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Tonni Agustiono Kurniawan
Abdelkader Anouzla *Editors*

Algae as a Natural Solution for Challenges in Water-Food-Energy Nexus

Toward Carbon Neutrality

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Preface

Welcome to our book, *Algae as a Natural Solution for Challenges in the Water-Food-Energy Nexus: Toward Carbon Neutrality*. In the following pages, we embark on a journey through the world of algae, a group of organisms that hold future promise for addressing critical global challenges such as energy shortage, water pollution, and climate change.

As we turn these pages, let us recognize the urgency of our mission. Algae—our ancient allies—are not merely a curiosity but a lifeline. They offer hope for a sustainable future, where water, food, and energy coexist harmoniously. Join us on this voyage as we unlock the potential of algae and steer toward a carbon-neutral horizon.

Currently, the planet faces an intricate web of interconnected challenges as the confluence of water, food, and energy (Selvaraj et al. 2023). The delicate balance between water availability, food security, climate change, and sustainable energy production is at the heart of this nexus. As humanity navigates the intricate web of interdependencies within this nexus, so does the urgency to find new innovations that harmonize the essential elements.

For millennia, humans have interacted with algae—both macro (seaweed and kelp) and micro (unicellular) to meet their needs (Tavares et al. 2023). The organisms have been cultivated as food sources, providing sustenance to coastal communities and nourishing our bodies. The remarkable potential of algae emerges as a beacon of hope, offering a natural-based solution to multifaceted problems that the world encounters. Nevertheless, presently their importance extends far beyond traditional cuisine.

Although being often overlooked in mainstream discourse, algae possess a wealth of untapped potential. They have a unique ability to convert sunlight and CO_2 into a wide range of biochemical compounds. Despite being categorized as animals, they metabolize the same way as plants, producing O_2 to replenish what humans consume. This cycle acts as a carbon capture system, whereby harmful CO_2 in the atmosphere is converted to useful O_2(Yang et al. 2024). Micro-algae produce a wide range of other compounds found inside the cells, and this makes them useful at combating the effects of climate change on the environment.

What makes them stand out in a complex of water, food, and energy nexus? They can promote:

1. *Resource efficiency*: Algae have evolved to be highly efficient at utilizing resources. Their ability to thrive in diverse environments—whether freshwater, brackish water, or even seawater—sets them apart from other organisms. By harnessing non-arable land and non-potable water, algae complement traditional agriculture (Yamashita et al. 2009).
2. *Carbon sequestration*: Algae's remarkable capacity to sequester CO_2 during photosynthesis contributes to their sustainability. As the world strives for carbon neutrality, algae play a vital role in mitigating its carbon footprint (Ren, 2021).
3. *Nutrient-rich biomass*: Algae produce proteins, lipids, and carbohydrates that are highly digestible. They are rich in essential fatty acids, vitamins, and minerals—an ideal nutritional profile for human need (Diaz et al. 2023).

With their unique capabilities, this book delves into the intricacies of large-scale algae production for food. Our contributors explore breeding techniques, cultivation methods, and the quest for enhanced nutritional qualities. Algae's journey from biofuel research to mainstream food utilization is another path paved with innovation (Srivastava et al. 2023). We also uncover the role of algae in sustainable agriculture, where they serve as biofertilizers, livestock feed supplements, and sources of plant-based protein. By delving into the burgeoning field of algal biofuels, the organisms hold the key to unlocking renewable energy sources that can power the world without exacerbating climate change.

In recent years, there has been an increased interest in growing algae in a rapidly evolving field of renewable energy. Tremendous research on micro-algae has claimed that the tiny organisms have potential in generating clean energy such as biofuels, high-valuable products like biofertilizers, bioplastics, supplements, and aquafeed, while mitigating environmental-related issues such as bio-adsorbent, biochar, and soil-mediated agent (Varela Villarreal et al. 2020).

For this purpose, natural solutions such as algae have been explored and widely applied globally in recent years to deal with climate change. One of the algal types is micro-algae that can be used for biodiesel production. Micro-algae are tiny reservoirs of a plethora of biofuels. Biofuels are the need of today, and researchers around the globe have explored the options for biological fuel production. Algae are an optimal raw material because they occupy between 4% and 7% of the surface area needed to produce the same yield of a land-based crop, do not require fresh water, can be grown in arid zones near the coast, and avoid monocultivation of products to make fuel (Kim et al. 2012; Milledge and Heaven, 2013; Farrokheh et al. 2021). Algae have inherent with the high-lipid content found in some species being a fundamental edge.

Another technological benefit is algae's high per-acre productivity. Since micro-algae are a unique food source, algal cultivation for fuel does not interfere with food production at the levels that cultivation of other feedstock such as corn. Because algae grow in different environments, it could be produced on acreage that is not agriculturally productive. The use of algal-based fuel would result in a tiny fraction of the net GHG that can be traced to fuel use presently. Scaling up algae farming could result in yields of commercial products other than fuel (Wagener, 1983).

