrium so that the oceans absorb CO_2 (Gill 2016) and take up about 25% of the anthropogenically emitted carbon dioxide (Gao et al. 2012b). The absorbed CO_2 forms carbonic acid with water which eventually dissociates into a carbonate ion and a proton which decreases the pH of the water causing ocean acidification (Doney et al. 2016).

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{1}$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^- \tag{2}$$

$$HCO_3^- \rightarrow H^+ + CO_3^{2-} \tag{3}$$

If the release of CO_2 into the atmosphere continues at the current rate, a pH drop is predicted by 0.3–0.4 units (Feely et al. 2004). Because the CO_2 availability is a bottleneck for photosynthesis, initially, it was assumed that any increase could augment productivity in aquatic primary producers. But detailed analysis gave inconsistent results (Gao and Campbell 2014). Some species indeed showed an increase in productivity, while others did not, and some even had a reduced growth rate at elevated CO_2 concentrations (Chen and Gao 2004; Kim 2006). In some diatoms, increased CO_2 levels augment growth and productivity (Low-Décarie et al. 2011; King et al. 2011). A study that compiled 69 experiments on ocean acidification (Bach and Taucher 2019) concluded that diatoms responded to high CO_2 in ca 60% of the studies, and from these almost 56% responded in a positive way (benefitted), while in 32% it had a negative impact. Ocean acidification can affect orientation and survival in fish larvae and reduce the fecundity of copepods (Siebeck et al. 2015; Thor and Dupont 2015). Thus, it may affect the community structure of phytoplankton populations with negative consequences for the food web.

Some green and red macroalgae have incrustations of $CaCO_3$ in their thallus, and some phytoplankton such as coccolithophorids and radiolaria have an exoskeleton of calcium carbonate (Marszalek 1975; Gao et al. 1993). Also, many zoological taxa, such as worms, mollusks, corals and cephalopods, have a calcified exo- or endoskeleton (Marin et al. 2012; Ries et al. 2009). Ocean acidification hampers the incorporation of calcium carbonate (Doney et al. 2016; Jokiel et al. 2016), and the organisms are exposed to higher solar UV radiation which is absorbed by the calcium carbonate skeleton (Gao et al. 2012a, b; Häder et al. 2015b).

Even though solar radiation is an essential requirement for all photosynthetic producers, excessive irradiances are a stress factor for the biota. In addition to extreme visible irradiances, high-energetic solar UV damages biomolecules, organelles, cells and organisms. UV-C radiation is quantitatively absorbed by oxygen and ozone in the atmosphere, and UV-B is strongly reduced by stratospheric and tropospheric ozone (Häder and Tevini 1987). In contrast, a large fraction of UV-A reaches the surface of the Earth (Steinbrecht et al. 2009). Anthropogenic release of chlorofluorocarbons (CFCs) and other trace gases catalytically damaged the stratospheric ozone layer resulting an increase in solar UV-B radiation starting in the late 1970s (Hoffmann et al. 2014). However, the ratification of the Montreal Protocol and its later amendments reversed this trend (Abbasi and Abbasi 2017), but because of the long lifetimes of the CFCs in the stratosphere, it is assumed that it will take half a century to reach pre-1980s values (Hoffmann et al. 2014). Climate change will affect future ozone depletion and solar UV levels (UNEP EEAP 2016).

UV-B radiation is absorbed by many biological targets such as proteins, lipids and membranes. It damages the DNA in organisms living in the photic zone and affects photosynthesis in primary producers which are exposed to solar radiation. Furthermore, it induces the production of reactive oxygen species when absorbed by cellular targets and organic matter in the water (Pallela 2014; Amado et al. 2015). Because of the shoaling of the UML, organisms experience higher UV radiation, even though the surface irradiance does not increase (Häder and Gao 2017; Gao and Häder 2017). Solar UV has been found to modify pollutants and often increase their toxicity such as crude oil products.

1.3 Aquatic Pollution

Given the fast-growing population, our species is not seriously protective of the limited resources on our planet (Campbell et al. 2017). Anthropogenic pollution of aquatic ecosystems threatens both the ecosystems and the dwindling food production in the oceans (Kirkman et al. 2020). Rather than recycling used materials, most end products are dumped either on land or at sea. Depositing excavated soil or material from torn-down buildings may not be seriously disastrous, but runoff from agricultural areas changes the ecostructure of coastal habitats and the food web (Myles 2017). Increasing concentrations of fertilizers and pesticides favor the expansion of marine dead zones with anoxic waters (Gattuso et al. 2018). Pharmaceuticals, drugs and household cleansers affect the coastal flora and fauna (Pariatamby and Bhatti 2020). Deliberate dumping of hazardous chemicals into the ocean results in biochemical and anatomical malformation and affects the size, growth and reproduction of invertebrates and vertebrates including sensitive fish species for human consumption (Clark et al. 2019). In addition, toxic materials such as heavy metals are waste products of industry which are accidentally or deliberately discarded into rivers and eventually reach a final destination in the oceans (Al Naggar et al. 2018).

Deposited arms and ammunition especially after the two world wars pose serious threats to the biota and human populations (Voie and Mariussen 2017). Nuclear wastes from power plants and warfare arsenal are difficult to dispose of, and many countries are still searching for safe and permanent repositories for radioactive materials. One periculous solution was found again by dumping the material in the oceans (Stolberg 2016). This strategy is also used to get rid of outdated space machinery such as satellites, rockets and spacecraft.

