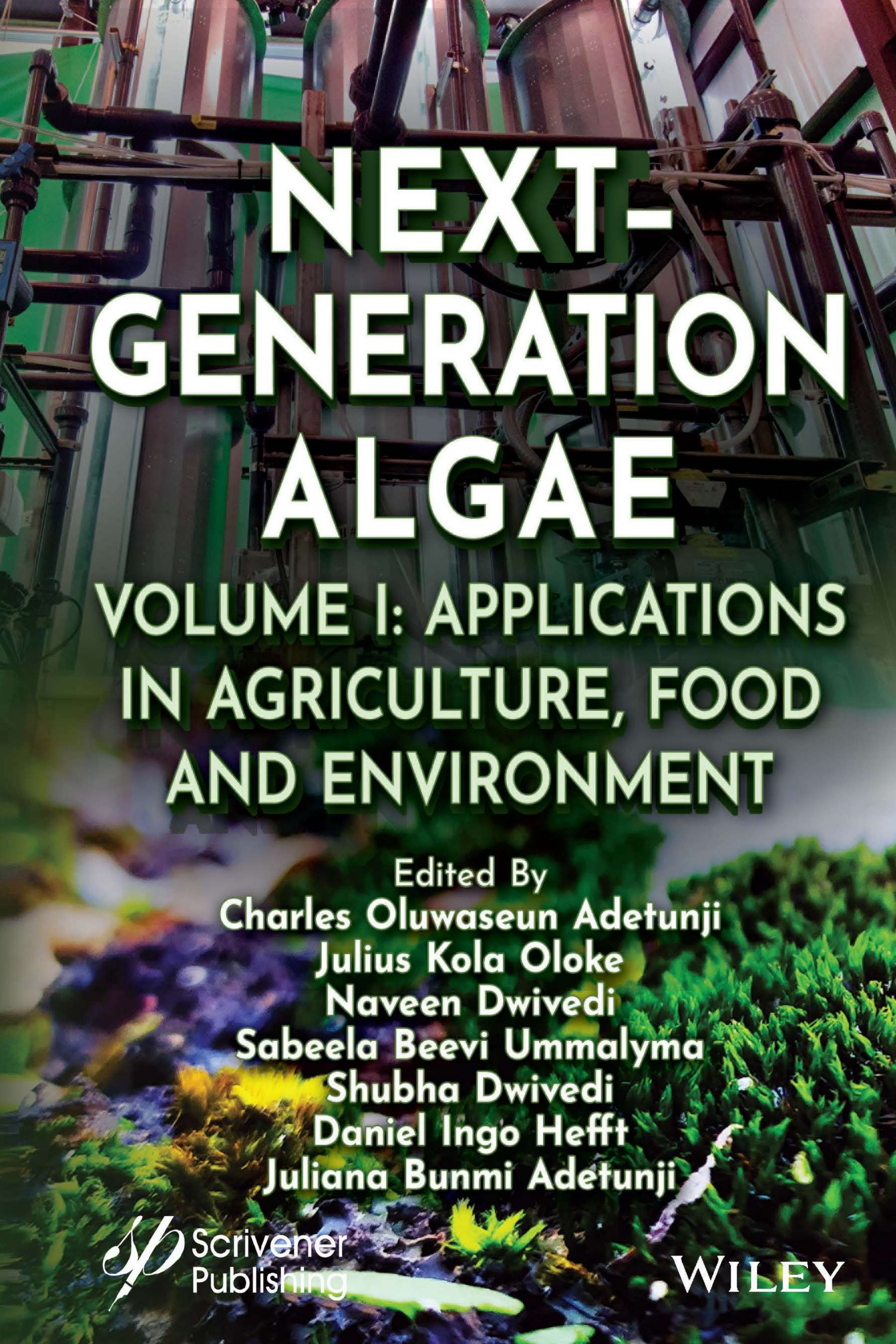

NEXT-GENERATION ALGAE

VOLUME I: APPLICATIONS IN AGRICULTURE, FOOD AND ENVIRONMENT

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Preface

The global population is projected to reach 9 billion by the year 2050. It is imperative to begin preparing for the challenges that come with accommodating this rapidly growing population. One of the most significant challenges will be to ensure that we can provide adequate food and nutritious diets to this growing population, as well as a healthy environment. The orthodox agricultural practice has depended heavily on non-renewable inputs such as pesticides, fertilizers, herbicides, and insecticides. Due to the rapid pace of industrialization and the continuous growth of human population, we are witnessing an alarming increase in environmental pollution caused by various anthropogenic and industrial activities. This has resulted in extensive damage to our environment. The majority of these pollutants are derived from inappropriate utilization and discharge of industrial effluents, fertilizers, pesticides, smelting and mining of ores, as well as the release of automobile exhaust and effluent from storage batteries. Additionally, the release of metalloids, heavy metals, petrochemicals, and petroleum hydrocarbons also contribute significantly to the problem. However, their introduction has led to increased agricultural production and significant advancements for humankind, but the application of agrochemicals has also resulted in numerous environmental and health hazards. Algae have been identified as a sustainable biotechnological resource that could help in resolving several of these problems.

This book provides up-to-date and cutting-edge information on the application of algae in producing sustainable solutions to various challenges that arise from an increase in agricultural production, as well as its utilization in bioremediation of industrial wastewater. Moreover, this book provides detailed information about the recent advancements in smart microalgae wastewater treatment using Internet of Things (IoT) and edge computing applications. Other topics covered include the use of microalgae in various applications (with past, present and future projections); the use of algae to remove arsenic; algae's role in plastic biodegradation, heavy metal bioremediation, and toxicity removal from industrial wastewater; the application of DNA transfer techniques in algae; the use of algae as food and in the production of food, ascorbic acid, health food, supplements, and food surrogates; relevant biostimulants and biofertilizers that could be derived from cyanobacterials and their role in sustainable agriculture; and algae's application in the effective production of biofuels and bioenergy.