Additionally, the utilization of algae for wastewater treatment helps to minimize the amount of organic matter and capture inorganic contaminants such as heavy metals. Although excess growth of algae can poison drinking water and contaminate water sources, they can provide dissolved oxygen (DO) to other living organisms or reduce DO significantly that massive fish die-offs take place (Macusi, 2008; Paul et al. 2020; Ismael et al. 2021).

Conversely, finding carbon capture technologies is vital to minimize GHG emissions in the world. The utilization of micro-algae with a higher capture rate than trees that can be produced in reactors, represents an option for capturing CO_2 in industries and cities. In addition, the research aims to produce in an environmentally sustainable way by extracting a by-product from a waste that has already been produced by another anthropogenic process.

We also explore how algae can be harnessed to purify contaminated water sources, providing a lifeline to communities grappling with water scarcity and pollution (Erler et al. 2018). However, water pollution due to algae has so far received little attention outside scientific circles. Hence, not many scientific books addressing the emerging paradigm of algal management with respect to the problems of algal pollution have been published.

At the heart of this book lies a profound exploration of the role algae can play in steering the world toward carbon neutrality. As the specter of climate change grows ever more ominous, urgent action is vital to mitigate GHG emissions and transition toward a low-carbon future (Malyan et al. 2021). Through rigorous research and insightful analysis, the contributors of this book illuminate the myriad ways in which algae can play key roles to this endeavor.

The journey through these pages takes us on a comprehensive tour of algae's vast potential. We examine the intricacies of algal biology, their diverse habitats, and their remarkable ability to thrive in a wide range of environmental conditions (Tang et al. 2021). From microscopic diatoms to towering kelp forests, from freshwater ponds to vast oceanic expanses, algae inhabit a multitude of niches, each offering unique opportunities for exploration and exploitation. Therefore, this book delves into the practical applications of algae across the water-food-energy nexus.

This book meets the need of our societies, university students and policy makers on scientific approaches to deal with algal pollution partly by using it as biodiesel production and as a biosorbent for water treatment. For this reason, this book disseminates knowledge to readers on how algae may contribute to emerging understanding in climate change mitigation with respect to the relationship between algae as a low-cost biomaterial and climate change that paves the ways for a new direction of mitigation and adaptation in the future (Ansar et al. 2023).

It is expected that this book will inspire layman and other readers on how to contribute to the UN SDGs #6 'Clean Water' by utilizing algae for biodiesel production wastewater treatment, food application, and climate change mitigation. Optimizing the benefits of both algal water treatment and biofuel production demands maximization of total nutrient removal, biomass production, and lipid content of the biomass because algal species known for high nutrient removal and lipid production are easily suspended single-celled algae that are technically difficult to harvest efficiently by gravity alone.

For this reason, this book provides an overview of challenges and opportunities for algal management to mitigate climate change by offering new perspectives on how to control water pollution due to algae, while converting it to biosorbent and biodiesel that could be commercialized in market. The work also explores how to improve the performance of algae for such purposes (Guan et al. 2023). By identifying existing knowledge gap, this work unlocks new research directions for further development of algal management to address global environmental pollution.

As the editors of this volume, we are deeply honored to present this compendium of knowledge to readers, who share our passion for sustainability and innovation. We extend our heartfelt gratitude to the contributors, whose expertise and dedication have enriched the pages with invaluable insights. It is our sincere hope that this book can serve as a catalyst for dialogue, inspiration, and action, spurring renewed efforts to harness the power of algae in service of a sustainable and equitable world.

In closing, we invite readers to embark on a journey of discovery, as this book explores the boundless potential of algae as a natural-based solution for the challenges facing the water-food-energy nexus. Together, let us chart a course toward a future, where carbon neutrality is not merely a distant dream, but a tangible reality, powered by the remarkable resilience and ingenuity of the natural world.

Xiamen, China
Mohammedia, Morocco
February 2024

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Contents

Part II
Algal Management in Wastewater Treatment

Chapter 10
Implementation of Algal Approach in Techno-socio-economical Aspect of Wastewater Treatment

Tazkiaturrizki, Astri Rinanti, Melati Ferianita Fachrul, Diana Irvindiaty Hendrawan, Sarah Aphirta, Sheilla Megagupita Putri Marendra, and Naomi Oshin Laurensa Sipahutar

Abstract The implementation of the algae approach in the technological, social, and economic aspects of wastewater treatment offers an environmentally friendly solution to address the problem of water pollution. Algae play an important role in absorbing pollutants, recovering nutrients, reducing greenhouse gas emissions, and producing biomass for renewable energy. Knowledge of their classification, characteristics, growth, reproduction, and interaction with the environment will help increase the effectiveness of wastewater treatment. The process of wastewater treatment by microalgae metabolic activity involves certain principles, mechanisms, systems, and technologies that enable the improvement of treatment parameters and efficiency. Integrating microalgae technology with other wastewater treatment technologies, such as hybrid systems and technology combinations, can improve overall system synergy and efficiency. Economic aspects and cost analysis need to

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be carefully considered, including investment costs, operations, economic studies, processing scale, and product marketing potential and sources of income. Meanwhile, the social and policy aspects discussed include public awareness and acceptance, policies and regulations that support the use of algae, as well as partnerships and collaboration between government, industry, and society. Case studies and real applications show experiences and lessons from implementation in various countries, as well as success factors and constraints in these implementations. In facing future challenges and prospects, it is necessary to carry out further research and development of algae technology to increase efficiency and innovation in wastewater treatment and overcome various obstacles that may be encountered during implementation.