Of growing concern is the disposal of plastic debris which either reaches the oceans by riverine transport or by winds and littering of coastal areas. This material is broken down by mechanical forces of wind and waves augmented by solar UV radiation (Díaz-Mendoza et al. 2020). Since the resulting microplastics have very long lifetimes on the order of decades to centuries, it accumulates both floating in the oceanic gyres or in the sediments. It affects the biota since it is mistaken for food by plankton and invertebrates and is bioaccumulated in the food web. Many fish samples in species destined for human consumption have been found to contain microplastic debris (Barboza et al. 2018).

This volume covers the major groups of pollutants in aquatic ecosystems and draws the conclusions on the damaging effects for the biota covering the individual taxa and the food web.

References

Abbasi S, Abbasi T (2017) Monitoring ozone loss and its consequences: past, present, and future. Ozone Hole. Springer, New York, NY, pp 121–131

Al Naggar Y, Khalil MS, Ghorab MA (2018) Environmental pollution by heavy metals in the aquatic ecosystems of Egypt. Open Acc J Toxicol 3:555603

Amado AM, Cotner JB, Cory RM, Edhlund BL, McNeill K (2015) Disentangling the interactions between photochemical and bacterial degradation of dissolved organic matter: amino acids play a central role. Microb Ecol 69(3):554–566

Bach T, Taucher J (2019) CO_2 effects on diatoms: a synthesis of more than a decade of ocean acidification experiments with natural communities. Ocean Sci J 15:1159–1175

Barboza LGA, Vethaak AD, Lavorante BR, Lundebye A-K, Guilhermino L (2018) Marine microplastic debris: an emerging issue for food security, food safety and human health. Mar Pollut Bull 133:336–348

Bjørklund KR, Kruglikova SB, Anderson OR (2012) Modern incursions of tropical radiolaria into the Arctic Ocean. J Micropalaeontology 31:139–158

Boretti A (2020) Covid 19 impact on atmospheric CO_2 concentration. Int J Glob Warming 21 (3):317–323

Brosnahan ML, Fischer AD, Lopez CB, Moore SK, Anderson DM (2020) Cyst-forming dinoflagellates in a warming climate. Harmful Algae 91:101728

Campbell BM, Beare DJ, Bennett EM, Hall-Spencer JM, Ingram JS, Jaramillo F, Ortiz R, Ramankutty N, Sayer JA, Shindell D (2017) Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecol Soc 22(4)

Chen X, Gao K (2004) Characterization of diurnal photosynthetic rhythms in the marine diatom *Skeletonema costatum* grown in synchronous culture under ambient and elevated CO_2. Funct Plant Biol 31(4):399–404

Clark CD, De Bruyn WJ, Aiona PD (2016) Temporal variation in optical properties of chromophoric dissolved organic matter (CDOM) in Southern California coastal waters with nearshore kelp and seagrass. Limnol Oceanogr 61(1):32–46

Clark B, Longo SB, Clausen R, Auerbach D (2019) From sea slaves to slime lines: commodification and unequal ecological exchange in global marine fisheries. In: Ecologically Unequal Exchange. Springer, pp 195–219

Díaz-Mendoza C, Mouthon-Bello J, Pérez-Herrera NL, Escobar-Díaz SM (2020) Plastics and microplastics, effects on marine coastal areas: a review. Environ Sci Pollut Res:1–10

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2016) Ocean acidification: the other CO_2 problem. Wash J Envtl L Pol'y 6:213

Falkowski P (2013) Primary productivity in the sea, vol 19. Springer Science & Business Media

Feely RA, Sabine CL, Lee K, Berelson W, Kleypas J, Fabry VJ, Millero FJ (2004) Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. Science 305(5682):362–366

Feister U, Häder D-P (2019) Solar UV radiation and penetration into water. In: Häder D-P, Gao K (eds) Aquatic Ecosystems in a Changing Climate. Taylor & Francis Group, Boca Raton, pp 12–31

Fischer CJ, Zhang J-Z, Baringer MO (2017) An estimate of diapycnal nutrient fluxes to the euphotic zone in the Florida Straits. Sci Reports 7:16098

Gafar N, Eyre B, Schulz K (2019) Particulate inorganic to organic carbon production as a predictor for coccolithophorid sensitivity to ongoing ocean acidification. Limnol Oceanogr Lett 4(3):62–70

Gao K, Campbell D (2014) Photophysiological responses of marine diatoms to elevated CO_2 and decreased pH: a review. Func Plant Biol 41:449–459. https://doi.org/10.1071/fp13247

Gao K, Häder D-P (2017) Effects of ocean acidification and UV radiation on marine photosynthetic carbon fixation. In: Kumar M, Ralph PJ (eds) Systems biology of marine ecosystems. Springer, Cham, Switzerland, pp 235–250

Gao K, Aruga Y, Asada K, Ishihara T, Akano T, Kiyohara M (1993) Calcification in the articulated coralline alga *Corallina pilulifera*, with special reference to the effect of elevated CO_2 concentration. Mar Biol 117:129–132

Gao K, Helbling EW, Häder D-P, Hutchins DA (2012a) Responses of marine primary producers to interactions between ocean acidification, solar radiation, and warming. Mar Ecol Prog Ser 470:167–189