This book is aimed at a diverse audience, including global leaders, industrialists, individuals in the food industry, agriculturists, the fishery sector, animal husbandry practitioners, investors, innovators, farmers, policy makers, extension workers, educators, researchers, and those in other interdisciplinary fields of science. It also serves as an educational resource manual and project guide for undergraduate and postgraduate students, as well as for educational institutions that seek to carry out research in the field of algae. Additionally, this book unites experts in relevant fields to describe the successful application of algae and its derivatives for bioremediation of extremely polluted environments, especially in water, air and soil. This book is highly recommended to a diverse community of professionals, scientists, environmentalists, industrialists, researchers, students in higher education, innovators, and policy makers who have an interest in bioremediation technologies and sustainable development.

I want to express my deepest appreciation to all the contributors who have dedicated their time and efforts to make this book a success. Furthermore, I want thank my coeditors for their effort and dedication during this project. Moreover, I wish to gratefully acknowledge the suggestions, help, and support of Martin Scrivener and others from Scrivener Publishing.

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Smart Microalgae Wastewater Treatment: IoT and Edge Computing Applications with LCA and Technoeconomic Analysis

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Abstract

The application of microalgae in applied biotechnological studies for different biomaterials, such as biodiesel, bioethanol, and other high-value bioproducts, has been gaining attention in recent years. Large-scale integrated microalgae-wastewater treatment facilities have emerged as a promising technology. Technoeconomic and life cycle analyses of integrated algae technology in municipal wastewater treatment plants (WWTPs) can reveal its potential as a viable market technology. Thus, integrated microalgae WWTPs is seen as a promising field and is getting attention from the scientific community due to its multifold benefits in terms of nitrogen and phosphorous removal with reduction of organic load, accumulation of heavy metals, and simultaneous production of value-added biomaterials.

This chapter was designed to provide concise details on recent advancements in biological and technological approaches, LCA studies, and IoT and edge computing-based modeling and monitoring of integrated microalgae WWTPs with a technoeconomic feasibility analysis for its assessment as a promising market technology. It is noteworthy that stakeholders have an interest in integrated microalgae WWTPs, but are looking for a standardized process, including design,

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data availability, and management aspects, along with a legislative framework that makes it simple to implement.