Keywords Wastewater treatment · Microalgae technology · Water pollution · Techno-socio-economical aspect · Environmentally friendly · Renewable energy

10.1 Introduction

10.1.1 Background on the Problem of Wastewater Treatment

Issues related to the implementation of the algae approach in the technological, social with regard to public awareness, and economic aspects of wastewater treatment involve various factors. The background of this issue encompasses several related aspects, including the increasing industrial activities and population growth, which have led to increasingly severe water pollution problems. Domestic and industrial wastewater contains pollutants such as excessive nutrients, heavy metals, and hazardous chemicals that can endanger the environment and human health. Conventional wastewater treatment methods—such as sedimentation, filtration, and biological treatment—have limitations in addressing various types of pollutants. Some methods also require high operational and maintenance costs and generate secondary waste that needs further treatment (Mitra et al. 2022).

Algae offer an environmentally friendly and sustainable alternative solution for wastewater treatment. Algae can absorb pollutants like excessive nutrients, heavy metals, and hazardous chemicals through bioaccumulation and biodegradation processes, often eliminating the need for chemical additives as shown in Fig. 10.1 (Valchev and Ribarova 2022). Furthermore, algae can be utilized for the production of biogas, biofuel, and other high-value products, thereby enhancing the economic aspects of wastewater treatment.

Wastewater treatment technology using algae is still relatively new and not yet fully developed. It creates challenges in adapting and integrating this technology into existing wastewater treatment systems. Additionally, the process efficiency, scalability, and maintenance of algae systems are also issues that need to be addressed. The implementation of the algae approach in wastewater treatment requires specific technologies and equipment, such as photobioreactors and environmental parameter

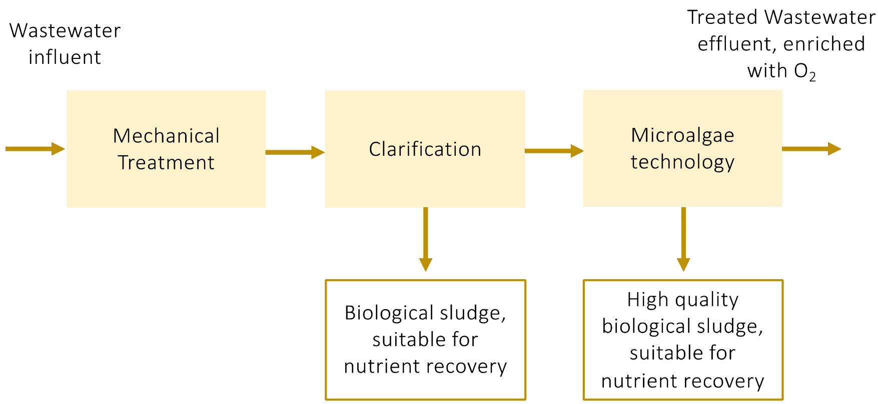

Fig. 10.1 Non-chemical usable

control systems as shown in Fig. 10.2 (You et al. 2023). Research and development of efficient and economical technologies are still needed to maximize the potential of algae in wastewater treatment.

The public may be unfamiliar with or uncertain about algae-based wastewater treatment technology; hence, effective education and socialization are necessary. Wastewater treatment with algae requires awareness and support from the public. Some individuals may not realize the importance of wastewater treatment or feel skeptical about the effectiveness of algae-based approaches. Public education and outreach are needed to enhance the understanding of the benefits and potential of this technology. From an economic perspective, implementing the algae approach in wastewater treatment requires significant initial investment, including installation,

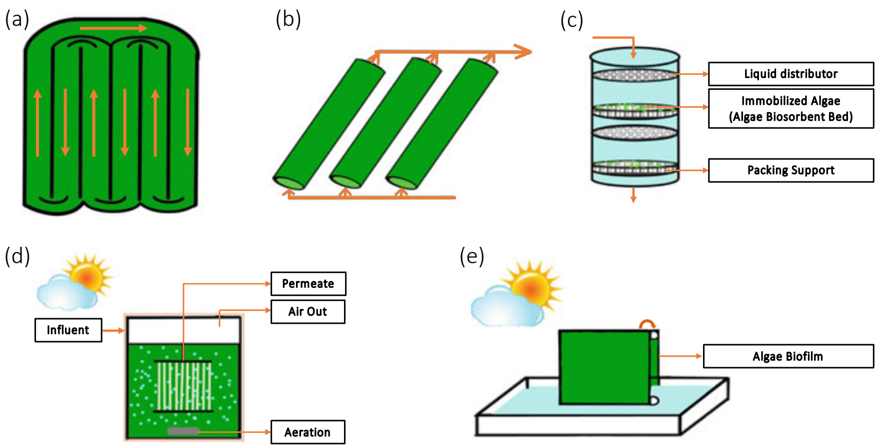

Fig. 10.2 Photobioreactor types. **a** Suspended open systems, **b** suspended closed systems, **c** immobilized algae system, **d** membrane photobioreactors, and **e** algae biofilm

operation, and maintenance costs. Additionally, high initial financing, regulations, and government support also present obstacles to the implementation of this technology. Further research and development to improve the efficiency and effectiveness of this technology also require substantial financial support. In many cases, collaboration between the government and private sectors is necessary to provide the required funding and incentives.