Gao KS, Xu JT, Gao G, Li YH, Hutchins DA, Huang BQ, Wang L, Zheng Y, Jin P, Cai XN, Häder DP, Li W, Xu K, Liu NN, Riebesell U (2012b) Rising CO_2 and increased light exposure synergistically reduce marine primary productivity. Nat Clim Change 2(7):519–523. https://doi.org/10.1038/nclimate1507

Gao K, Beardall J, Häder DP, Hall-Spencer JM, Gao G, Hutchins DA (2019) Effects of ocean acidification on marine photosynthetic organisms under the concurrent influences of warming, UV radiation and deoxygenation. Front Mar Sci 6:322

Garcia-Vaquero M, Hayes M (2016) Red and green macroalgae for fish and animal feed and human functional food development. Food Rev Int 32(1):15–45

Gattuso J-P, Magnan AK, Bopp L, Cheung WW, Duarte CM, Hinkel J, Mcleod E, Micheli F, Oschlies A, Williamson P (2018) Ocean solutions to address climate change and its effects on marine ecosystems. Front Mar Sci 5:337

Gill AE (2016) Atmosphere—ocean dynamics. Elsevier

Gubelit Y, Polyak Y, Dembska G, Pazikowska-Sapota G, Zegarowski L, Kochura D, Krivorotov D, Podgornaya E, Burova O, Maazouzi C (2016) Nutrient and metal pollution of the eastern Gulf of Finland coastline: Sediments, macroalgae, microbiota. Sci Total Environ 550:806–819

Häder D-P, Gao K (2017) The impacts of climate change on marine phytoplankton. In: Phillips BF, Pérez-Ramírez M (eds) Climate change impacts on fisheries and aquaculture. A global analysis, vol 2. Wiley, Hoboken, NJ, pp 901–928

Häder D-P, Horneck G (2018) Bioassays for solar UV radiation. In: Häder D-P, Erzinger GS (eds) Bioassays. Advanced methods and applications. Elsevier, Atlanta, GA, pp 331–346

Häder D-P, Tevini M (1987) General photobiology. Pergamon, Oxford, UK

Häder D-P, Williamson CE, Wängberg S-Å, Rautio M, Rose KC, Gao K, Helbling EW, Sinha RP, Worrest R (2015b) Effects of UV radiation on aquatic ecosystems and interactions with other environmental factors. Photochem Photobiol Sci 14(1):108–126

Hain MP, Sigmal D, Haug GH (2014) The biological pump in the past. Reference module in earth systems and environmental sciences, treatise on geochemistry (2nd edn). The oceans and marine geochemistry, vol 8. Elsevier, The Netherlands, pp 485–517

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE (2008) A global map of human impact on marine ecosystems. Science 319 (5865):948–952

Harada M, Nagano A, Yagi S, Furukawa R, Yokobori S-i, Yamagishi A (2019) Planktonic adaptive evolution to the sea surface temperature in the Neoproterozoic inferred from ancestral NDK of marine cyanobacteria. Earth Planet Sci Lett 522:98–106

Harley C (2014) Seaweed responses to climate change: predictions, observations, and knowledge gaps. In: Salish sea ecosystem conference

Hoffmann L, Hoppe C, Müller R, Dutton G, Gille J, Griessbach S, Jones A, Meyer C, Spang R, Volk C (2014) Stratospheric lifetime ratio of CFC-11 and CFC-12 from satellite and model climatologies. Atmos Chem Phys 14(22):12479–12497

http://earth.columbia.edu, http://earth.columbia.edu/articles/view/2993

Hussey NE, MacNeil MA, McMeans BC, Olin JA, Dudley SF, Cliff G, Wintner SP, Fennessy ST, Fisk AT (2014) Rescaling the trophic structure of marine food webs. Ecol Lett 17(2):239–250

Ismail MM, Alotaibi BS, El-Sheekh MM (2020) Therapeutic uses of red macroalgae. Molecules 25(19):4411

Jenkins GP, Black KP (2019) Contrasting impact of diatoms on dominant calanoid and cyclopoid copepods in a temperate bay. Estuar Coast Shelf Sci 217:211–217

Jokiel PL, Jury CP, Kuffner IB (2016) Coral calcification and ocean acidification. In: Hubbard D, Rogers C, Lipps J, Stanley JG (eds) Coral reefs at the crossroads. Coral reefs of the world, vol 8. Springer, Dordrecht, pp 7–45

Khyade VB, Swaminathan MS (2016) Water: the pacemaker for life of Earth. World Sci News 44:93–125

Kim J-H (2006) The effect of seawater CO_2 concentration on growth of a natural phytoplankton assemblage in a controlled mesocosm experiment. Limnol Oceanogr 51:1629–1636

King AL, Sanudo-Wilhelmy SA, Leblanc K, Hutchins DA, Fu F (2011) CO_2 and vitamin B_{12} interactions determine bioactive trace metal requirements of a subarctic Pacific diatom. The ISME J 5(8):1388–1396

Kirkman SP, Baliwe NG, Nhleko J, Pfaff MC (2020) Ecosystem health and human wealth–a comparison of sub-Saharan African large marine ecosystems. Environ Dev:100551

Knutti R, Rogelj J, Sedláček J, Fischer EM (2016) A scientific critique of the two-degree climate change target. Nat Geosci 9(1):13–18