Keywords: Microalgae biorefinery, wastewater treatment, life cycle assessment, emergy analysis, IoT and edge computing

1.1 Introduction

It is noteworthy that global warming is considered a major issue for many countries around the world. Due to the recent pace of industrialization and urbanization, the emission of different greenhouse gases (GHGs), such as carbon dioxide (CO_2), has led to climate change. Thus, the agreement between world nations known as the Kyoto Protocol was enforced in 1997 to ensure the specific reduction of GHGs by countries. Among the different GHGs, CO_2 is considered to be the largest contributor to the greenhouse effect, and CO_2 mitigation strategies will directly affect the total GHGs emissions. In order to remove the excess atmospheric CO_2 emission, the following methods have been adopted worldwide: (i) Physicochemical processes, including solvent scrubbing, adsorption, absorption, cryogenics and membranes, (ii) Ocean storage of CO_2 and (iii) Biological transformation and mitigation of CO_2 to organic matter using a biological system [1].

Globally, about a 40% water deficit is predicted by 2030, along with several unavoidable challenges associated with societal and economic development in view of current perspectives on the increasing demand for water and lack of water reclamation technology [2]. The conventional wastewater treatment processes, viz. aerobic activated sludge-based process, nitrification-denitrification, and phosphorous removal, are facing challenges to meet the stringent nutrients discharge standards and a large amount of wastewater effluent is still being discharged with nutrients contents, resulting in eutrophication in the aquatic environment [2]. In addition, there are several other disadvantages, such as the high energy consumption, carbon emission, additional sludge discharge, and instability associated with these conventional processes, which can hinder the sustainability-based low carbon, low energy consumption, and resource recycling associated wastewater treatment [1].

Thus, the microalgae-related wastewater treatment (MBWT) process has been gaining attention in recent years and is considered as one of the most promising advanced technologies for sustainable wastewater treatment and efficient nutrient recovery from wastewater. The feasibility of microalgae-related treatment of wastewater generated from different sources, such as municipal, agricultural, and industrial, is being exploited as a tertiary wastewater treatment by many researchers because of its advantages as a highly efficient process for nutrient removal [3–7]. A symbiotic relationship between microalgae and the bacterial population of wastewater was reported by Oswald *et al.*, who observed the efficiency of microalgae in the enhancement of hazardous compounds removal with protection of the bacterial population [8]. Under symbiotic relationship, microalgae utilize CO_2 (produced through aerobic metabolism of bacteria) through the process of photosynthesis and generated O_2 could be utilized by the heterotrophic bacterial population for the assimilation of waste organic compounds. This created the idea of utilizing microalgae for wastewater treatment for the removal of excess nutrients of wastewater effluent and to reduce the risk of the eutrophication threat to natural water bodies. Furthermore, the microalgal biomass produced in wastewater treatment could be considered for "value-added product from waste" as a feedstock in further biorefinery processes [9–11] (Figure 1.1).

In this chapter, recent advancements with respect to diversity of microalgae, process system, internet of things (IoT) and edge computing-based process monitoring and control, and life cycle assessment (LCA)-based techno-economic feasibility analysis of microalgae-based wastewater treatment process are discussed. The details of psychrophilic, thermophilic and acidophilic microalgae and their roles in high-tech, low-cost, and environmentally friendly wastewater treatment process are discussed. Also, the different process systems associated with CO_2 bio-fixation with simultaneous

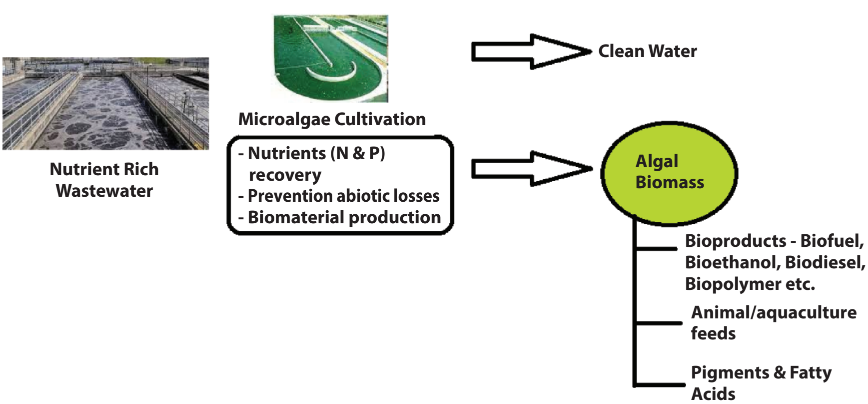

Figure 1.1 Resource recovery from microalgae-based wastewater treatment system for circular bioeconomy.

wastewater treatment are discussed. In addition, the application of emerging technologies, such as IoT automation, to microalgae-related technologies and machine learning approaches for data acquisition, monitoring and analysis of microalgae-based wastewater treatment system is discussed in view of the establishment of an integrated microalgae-wastewater treatment-based biorefinery and bioeconomy. Finally, the evaluation of microalgae-based carbon capture technology associated with wastewater is provided in terms of life cycle assessment, emergy analysis, and material flow analysis.