The existing regulations and policies may not yet facilitate the implementation of the algae approach in wastewater treatment. The government needs to review and update the existing policies and regulations to create a conducive environment for the development and application of this technology. The implementation of the algae approach in wastewater treatment requires collaboration between the industrial sector, the government, and society (Obaideen et al. 2022). Creating supportive policies, increasing public awareness, and investing in research and technology development are crucial steps to address these challenges. The hurdles in coordination and integration of efforts from various stakeholders can hinder the implementation of this technology.

10.1.2 The Importance of Environmentally-Friendly Technology in Wastewater Treatment

Eco-friendly technology in wastewater treatment is pivotal for several reasons:

(1) Wastewater treatment with environmentally-friendly technology helps maintain the quality of water resources such as rivers, lakes, and groundwater. By reducing contamination and pollution, this technology ensures that water resources remain safe and suitable for various purposes, e.g., consumption, irrigation, and industrial use. Wastewater treatment with environmentally-friendly methods, like the algae approach, helps reduce water pollution and protect existing water resources. Preserving water resources supports aquatic life, agricultural needs, industries, and human consumption.
(2) Environmentally-friendly technology in wastewater treatment reduces negative impacts on ecosystems and biodiversity. Poorly treated water pollution can threaten the lives of flora and fauna and disrupt the ecosystem balance. By employing environmentally-friendly technology, we contribute to environmental protection and the preservation of biodiversity.
(3) Environmentally-friendly technology reduces greenhouse gas emissions and air pollution often generated by conventional wastewater treatment methods. It contributes to global efforts to mitigate climate change impacts and maintain air quality.
(4) Effective wastewater treatment with environmentally-friendly technology reduces the dissemination of waterborne diseases such as diarrhea and cholera, thereby improving public health and well-being. Poorly treated wastewater

can contaminate drinking water sources and contribute to disease transmission. Environmentally-friendly wastewater treatment technology helps reduce the risk of waterborne diseases and enhances the quality of life.

(5) Environmentally-friendly technology in wastewater treatment often reduces energy and hazardous chemical consumption. Eco-friendly methods like the algae approach utilize natural and renewable resources, such as sunlight, to produce the energy needed in the treatment process. It decreases reliance on fossil energy sources and enhances the sustainability of the system. Algae-based approaches, for instance, leverage natural biological processes that produce minimal residue and have lower environmental impact compared to conventional methods. Environmentally-friendly wastewater treatment technology also includes resource recovery methods, such as nutrient and energy extraction from wastewater. For example, microorganisms in the algae approach can convert nutrients in wastewater into biomass, which can be used as feedstock for energy production or other high-value products.

(6) Implementing environmentally-friendly technology in wastewater treatment creates new economic opportunities, such as the development of innovative products and technologies, job creation, and cost savings. The development and implementation of environmentally-friendly wastewater treatment technology foster new business opportunities and employment in the green industry. Furthermore, it supports sustainable economic growth and encourages a transition towards a circular economy. For instance, in the algae-based approach, algae grown in the wastewater treatment process can be used as raw material sources for fisheries, animal feed, bioenergy, or pharmaceutical products.

(7) Implementing environmentally-friendly technology in wastewater treatment can serve as a means to raise public awareness regarding the importance of water resources and environmental preservation. It will encourage more environmentally-friendly behaviors and support for sustainable environmental policies.

(8) The use of environmentally-friendly technology in wastewater treatment enables companies and governments to comply with increasingly strict environmental regulations and avoid penalties or fines that may arise from violations.

To ensure environmental sustainability and societal well-being, it is essential to adopt environmentally-friendly technology in wastewater treatment, such as the algae-based approach, which combines technological, social, and economic advantages (Zapata-Mendoza et al. 2022; Siwi et al. 2017).