Konda NM, Singh S, Simmons BA, Klein-Marcuschamer D (2015) An investigation on the economic feasibility of macroalgae as a potential feedstock for biorefineries. BioEnergy Res 8 (3):1046–1056

Kossin JP, Knapp KR, Olander TL, Velden CS (2020) Global increase in major tropical cyclone exceedance probability over the past four decades. Proc Nat Acad Sci USA 117(22):11975–11980

Larson E, Portmann R, Solomon S, Murphy D (2020) Decadal attribution of historic temperature and ocean heat content change to anthropogenic emissions. Geophys Res Lett 47(3): e2019GL085905

Laurenceau-Cornec EC, Trull T, Davies DM, Bray SG, Doran J, Planchon F, Carlotti F, Jouander M, Cavagna A-J, Waite A (2015) The relative importance of phytoplankton aggregates and zooplankton fecal pellets to carbon export: insights from free-drifting sediment trap deployments in naturally iron-fertilised waters near the Kerguelen Plateau. Biogeosciences 12:1007–1027

Low-Décarie E, Fussmann GF, Bell G (2011) The effect of elevated CO_2 on growth and competition in experimental phytoplankton communities. Glob Change Biol 17(8):2525–2535

Mac Monagail M, Cornish L, Morrison L, Araújo R, Critchley AT (2017) Sustainable harvesting of wild seaweed resources. Eur J Phycol 52(4):371–390

Marin F, Le Roy N, Marie B (2012) The formation and mineralization of mollusk shell. Front Biosci 4(1099):125

Marszalek D (1975) Calcisphere ultrastructure and skeletal aragonite from the alga *Acetabularia antillana*. J Sediment Res 45(1)

Myles PB (2017) Maritime clusters and the ocean economy: an integrated approach to managing coastal and marine space. Routledge

Oziel L, Baudena A, Ardyna M, Massicotte P, Randelhoff A, Sallée J-B, Ingvaldsen RB, Devred E, Babin M (2020) Faster Atlantic currents drive poleward expansion of temperate phytoplankton in the Arctic Ocean. Nat Commun 11(1):1–8

Pallela R (2014) Antioxidants from marine organisms and skin care. In: Laher I (ed) Systems biology of free radicals and antioxidants. Springer, Berlin, Heidelberg, pp 3771–3783

Pariatamby A, Bhatti MS (2020) Waste management challenges in Malaysia. In: Sustainable waste management challenges in developing countries. IGI Global, pp 186–222

Pinto MIA (2015) Pesticides in water, sediments and biota of semi-closed coastal lagoons: sources, pathways and impact on aquatic organisms. Universidade Nova

Quillien N, Nordström MC, Schaal G, Bonsdorff E, Grall J (2016) Opportunistic basal resource simplifies food web structure and functioning of a highly dynamic marine environment. J Exp Mar Biol Ecol 477:92–102

Richmond S, Stevens T (2014) Classifying benthic biotopes on sub-tropical continental shelf reefs: how useful are abiotic surrogates? Estuar Coast Shelf Sci 138:79–89

Ries JB, Cohen AL, McCorkle DC (2009) Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. Geology 37(12):1131–1134

Sampaio E, Rodil IF, Vaz-Pinto F, Fernández A, Arenas F (2017) Interaction strength between different grazers and macroalgae mediated by ocean acidification over warming gradients. Mar Environ Res 125:25–33

Santos J, Cesarin A, Sales C, Triano M, Martins P, Braga A, Neto N, Barroso A, Alves P, Huaman C (2017) Increase of atmosphere CO_2 concentration and its effects on culture/weed interaction. World Academy of Science EaT. Int J Biol Biomol Agri Food Biotechnol Eng 11:419–426

Seghetta M, Hou X, Bastianoni S, Bjerre A-B, Thomsen M (2016) Life cycle assessment of macroalgal biorefinery for the production of ethanol, proteins and fertilizers–a step towards a regenerative bioeconomy. J Clean Prod 137:1158–1169

Siebeck UE, O'Connor J, Braun C, Leis JM (2015) Do human activities influence survival and orientation abilities of larval fishes in the ocean?. Integr Zool 10(1):65–82

Sigman DM, Haug GH (2006) The biological pump in the past. Treatise on geochemistry, vol 6. Pergamon Press, New York, pp 491–528

Steinbrecht W, Claude H, Schönenborn F, McDermid IS, Leblanc T, Godin-Beekman S, Keckhut P, Hauchecorne A, van Gijsel JAE, Swart DPJ, Bodeker GE, Parrish A, Boyd IS, Kämpfer N, Hocke K, Stolarski R, Frith SM, Thomason LW, Remsberg EE, von Savigny C, Rozanov A, Burrows JP (2009) Ozone and temperature trends in the upper stratosphere at five stations of the network for the detection of atmospheric composition change. Int J Remote Sens 30(15–16):1989–2009

Stolberg E-M (2016) 'From icy backwater to nuclear waste ground': the Russian Arctic ocean in the twentieth century. In: Sea narratives: cultural responses to the sea, 1600–present. Springer, pp 111–137

Sully S, Burkepile D, Donovan M, Hodgson G, Van Woesik R (2019) A global analysis of coral bleaching over the past two decades. Nat Commun 10(1):1–5

Thomas MK, Kremer CT, Klausmeier CA, Litchman E (2012) A global pattern of thermal adaptation in marine phytoplankton. Science 338(6110):1085–1088