1.2 Importance and Potential of Extremophilic Microalgae-Based Wastewater Treatment (WWT) Plant

The essential importance of water to life on Earth is threatened by water pollution, which is a significant environmental concern [12]. Water contamination may be caused by anthropogenic or natural activity. The most important causes of human-made water pollution are harmful products from manufacturing processing and effluent making from businesses such as petrochemical plants and pulp and paper mills [13]. The hazardous and carcinogenic organic pollution emitted by crude oil, pharma, petrochemical and coal industries is recognized as being phenol and phenol compounds [14, 15]. Several research studies have examined the biological removal by microalgae of carbonate, nitrogen, and phosphorus through wastewater fluids. Different microalgal species are used in diverse types of wastewaters, including municipal, farming, brewery, refineries and industrial effluents with different efficiencies of treatment and microalgal growth [16–18].

There are numerous benefits to biological approaches, with certain microorganisms reporting degradation of phenols and phenolic compounds up to 1 g/L [15, 19]. The focus on harsh conditions has grown throughout the last few decades, resulting in a pure culture being obtained of unidentified extremophilic microorganisms and their associated metabolites [20]. Such extremophilic bacteria can provide crucial knowledge about ecological and biochemical responses and can lead to biotechnology or commercial uses [21, 22]. Extreme thermophiles currently have great potential and, while utilizing a contemporary understanding of genetics of these microbes, their application in renewable feedstock production by means of metabolic engineering will further increase [23]. Thermophilic microalgae are also used to find enough enzymes that then are integrated into plant genomes to increase their output and resistance to production [15]. Micro-algae separation and selection allow high quantities of biomass and important chemicals such as lipids to be produced in an industrial way [22, 24, 25]. The capacity to extract ammonium from wastewater at temperatures of 40-42 °C and light intensities of 2,500 μmol m^2/s for 5 h in a day was studied using a green microalga *Chlorella sorokiniana* isolated from a wastewater stabilization pond at La Paz, Baja California Sur, Mexico [15, 26]. Thermophilic microalgae may obviously be utilized as a gene pool to identify thermostable enzymes which can be employed in dry locations for improved stability and culture in such settings [27]. Thermophilic microalgae are becoming increasingly more important since they can live at high CO_2 levels. This characteristic makes them attractive candidates for CO_2 emissions from industrial flue gases and adds a step towards global warming reduction. Thermophilic microalgae are efficiently employed to bioremediate harmful industrial effluents and wastewater regardless of origin [15].

1.3 Status of Microalgae-Based WWT Plants

1.3.1 Conditions and Requirements (Abiotic and Biotic Requirements, Nutrients Requirement)

Wastewater remediation is required for preventing pollution and contamination of freshwater bodies as well as for effective reuse of the treated wastewater for sustainability. An ever-increasing population, reduction of freshwater availability, expanding industrialization, and growing human development index (HDI) has increased the demand for wastewater recycling and its sustainable utilization to help manage the precious potable water resources globally in the 21st century [28].

Wastewater is treated conventionally using four types of treatment methods based on the technology used or the category of inflow water. The different treatment plant types are sewage treatment plants (STPs), effluent treatment plants (ETPs), activated sludge plants (ASPs), and common and combined effluent treatment plants (CETPs). Most of the resultant treated water is used for non-potable applications after secondary treatments itself because of technological and/or logistical limitations [29, 30] and non-mandatory status of the tertiary treatment. However, this type of treated water often does not meet the minimum quality standards of water reuse and once released into water bodies it rapidly brings down the dissolved oxygen (DO) and causes pH fluctuation, resulting in the creation of dead aquatic zones and an increase in the overall toxicity [31, 32]. Moreover, these conventional wastewater treatment plants (CWWTPs) are energy intensive and require high operational and maintenance cost [33, 34]. In such a scenario, where the conventional systems are already posing challenges, an ever-increasing population will further stress the global wastewater treatment and reuse scenario as the nutrient load of nitrogen and phosphorus will increase, which will further call for a mandatory tertiary treatment [35–38]. Studies have shown that microalgae are excellent candidates for nitrogen and phosphorus removal and are better than other classes of microorganisms. Being photosynthetic and highly adaptive in their environment, microalgae are also considered the best candidates for tertiary treatment systems. The autotrophic nature of these organisms reduces the system's energy footprint and atmospheric carbon sequestering along with N and PO_4^- removal, which is an added bonus to the environment [39–44].