10.1.3 The Role of Algae in Wastewater Treatment

Microalgae have several advantages compared to physical and chemical treatment methods in heavy metal absorption from wastewater. The significant role of microalgae in wastewater treatment lies in their ability to remove pollutants, produce high-value biomass, and potentially reduce greenhouse gas emissions. Some roles of microalgae in wastewater treatment are as follows:

(1) Biofiltration and nutrient absorption: Microalgae can form biofilms on various surfaces, such as biological disks, during the biofiltration process. These biofilms enable microalgae to absorb pollutants from wastewater, including heavy metals and organic compounds. This process helps reduce the concentration of pollutants in wastewater and improves water quality, involving the absorption, biodegradation, and bioaccumulation of pollutants by microalgae. For instance, microalgae can remove nitrogen and phosphorus from wastewater by assimilating the pollutants as nutrients for growth. Microalgae require nutrients like nitrogen and phosphorus for growth and reproduction (Yaakob et al. 2021). Wastewater rich in these essential elements serves as a good nutrient source for microalgae. When microalgae absorb these nutrients from wastewater, the nutrient content in the wastewater decreases, thereby reducing the potential for environmental pollution and eutrophication. Therefore, algae are considered efficient in removing excess nutrients from wastewater, such as phosphate and nitrogen. These nutrients are major pollutants responsible for water eutrophication. Algae convert these nutrients into biomass through photosynthesis and cell growth.
(2) Biodegradability: Microalgae are living organisms that can easily degrade in the environment after accumulating heavy metals. This means that algae-based methods are more environmentally friendly compared to physical and chemical methods, which often result in secondary waste that is difficult to degrade or requires further management (Touliabah et al. 2022; Kautsar et al. 2021).
(3) Bioremediation and phytoremediation: Microalgae as living organisms play a crucial role in bioremediation of wastewater due to their ability to absorb and accumulate pollutants in water. Specifically, since microalgae are producers or similar to plants (phyto), the process of removing heavy metals and other pollutants from wastewater is called phytoremediation. Algae can absorb, accumulate, and transform heavy metals into less hazardous and stable forms, thereby reducing the toxicity of wastewater. This process involves the absorption of heavy metals, excess nutrients, and organic compounds by algae through bioadsorption, biosorption, and biodegradation processes.
(4) Reduction of pathogenic microorganisms: Some types of algae, especially microalgae, can reduce the number of pathogens in wastewater through predation, competition, and production of antimicrobial compounds. It helps decrease the spread of water-related diseases.
(5) Biomitigation: Microalgae photosynthesize to convert carbon dioxide (CO_2) from the air into biomass (Onyeaka et al. 2021). This process helps reduce CO_2 emissions produced by industrial sectors and power plants, thus mitigating the impact of climate change. Additionally, using algae in wastewater treatment reduces the need for conventional aerobic processes that generate greenhouse gas emissions such as methane and nitrous oxide. Through photosynthesis, algae also produce oxygen as a byproduct, which enhances water quality by

increasing dissolved oxygen levels. This condition supports aquatic life and other biological processes in water bodies.

(6) Bioproduction of high-value biomass: Microalgae can produce biomass that can be used for various applications, such as raw materials for bioenergy (biofuel), animal feed, fertilizers, and high-value products like pigments, omega-3 fatty acids, and proteins. Thus, algae not only treat wastewater but also create valuable commercial products, promoting new business opportunities and supports the circular economy.

(7) Anaerobic wastewater treatment: Microalgae can be combined with bacteria in anaerobic wastewater treatment systems to produce biogas (Kazimierowicz et al. 2023). Microalgae supply oxygen through photosynthesis to support bacterial growth, which subsequently generates biogas that can be used as a renewable energy source.

Implementing the utilization of algae in wastewater treatment based on technological, social, and economic aspects requires consideration of the above roles of algae. Integrating algae-based technology into existing wastewater treatment systems and developing new methods involving algae will contribute to more efficient, sustainable, and environmentally-friendly wastewater treatment (Maryjoseph and Ketheesan 2020). To implement the algae approach in wastewater treatment, systems such as photobioreactors, algae ponds, and hybrid systems with conventional technologies can be used. The success of implementing this technology will depend on the type of algae used, environmental conditions, and technological, social, and economic support.

(8) Operational conditions: The use of microalgae in wastewater treatment generally requires lighter operational conditions (e.g., temperature, pressure, and pH) compared to physical and chemical methods. This reduces energy consumption and operational costs in wastewater treatment systems and decreases the risk of accidents and environmental damage that may occur due to extreme operational conditions.

10.2 Algae Biology and Ecology

10.2.1 Classification and Characteristics of Algae

The ecological aspects of algae classification and characteristics are crucial for understanding how they can be utilized in the implementation of the algae approach in the technological, social, and economic aspects of wastewater treatment. Several characteristics and classifications of algae can be categorized based on various criteria, such as photosynthetic pigments, cell shape, and cell wall composition. Generally, algae are divided into several main groups, including:

Cyanobacteria, also known as blue-green algae, are prokaryotes capable of performing oxygenic photosynthesis found in diverse environments, ranging from fresh to saline water, soil, and even extreme environments such as hot springs and polar regions. Through oxygenic photosynthesis, oxygen is produced as a byproduct of water splitting. This process has a significant impact on the Earth's atmosphere, transforming the early carbon dioxide-rich atmosphere into one with higher oxygen content. This transformation enabled the development of life as we know it today. *Cyanobacteria* play a crucial role in nutrient and oxygen cycles on Earth and represent one of the earliest groups of photosynthetic organisms. Their photosynthetic ability is essential in the history of life on Earth.