Thor P, Dupont S (2015) Transgenerational effects alleviate severe fecundity loss during ocean acidification in a ubiquitous planktonic copepod. Glob Change Biol 21(6):2261–2271

Torres MD, Flórez-Fernández N, Domínguez H (2019) Integral utilization of red seaweed for bioactive production. Marine Drugs 17(6):314

Ullah H, Nagelkerken I, Goldenberg SU, Fordham DA (2018) Climate change could drive marine food web collapse through altered trophic flows and cyanobacterial proliferation. PLoS Biol 16 (1):e2003446

UNEP EEAP (2016) Environmental effects of ozone depletion and its interactions with climate change: progress report, 2015. Photochem Photobiol Sci 15(2):141–174. https://doi.org/10.1039/c6pp90004f

Voie ØA, Mariussen E (2017) Risk assessment of sea dumped conventional munitions. Propellants, Explos, Pyrotech 42(1):98–105

Chapter 2
Pollution Affecting Cyanobacteria in Aquatic Habitats

Abha Pandey, Sonal Mishra, Neha Kumari, Vidya Singh, and Rajeshwar P. Sinha

Abstract Aquatic ecosystems comprise the largest portion (∼72%) of the biosphere and play a crucial role in stabilizing the global climate as well as providing a large array of services for a fast-growing human population. Nowadays, there is a growing amount of data that prove that many anthropogenic pollutants from agricultural, urban and industrial wastes are dumped in the aquatic ecosystems and accumulate in many environments, including the habitats of marine and freshwater cyanobacteria. Cyanobacteria, as a natural part of phytoplankton assemblages, are known for their role as dominant primary producers and base of aquatic food webs. These microorganisms are continuously exposed to various concentrations of the pollutants that are present in their habitats and affect cyanobacterial communities at different levels such as abundance, growth strategies, succession patterns and dominance. Even if no direct changes in cyanobacterial communities are visible, the pollutants may accumulate in cyanobacteria and be passed onto higher trophic levels in a cascading manner, resulting in biomagnifications of certain pollutants. The most common pollutants in aquatic ecosystems are heavy metals, herbicides, pesticides, nutrients, pharmaceuticals, polycyclic aromatic hydrocarbons and microplastics. It is important to determine their concentrations in cyanobacterial cells and in their environment to know the possibility of contaminants that might be transferred to higher trophic levels. However, some strains of cyanobacteria are capable of metabolizing these pollutants that makes them less toxic or sometimes they even remove pollutants from the environment. This chapter highlights the toxic effects of different types of pollution (both point sources and non-point sources) on cyanobacterial communities in aquatic habitats. The anthropocentric concept of "pollution" and the links between pollution, eutrophication and harmful algal blooms (HABs) are also analyzed. An understanding of the synergistic interactions between these aspects and climate change effects will be useful to devise suitable remediation strategies for future use.

A. Pandey · S. Mishra · N. Kumari · V. Singh · R. P. Sinha (✉)
Laboratory of Photobiology and Molecular Microbiology, Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi 221005, India

D.-P. Häder et al. (eds.), *Anthropogenic Pollution of Aquatic Ecosystems*,
https://doi.org/10.1007/978-3-030-75602-4_2

Keywords Aquatic ecosystems · Cyanobacteria · Eutrophication · Heavy metal · Pollutants

2.1 Introduction

Cyanobacteria are ubiquitous across various environments ranging from terrestrial to aquatic ecosystems. An aquatic environment can be classified into two major divisions—freshwater environment and marine environment based on salinity. Cyanobacteria are prevalently found in both these types of aquatic environments and contributing to ecosystem-level processes by playing a major role in the biogeochemical cycle. Marine environments consist of approximately 71% of the Earth’s surface and are made up of oceans, estuaries, coral reefs and coastal ecosystems, whereas freshwater ecosystems cover less than 1% of the Earth's surface and are comprised of lentic, lotic, river water, lakes, aquifers and wetland ecosystems. Together these environments are responsible for 50% of the world's net primary production (Alexander and Fairbridge 1999). Even though the standing crop of aquatic primary producers is only about 1% when compared to that of primary producers from terrestrial ecosystems, the former rival their terrestrial counterparts in producing 50% of the biomass, incorporating 50% of the anthropogenically released CO_2 and being responsible for 50% of the oxygen emission on this planet (Longhurst et al. 1995; Rousseaux and Gregg 2014). About 90% of anthropogenically released CO_2 is taken up by the oceans (Reid and Hill 2016) and by funneling excess CO_2 to the deep-sea sediments via the biological pump they help to mitigate global change (Hain et al. 2014).