Wastewaters are complex systems, their treatment is not as straightforward as often understood in terms of biochemical oxygen demand (BOD), chemical oxygen demand (COD) and sludge. Their temporal and spatial characteristics depend on their source, geophysical conditions, factors such as temperature and pH, effluent and nutrient load, physical and chemical impurities, biotic load and flow regime, treatment system size, treatment protocol, transformation products and treatment technology, etc. Besides the composition of the wastewater, wastewater treatment at a national/regional level also depends upon the environmental policy, water resource availability, water withdrawn and water stress [45]. Nevertheless, the present discussion is focused on microalgae-based wastewater treatment plants and only the factors that directly affect these plants will be discussed in this section. The following table shows some of the recent works on biotic and abiotic factors of microalgae-based WWT. This will help to develop more clarity on biotic-abiotic factors and growth conditions for microalgae as well as its potential as a wastewater treatment candidate. From Table 1.1 it can be clearly understood that microalgae are a good candidate for nitrogen and phosphorus removal under all different system configurations. They are even effective in untreated wastewaters and can be employed along with conventional treatment methods. It can be further observed from the literature cited in the table that the best results are obtained with natural consortia instead of using a single isolated species [39]. In addition to the use of natural consortia, a combination with aerobic bacteria seems to give better results as has been suggested in many studies in the literature cited in this table. It is also proved that aerobic

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement.

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Lighting, pH Temperature CO_2 Total Nitrogen (TN) Total Phosphorus (TP)	Species of microalgae and bacterial consortia, cell density, cell size and biovolume *Franceia amphitricha* *Scenedesmus* sp. *Chlorella* sp. *Chlorellaceae* *Chlamydomonas* sp. *Desmodesmus* sp.	New isolated species	Anaerobic digested (AD) effluent sample	600-L horizontal tubular photo-bioreactors	- 99% removal of (TN) and Total Phosphorus (TP).	[40]

(Continued)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. (*Continued*)

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Irradiance Temperature Orbital Shaking	3 fluoroquinolones- ofloxacin, ciprofloxacin, norfloxacin; 3 macrolides - azithromycin, erythromycin, clarithromycin; and 3 antibiotics - trimethoprim, pipemidic acid, sulfapyridine	*Chlamydomonas reinhardtii* (UTEX ID 2243), *Chlorella sorokiniana* (UTEX ID 1663), *Dunaliella tertiolecta* (UTEX ID LB999) and *Pseudokirchneriella subcapitata* (UTEX ID 1648)	Direct toilet water	1200L Photobioreactor and a suspect screening methodology for assessment of the transformation products (TPs) generated from 9 antibiotics	- Microalgae ability for macrolide biotransformation. - 40 different TPs were identified.	[53]
COD, TSS, Total nitrogen (TN), Total Phosphorus (TP) pH, Temp Total solar irradiance	Interaction of several species	*Leptolyngbya* sp. *Synechococcus* sp. *Chlorella* sp. *Parachlorella* sp. *Dictyosphaerium* sp. *Scenedesmus* sp. *Desmodesmus* sp. *Pediastrum* sp. *Zooplankton Daphnia* sp.	Untreated influent wastewater	High-rate algal ponds (HRAPs)	- Microalgae biodiversity plays critically essential role in high productivity of HRAPs treating municipal wastewater.	[54]

(*Continued*)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. (*Continued*)