Cyanobacteria contain chlorophyll a, the primary pigment found in all photosynthetic organisms. Moreover, these microalgae contain additional pigments known as phycobiliproteins, such as allophycocyanin and phycocyanin, which give *Cyanobacteria* their characteristic blue-green color. These phycobiliproteins help absorb light of various wavelengths and enhance photosynthetic efficiency. *Cyanobacteria* employ two photosystems (Photosystem I and Photosystem II) in the photosynthesis process, similar to green plants and algae. These photosystems work together to produce energy (ATP) and electron carriers (NADPH) required for converting carbon dioxide into carbohydrates.

Some *Cyanobacteria* are also capable of nitrogen fixation, converting atmospheric nitrogen gas (N_2) into ammonia (NH_3) usable by other organisms. This process contributes to the nitrogen cycle and enables *Cyanobacteria* to thrive in environments with low nitrogen availability. Certain *Cyanobacteria* possess specialized structures called heterocysts, allowing them to separate photosynthetic activity and nitrogen fixation within a single organism. This separation is essential as the enzyme nitrogenase, used for nitrogen fixation, is highly sensitive to oxygen. By separating these processes, *Cyanobacteria* can maintain efficient photosynthesis while facilitating nitrogen fixation.

Cyanobacteria play a crucial role in wastewater treatment due to their ability to remove pollutants, absorb excess nutrients, and produce oxygen through photosynthesis. Some common cyanobacteria species used in wastewater treatment are as follows:

(a) *Anabaena*, a filamentous *Cyanobacteria* genus capable of nitrogen fixation. This species has been employed in wastewater treatment to remove excess nitrogen and phosphorus and aid in controlling harmful algae growth.
(b) Like *Anabaena*, *Nostoc* is also a filamentous *Cyanobacteria* capable of nitrogen fixation (Kollmen and Strieth 2022). This species has been utilized in wastewater treatment to reduce excess nutrients, particularly nitrogen and phosphorus.
(c) *Microcystis* is a colonial *Cyanobacteria* found in freshwater. Although known for producing the microcystin toxin, this species has also been used in wastewater treatment to remove excess nutrients and certain pollutants (Xiao et al. 2018).
(d) *Oscillatoria* is a freshwater blue-green alga that can be harnessed in wastewater treatment to remove pollutants such as heavy metals and absorb excess nutrients (Ankit et al. 2022).

(e) *Phormidium* is commonly found in freshwater environments. This species is reported to reduce excess nutrients and remove some pollutants, such as heavy metals, from wastewater (Lakmali et al. 2022).
(f) *Spirulina* (now popular as *Arthrospira*) is a filamentous *Cyanobacteria* known as a food supplement due to its high protein, vitamin, and mineral content. Additionally, *Spirulina* is used in wastewater treatment to remove excess nutrients and pollutants, such as heavy metals (Nege et al. 2020).

Chlorophyta, or green algae, is a large group of photosynthetic organisms found in various environments such as freshwater, saline water, soil, and even extreme environments like snow and ice (Cho et al. 2022). Green algae exhibit a wide diversity of forms and sizes, ranging from single-celled organisms to colonial and filamentous structures, as well as larger macroalgae known as *Ulvophyceae*. One of the distinguishing characteristics of *Chlorophyta* from other algal groups is the presence of chlorophyll a and chlorophyll b as the primary pigments used in the photosynthesis process. These pigments give them their characteristic green color. Besides chlorophyll, green algae contain carotenoids and xanthophylls, which play roles in light absorption and protect cells from oxidative stress.

The cell walls of green algae are typically made of cellulose, providing structure and mechanical support. In some cases, the cell walls may also contain other polysaccharides such as pectin and hemicellulose. Similar to *Cyanobacteria* and green plants, green algae utilize two photosystems (Photosystem I and Photosystem II) in the photosynthesis. The outcome of this process is the production of oxygen, energy (ATP), and electron carriers (NADPH) used to convert carbon dioxide into carbohydrates. Green algae exhibit a highly diverse reproductive strategy, including asexual reproduction through cell division, fragmentation, and the formation of asexual spores, as well as sexual reproduction involving gametes and zygospores. Traditionally, green algae are classified into three main classes, namely *Chlorophyceae*, *Charophyceae*, and *Ulvophyceae*, based on cell form and structure, pigments, and reproductive patterns. However, this classification continues to evolve with further genetic research. Green algae play vital roles in ecosystems, serving as primary producers in food chains, oxygen producers, and carbon fixers.

Green algae play a significant role in wastewater treatment due to their ability to absorb excess nutrients, remove pollutants, and produce oxygen through the photosynthesis process. Some common genera of green algae used in wastewater treatment are as follows:

(a) *Chlorella* is a genus of microscopic green algae, known for its rapid growth and high photosynthetic efficiency. *Chlorella* has been employed in wastewater treatment to remove excess nutrients such as nitrogen and phosphorus, as well as some pollutants like heavy metals (Karima et al. 2018).
(b) *Scenedesmus* is a colonial genus of green algae commonly found in freshwater. This species has been utilized in wastewater treatment to reduce excessive nutrient content, particularly nitrogen and phosphorus (Qader and Shek 2023), and to remove pollutants such as heavy metals.