Aquatic ecosystems are exploited to provide food, transportation and recreation. Marine ecosystems also provide ingredients for fertilizers, additives and cosmetics, whereas freshwater ecosystems are utilized to provide water for drinking, sanitation and agricultural and industrial uses. Anthropogenic activities have also a severe impact on aquatic ecosystems, which are also increasingly affected by global change, urban and tourism developments and the unsustainable exploitation of aquatic resources. Pollution of water bodies from agricultural, industrial and urban runoffs and waste disposal threatens the supply of clean drinking water and has negative impacts on marine and freshwater organisms (Beiras 2018; Verhougstraete et al. 2015). Pollution in aquatic habitats may inhibit cyanobacterial growth (Fig. 2.1). Coastal areas make up approximately 7% of marine environments, but due to their high primary productivity, they provide over 50% of food for oceanic ecosystems (Alexander and Fairbridge 1999). However, they are also highly impacted by pollutants. The aquatic environment is contaminated by a variety of synthetic compounds due to anthropogenic discharges like chemical and industrial processes. For example, organic loads can enter riverine or estuarine water, thereby altering the organic pool, and affect degradation processes undertaken by in situ aquatic microbial communities. Microbial communities are affected by various chemicals that are used in industries as they are discharged in the aquatic ecosystem. Many chemical compounds used for industrial enterprises are usually toxic and persistent, but microbial communities are capable of degrading these toxic chemical compounds. The extent of degradation of these chemical compounds by microbes is influenced by the physical and chemical factors persisting in the aquatic systems. For example, aquatic contaminants of hydrophobic nature can result in physical portioning by interacting with dissolved organic matter and particulate organic matter present in the water column (Akkanen et al. 2004; Lin et al. 2003) resulting in a closer association of susceptible substrate and the microbial communities participating in the degradation of chemical compounds. However, partitioning can also result in the concentration of the contaminant to toxic levels, thus leading to suppression of microbes-mediated biodegradation processes, and this can ultimately affect overall biological communities in an aquatic ecosystem.

Cyanobacteria are one of the largest, extremely diverse, phylogenetically oldest lineages and have continuously existed in the biosphere of the Earth for billions of years. These organisms increased the oxygen concentration in the Earth's atmosphere and changed the atmosphere toward the oxygen-based life. Cyanobacteria are Gram-negative prokaryotes, and together with bacteria, they were among the first organisms capable of converting solar light energy into chemical bond energy by managing the flow of electrons in specifically adapted photosystems. They have a unique property of photosynthesis in the whole plant kingdom according to the endosymbiosis theory. Cyanobacteria are found in marine and freshwater environments and form a disparate polyphyletic group of unicellular or simple multicellular microorganisms. These organisms can also be found in several terrestrial habitats, encompassing caves, rocks and soil and therefore are recurrently exposed to varying natural and anthropogenic stressors. Cyanobacteria have evolved various

Fig. 2.1 Pollution-driven inhibition of cyanobacterial growth in a large Kund (water body) in Varanasi, India (Photograph by S. Mishra)

sensory mechanisms and adaptive systems to overcome changes occurring in the environment in which they are present.

This chapter focuses on pollutants that routinely enter freshwater and marine environments and attempts to decipher the effects of different types of pollution on cyanobacteria. Furthermore, many mechanisms that let the cyanobacterial species to survive in harsh conditions are emphasized in the context of the presence of chemical pollutants (concerning their determination) in cyanobacterial habitats and inside cells, due to the disquieting transfer of these substances to higher trophic levels.

2.2 Effects of Atmospheric Trace Gases and Pollutants on Cyanobacteria

2.2.1 Atmospheric Carbon Dioxide

Cyanobacteria contribute significantly to the equilibrium of the Earth's atmosphere by absorbing carbon dioxide and producing oxygen. The CO_2 absorbs strongly in the infrared region of the electromagnetic spectrum and thus involved in the greenhouse effect. The increasing concentration of atmospheric CO_2 and high temperature affect the growth of several photosynthetic organisms. At present, the global efforts are conducted toward reducing the production, increasing the utilization of CO_2 and sequestering of carbon in living biomass and soils (Wang and Hsieh 2002). The photosynthetic rate and growth of cyanobacteria are altered by the concentration of CO_2. It has been reported that cyanobacteria have a great potential for CO_2 fixation (Hanagata et al. 1992). Fogg and Than-Tun (1960) reported that 5% CO_2 was toxic for *Anabaena cylindrica*. The supply of an increased level of CO_2 enhances the biomass production of algae to a certain extent. The survival of cyanobacteria depends on their ability to acclimate to environmental changes.

Global warming increases the surface temperature. Environmental parameters such as temperature and pH affect cyanobacterial growth. Mishra et al. (2019a) observed the effect of temperature and pH on cyanobacteria. At high temperature (>32 °C) and low pH (<6.5), the solubility of O_2 decreases and with heavy metals in aquatic habitats increases which is responsible for increasing toxicity and ultimately death of organisms (Fig. 2.2). Staal et al. (2003) have reported that a high temperature had negatively impacted the N_2-fixing heterocystous cyanobacteria in the tropical oceans. Idso et al. (1989) observed a similar effect of CO_2 enrichment in *Azolla*, a fern harboring a cyanobacterium, *Anabaena azollae*. Strother (2008) suggested that there was a continuous procurement of carbon concentration mechanisms that is required for inorganic carbon uptake by the anabolic physiology of cyanobacteria and algae.