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
CO_x, NO_x, SO_x, pH, Light, temperature, wind (m/s), precipitation (mm), relative humidity (%) DO	Consortium of local freshwater green algae	*Chlorella* sp., *Scenedesmus dimorphus*, *Scenedesmus quadricauda*, and *Desmodesmus armatus*, *Coelastrum microporum*	Municipal untreated wastewater and CO_2 from CHP plant	Raceway pond systems	- In wastewater treatment process, the interaction between bacteria and microalgae plays a crucial role.	[55]
nitrogen (N), phosphorus (P), magnesium (Mg), carbonate (CO_3) and gamma radiation	-	*Chlorella vulgaris*	Synthetic media	Lab-scale setup	- Biomass increase with high N and P and low Mg and CO_3, Lipid accumulation increase with low N and P and high Mg and CO_3. - Gamma radiation has negative effect on biomass and lipid accumulation.	[56]

(*Continued*)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. (*Continued*)

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Autotrophic and heterotrophic growth conditions	-	*Auxenochlorella protothecoides*	Synthetic media	Lab-scale setup	- Hub genes defined	[57]
Ammonium urea, and Nitrate as nitrogen source	Algal consortium	*Tetraselmis* sp. (UTEX LB 2767), *Raphidocelis subcapitata* (UTEX 1648), *Chlamydomonas reinhardtii* (UTEX 2243), and *Scenedesmus obliquus* (UTEX 393) *Navicula* sp.	Wastewater as a feedstock	Lab-scale setup	- In heterogeneous nitrogen environments, functional diversity increases with species complementarity and productivity	[58]

(*Continued*)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. (*Continued*)

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Ammonium as Nitrogen source	Bacteria derived from the AD effluents interactions with the *Chlorella* species	*Chlorella vulgaris* (KCTC AG10002) and *Chlorella protothecoides* (UTEX 1806)	AD effluents from four different lab-scale anaerobic digesters	Lab-scale setup	- A viable way to treat and value-add the wastewater effluents by *Chlorella* cultured on AD effluents	[59]
pH, EC, TS, TDS, TSS, DO, COD, Ammonia, Nitrate, Phosphate	Varying concentrations of same algal species at different HRT	*Chlorella vulgaris*	Raw domestic wastewater	Lab-scale setup	- Addition of microalgae to CWWTs can be a solution for pollution control	[32]
pH Nitrogen and phosphorus	Microalgae consortia	Different naturally occurring sewage algal species	Comparative study on wastewater and artificial media	Lab-scale setup	- Microalgae consortia has effectively removed phosphate and nitrogen with real wastewater instead of from synthetic media	[44]

bacteria support microalgal photosynthetic rates by reducing the micro-environments around the microalga and thereby help faster, better, energy smart and sustainable treatment of wastewater; whereas the conventional wastewater treatment is both oxygen and energy intensive, and thus less environmentally friendly and less sustainable [46]. Moreover, from Table 1.1, it can be further observed that if the microalgae are autotrophic there are fewer requirements on the surrounding media and the biomass produced can be further utilized or valorized, unlike the CWWTs [30, 42, 47, 48]. Microalgae has proven to be good in most of the wastewater treatment studies, except for complex wastes like phenols [49] and hydrocarbons [40, 50–52].

1.3.2 Microalgae-Based WWT System – Photobioreactor System in Suspension and Immobilized Model

Microalgae culture systems are vast. In wastewater treatment, local consortia of microalgae is preferably cultured in open raceway ponds or high-rate algal ponds (HRAPs). However, algae cultivation is done in a photobioreactor (PBR) either for culture valorization, biomaterial production or for high lipid production as well as to study the finer nuances of R&D on a specific species or an improved strain [60–62]. Nevertheless, the use of a photobioreactor for treatment of wastewater could undermine the overall cost and energy efficiency [63].

Microalgae is adventitious over filamentous as well as macroalgae in terms of its feasibility of culture in suspension as well as in immobilized forms [64]. With the advancement of information technology, control and feedback loops, automation, etc., PBR has gone from lab scale to pilot scale in the last two decades. Although giving a complete overview of the two decades of PBR algal cultivation is difficult and beyond the scope here, a few suspensions and immobilized algal culture studies are presented in Table 1.2.

1.3.3 Evaluation of Treatment Performance

Performance evaluation (PE) of a system is important for optimization of a process and is extensively applied in wastewater treatment processes. It is reported that the PE data do not provide suitable operational information for the optimization of individual units involved in a WWTP; however, they are important indicators for the overall performance of the system [78]. A good system performance can significantly reduce the operation