(c) *Haematococcus* is a microscopic green algae known as a producer of astaxanthin, an antioxidant pigment with various applications in the nutraceutical and cosmetic industries (Oslan et al. 2021). *Haematococcus* is also used in wastewater treatment to remove excess nutrients and some pollutants.
(d) *Spirogyra* is a filamentous genus of green algae frequently found in freshwater. This species has been employed in wastewater treatment to eliminate excess nutrients, especially nitrogen and phosphorus (Muriuki Githaiga et al. 2020), and to reduce pollutant content, including heavy metals.
(e) *Volvox* is a colonial green algae composed of cells arranged in a spherical shape. This species has been used in wastewater treatment to reduce excessive nutrient content and remove pollutants, such as heavy metals (Diaconu et al. 2023).
(f) *Dunaliella* is a microscopic green algae known as a producer of beta-carotene, a pigment used in food and supplement industries. While the following studies do not specifically discuss *Dunaliella's* application in wastewater treatment containing heavy metals and excess nutrients, they describe the algae's potential in wastewater treatment through phototrophy, mixotrophy, and production of extracellular polymeric substances that can function as biosorbents (Mega et al. 2021).

Phaeophyta, also known as brown algae, is a group of algae primarily found in marine and some freshwater environments. Brown algae encompass a wide range of forms, from microscopic filamentous types to larger macroalgae known as seaweeds (Hakim and Patel 2020). Brown algae contain both chlorophyll a and chlorophyll c, as well as an additional pigment called fucoxanthin, which imparts the characteristic brown color. These pigments are used in the process of photosynthesis. Additionally, brown algae contain various carotenoids and xanthophylls.

The cell walls of brown algae are composed of cellulose and a specific polysaccharide called alginate. Alginate is commercially used as a thickening and binding agent in various food and pharmaceutical products. Brown algae employ two photosystems (Photosystem I and Photosystem II) in the photosynthesis, similar to green algae and *Cyanobacteria.* The result of this process is the production of oxygen, energy (ATP), and electron carrier molecules (NADPH), which are utilized to convert carbon dioxide into carbohydrates. Reproduction in *Phaeophyta* involves a life cycle with three different generations: the haploid gametophyte, the diploid sporophyte, and the tetrasporophyte. Sexual and asexual reproduction occur at different stages in this life cycle. Traditionally, *Phaeophyta* is classified into several orders based on morphology and reproductive structures, such as *Fucales*, *Laminariales*, *Ectocarpales*, and *Sphacelariales.* However, this classification continues to evolve with further genetic research.

Brown algae play a crucial role in ecosystems, particularly as primary producers in marine food chains and as habitats for many marine species. They also have various commercial applications, such as in the production of alginates, foods, and nutritional supplements (e.g., fucoidan and laminarin). While brown algae are less commonly used in wastewater treatment compared to green algae and *Cyanobacteria*, some species have been studied for their ability to remove pollutants and excess nutrients from wastewater. Several potentially beneficial brown algae species in wastewater treatment include:

(a) *Ascophyllum nodosum*, also known as knotted wrack, is a brown algae species found on rocky shores in cold marine regions. This species has been studied for its ability to remove heavy metals, such as copper, lead, and zinc, from wastewater.
(b) *Sargassum muticum* and *Sargassum vulgare* have been studied for their ability to remove excess nutrients, such as phosphate and nitrate, as well as heavy metals like lead and mercury, from wastewater (Hansen et al. 2023).
(c) *Fucus vesiculosus* and *Fucus serratus* have been studied for their ability to remove heavy metals, such as cadmium, copper, and nickel, from wastewater (Hansen et al. 2023).
(d) *Laminaria*, also known as kelp, including *Laminaria digitata* and *Laminaria hyperborea*, has been researched for its ability to remove heavy metals, such as lead and zinc, from wastewater (Venardou et al. 2023).

Selecting the appropriate brown algae species and managing environmental conditions are crucial to optimize the wastewater treatment process using brown algae.

Rhodophyta, or red algae, is a group of algae primarily found in marine waters, although some species are also found in freshwater and wet terrestrial environments (Cotas et al. 2020). Red algae exhibit diverse forms and sizes, ranging from microscopic filaments to more complex macroalgae known as seaweeds (Hakim and Patel 2020). Red algae contain chlorophyll a and chlorophyll d as well as additional pigments called phycobiliproteins, which give them their distinctive red color. These pigments are involved in the photosynthesis process. Red algae also contain carotenoids and other xanthophylls. Their cell walls consist of cellulose, special polysaccharides called agar and carrageenan, as well as proteins. Agar and carrageenan are commercially used as thickeners and binders in various food and pharmaceutical products.