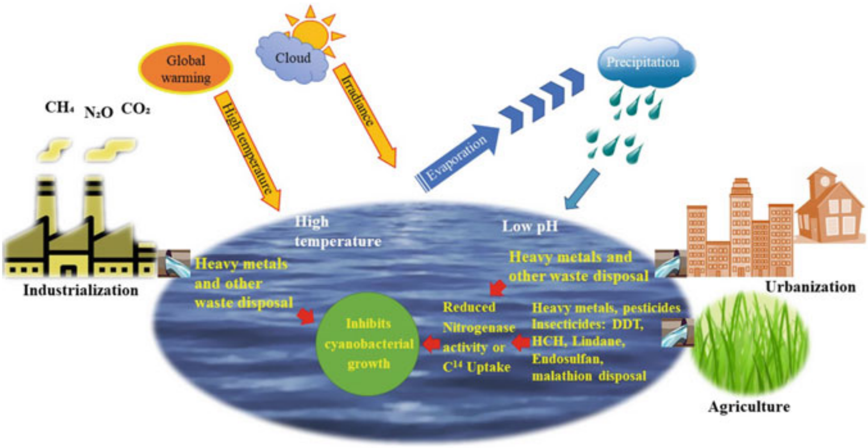

Fig. 2.2 Schematic illustration depicting the waste disposal of heavy metals, pesticides, insecticides (DDT, HCH, lindane, endosulfan, malathion) and other pollutants through industrialization, urbanization and agricultural process. These disposals inhibit cyanobacterial growth by reducing the nitrogenase activity or carbon uptake. Ozone depleting gases (e.g., CO_2, N_2O, CH_4) emanating from industries are responsible for global climate change or global warming and are also responsible for the decrease in pH through acidification by CO_2. Under these conditions, heavy metals become more soluble in aquatic habitat and inhibit cyanobacterial growth

2.2.2 Atmospheric Oxygen

Walker (1984) suggested that initially, Earth's atmosphere was anaerobic until the evolution of a form of photosynthesis that was able to utilize water as a reductant. The climatic devastation of glaciations and consequent changes in atmospheric composition lead to a major biological revolution in 3.0–2.7 Ga, characterized by the emergence of new low-temperature adapted taxa cyanobacteria (Lowe and Tice 2007). Cyanobacteria increased the atmospheric oxygen (O_2) from zero to the present 0.2 atmospheres. Water blooms are formed in several fish ponds where cyanobacteria are the major part of phytoplanktonic biomass that results in massive mortality among the fish due to the depletion of O_2 after the bloom collapses (Sevrin-Reyssac and Pletikosic 1990). Hirata et al. (2003) reported that the production of a violet pigment was increased by the cultivation of *Nostoc spongiaeforme* TISTR 8169 with 1 or 2 mM of H_2O_2. Oxidative stress, higher temperature and more intense light are responsible for the synthesis of Nostocine A that generate toxic reactive oxygen species in the cells of target organisms. The reactive oxygen species were involved in the oxidative damage of the cyanobacterium *Anabaena* sp. and *Nostoc* sp. caused by UV-B radiation (He and Häder 2002; Pandey et al. 2020).

Holzinger and Lütz (2006) and Björn (2007) reviewed the UV effects on cyanobacteria including the destruction in chloroplasts and mitochondria and the occurrence of structures that were likely to be related to the UV stress. Wang et al. (2008) showed that the photosynthetic activity is decreased and lipid peroxidation is enhanced in a desert cyanobacterium (*Nostoc* sp.) by UV-B radiation. The exogenous supply of antioxidants such as ascorbate acid and N-acetylcysteine had protective effects on cells of *Nostoc* sp. directly against reactive oxygen species initiated by UV-B radiation, as did sodium nitroprusside, which served as a signal molecule in the formation of algal cell protection of Photosystem II and as a reactive oxygen species scavenger. Sinha and Häder (2008) suggested that the synthesis of UV-absorbing/screening compounds such as mycosporine-like amino acids (MAAs) and scytonemin is involved in the prevention of UV-induced photodamage by absorbing UV-A and/or UV-B.

2.3 Effects of Organic Pollutants on Cyanobacteria

Many cyanobacterial species are sensitive to organochlorine chemicals, and the effects depend on the type and nature of the chemicals, the organisms and the environmental conditions. Most common organic pollutants are based on aliphatic, alicyclic or aromatic structures and most of the organic carbon accessible to microorganisms. In the environment, the majority of organic carbons available to microorganisms are photosynthetically fixed carbon compounds. Hence, several man-made organic chemicals resembling naturally occurring organic carbon can be easily degraded. However, the man-made chemicals may change the carrying capacity of the environment (i.e., the maximum level of microbial activity that can be expected under a particular environmental condition). Organic pesticides are a series of diverse chemical compounds used to control major pests, but their inappropriate application may affect non-target organisms like cyanobacteria.

2.3.1 Organochlorine Insecticides

Organochlorines are carbon-based substances that have one or more chlorine atoms. In these compounds, chlorine is highly reactive, and many organochlorines persist for a longer period in the environment after their initial use, and they are readily stored in fatty tissues and can bioaccumulate through the aquatic food chain.

2.3.1.1 DDT

Among the organic contaminants of great concern, the persistent organochlorine insecticide, DDT (1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane) and its principal metabolites, DDE (1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethylene) and DDD (1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethane) are most widely distributed in the environment worldwide, despite its poor water solubility. The commercial use of DDT was banned four decades ago, although they exist for a long time in several parts of the world. Lal et al. (1987a) reported that DDT hampered the growth of *Anabaena* sp. but stimulated the growth of *Aulosira* sp. When these organisms were treated for 35 days, then they recovered from the toxic effect. Photosynthesis in *Anabaena* sp. and *Aulosira* sp. was inhibited at all concentrations of DDT. In another report, Lal et al. (1987b) also observed that *Anabaena* sp. and *Aulosira fertilissima* showed a remarkable potential to accumulate DDT. The bioconcentration of DDT in *Anabaena* sp. and *A. fertilissima* varied from 3 to 1568 μg g^{-1} and from 6 to 1429 μg g^{-1}, respectively. Additionally, *Anabaena* sp. and *A. fertilissima* metabolized DDT to DDD as a major metabolite and DDE as a minor metabolite.

2.3.1.2 HCH

The isomeric mixture of HCH (1,2,3,4,5,6-hexachlorocyclohexane) is a first-generation organochlorine insecticide used widely in agriculture and public health. γ-HCH (lindane) is the most common insecticide among the isomers. HCH wastes that are generated during the production of lindane contain more than 85% of non-insecticidal isomers. Although HCH is known to be less persistent than DDT, HCH isomers persist in the soil and water at heavily contaminated sites after receiving wastes for a long time near the production sites. The use of the commercial formulation (isomeric mixture) of HCH has been banned or restricted in many countries due to the biomagnification of HCH isomers in the food chain. The concentrations of α-and γ-hexachlorocyclohexane were found to be high in the northern waters in the Arctic Ocean due to lower water temperature that reduced its transport to the atmosphere. However, the levels of heavy metals, alkanes, polyaromatic hydrocarbons (PAH) and organochlorines in northern waters were comparable to those in uncontaminated ocean waters in the mid-latitudes (Muir et al. 1992). The bioaccumulation of organochlorines and heavy metals in Arctic marine food chains begins with exotic ice algae or phytoplankton in surface waters. In the trophic compartments of Mar Menor, an oligotrophic coastal lagoon located in Spain, residues of organochlorine insecticides and/or any of their analyzed metabolites were detected in 70.5% of the total of 78 samples of water, sediment and benthic organisms, albeit at small concentrations. Among the detected compounds, HCH stood out second (47.4%) to endosulfan (51.3%) in the analyzed samples (Pérez-Ruzafa et al. 2000). Lindane acts as an insecticide, acaricide and rodenticide. Due to biomagnification of β-isomer, the isomeric mixture of HCH formulations has been banned in most countries, but lindane is used in some countries. Because cyanobacteria are a primary base of the aquatic food web and act as an important biofertilizer for rice cultivation, their protection from the grazers or tolerance to residual effects of toxicants is necessary for the enrichment of soil fertility. In 1983, Grant and coworkers examined the potential of lindane to control ostracods grazing on blue-green algae that play a major role in nitrogen fixation in flooded rice soils. An inhibition in the biomass production and the photosynthetic rate was seen in *Anabaena* sp. exposed to different concentrations (0.5, 1.0, 1.5, and 2.0 μg mL^{-1}) of lindane (Babu et al. 2001). The cyanobacterial species capable of controlling pollution were found in freshwater ecosystems like the Egyptian Lakes Qaroun and Mariut, as some species showed toxicity or stimulation due to lindane (5 and 10 μg mL^{-1}) resulting from agricultural runoff (El-Bestawy et al. 2007).

2.3.1.3 Endosulfan

The toxic forms of endosulfan (6,7,8,10,10-hexachloro-1,5,51,6,9,9-hexahydro-6,9-methano-2,4,3-benzadioxathiepin 3-oxide) are α or β endosulfan and endosulfan sulfate. Endosulfan applied to non-flooded soils at levels close to the recommended rates resulted in an increment of the total population of cyanobacteria (Muralikrishna and Venkateswarlu 1984). Endosulfan has an adverse effect on the growth of *Anabaena* sp. and *A. fertilissima* even at 1 μg mL^{-1} with inhibition being significantly above 50% at 20 μg mL^{-1} (Tandon et al. 1988). The application of 20 μg mL^{-1} endosulfan caused filaments clumping in *A. fertilissima* and also lowered ^{14}C uptake and nitrogenase activities. However, the amounts of ethylene produced from acetylene used for an indirect assay of nitrogen fixation were equal to or above control levels and did not affect the nitrogen fixation (Tandon et al. 1988). Endosulfan or endosulfan sulfate chemicals eliminated *Gloeocapsa* sp. and *Nostoc* sp. in non-flooded as well as flooded conditions. In an earlier study, *Anabaena* sp. has been shown to degrade endosulfan, but endosulfan sulfate was not detected in this case (Shivaramaiah 2000). The stress responses in terms of oxidative stress, the role of proline and antioxidant enzymes involved in free radical detoxification in three cyanobacterial strains (viz., *A. fertilissima*, *Anabaena variabilis* and *Nostoc muscorum*) exposed to endosulfan were studied (Kumar et al. 2008). The growth, photosynthetic pigments and carbohydrate contents were reduced, while the total protein, proline, malondialdehyde, superoxide dismutase, ascorbate peroxidase and catalase were increased at higher doses of endosulfan while photosynthetic pigments were enhanced at a lower concentration of endosulfan. This increased level of malondialdehyde indicates that free radicals, catalase, ascorbate peroxidase, superoxide dismutase and proline were involved in the free radical-scavenging mechanism.

2.3.2 Organophosphorus Insecticides

2.3.2.1 Monocrotophos and Quinalphos

Monocrotophos was toxic to *Nostoc linckia* at 100 μg mL^{-1} and to *Phormidium tenue* at 50 and 100 μg mL^{-1}, while the growth of these two cyanobacteria was enhanced at a lower concentration (Megharaj et al. 1987). Rajendran et al. (2007)