Red algae utilize two photosystems (Photosystem I and Photosystem II) in the process of photosynthesis, similar to green algae and *Cyanobacteria.* However, due to the presence of chlorophyll d and phycobiliproteins, red algae can utilize a different spectrum of light for photosynthesis compared to other algal groups. Reproduction in *Rhodophyta* involves a life cycle with three different generations: haploid gametophyte, diploid sporophyte, and carposporophyte. Sexual and asexual reproduction occur at different stages in this life cycle (Vieira et al. 2018). Traditionally, *Rhodophyta* is classified into several classes based on their morphology and reproductive structures, namely *Florideophyceae*, *Bangiophyceae*, and *Cyanidiophyceae.* However, this classification continues to evolve with further genetic research.

Red algae play a vital role in ecosystems, particularly as primary producers in marine food chains and as habitats for numerous marine species. They also have diverse commercial applications, including the production of agar, carrageenan, and nutritional supplements (e.g., proteins and pigments). Although the use of

Rhodophyta in wastewater treatment has not been extensively explored, some studies have shown the potential of red algae in removing pollutants such as heavy metals and excess nutrients from wastewater. Several *Rhodophyta* species that may be beneficial in wastewater treatment are as follows:

(a) *Gracilaria verrucosa* has the ability to remove excess nutrients, such as phosphates and nitrates, as well as heavy metals, such as lead and mercury, from wastewater.
(b) Gelidium species like *Gelidium amansii* and *Gelidium elegans* have the ability to absorb heavy metals, such as cadmium, copper, and nickel, from wastewater.
(c) *Palmaria palmata* and *Palmaria decipiens* have been reported to effectively remove excess nutrients, such as phosphates and nitrates, from wastewater.
(d) *Chondrus crispus* and *Chondrus ocellatus* possess the ability to remove heavy metals, such as lead and zinc, from wastewater.
(e) *Porphyra* is a genus of red algae that includes many species used in the production of nori, a traditional Japanese food. Some studies have shown that *Porphyra yezoensis* is effective in removing excess nutrients, such as phosphates and nitrates, from wastewater.

When used in wastewater treatment, red algae, such as the aforementioned species, can help reduce contaminants through biosorption and bioaccumulation processes—pollutants bind to the cell walls or are internalized into the algae cells, thereby reducing their concentration in wastewater.

Diatom (*Bacillariophyta*) is a group of microscopic algae found in various freshwater and marine habitats (Fu et al. 2022). Diatoms are known to play a crucial role in aquatic ecosystems and the carbon cycle, acting as primary producers in aquatic food chains. Diatoms have a unique cell wall called a frustule, made of biogenic silica (SiO_2). The frustule has a complex layered structure with repeating patterns and pores, giving diatoms their distinctive shapes and strength. Diatoms contain chlorophyll a and chlorophyll c, as well as additional pigments called fucoxanthin, which impart the characteristic golden-brown color. These pigments are used in the photosynthesis process. Additionally, diatoms also contain carotenoids and other xanthophylls. Diatoms utilize two photosystems (Photosystem I and Photosystem II) in the photosynthesis, similar to green algae and cyanobacteria. However, due to the presence of chlorophyll c and fucoxanthin, diatoms can use a different spectrum of light for photosynthesis compared to other algal groups.

Diatoms mainly reproduce asexually through binary fission. As the silica cell wall cannot expand, diatoms produce smaller daughter cells from the parent cell. Sexual reproduction also occurs in some diatom species, although it is less common. Diatoms are traditionally classified into two main groups based on frustule morphology: centric diatoms (Centrales), which have radial symmetry, and pennate diatoms (Pennales), which have bilateral symmetry. However, this classification continues to evolve with further genetic research. Diatoms have various commercial applications, such as the production of biosilica, pigments, and nutritional supplements (e.g., omega-3 fatty acids) (Sharma et al. 2021). Diatoms have also been studied for their potential in wastewater treatment, particularly in removing excess nutrients such as phosphates and nitrates, as well as organic pollutants and heavy metals. Diatoms can accumulate these pollutants within their cells or remove them through biodegradation and biosorption processes, thereby reducing pollutant concentrations in wastewater and improving water quality. The following are some diatoms that have potential benefits in wastewater treatment:

(a) *Phaeodactylum tricornutum* is a marine diatom that has been studied for its ability to remove excess nutrients such as phosphates and nitrates, as well as heavy metals like copper, cadmium, and lead from wastewater.
(b) *Nitzschia palea* is a freshwater diatom that has been studied for its ability to remove organic pollutants such as phenol and volatile organic chemicals from wastewater (Sudarshan et al. 2019).
(c) *Navicula* is capable of removing excess nutrients such as phosphates and nitrates, as well as heavy metals like chromium, nickel, and zinc from wastewater (Chugh et al. 2022).
(d) Pinnularia is capable of removing pollutants like heavy metals and excess nutrients from wastewater (Bwapwa et al. 2017).
(e) Thalassiosira can remove excess nutrients and organic pollutants from wastewater (Al-Jabri et al. 2021).

Algae have specific characteristics that can be described as follows (Babich et al. 2022):

(1) Algae obtain energy through photosynthesis, converting sunlight energy into chemical energy stored in chemical bonds. The ability of algae to photosynthesize depends on the photosynthetic pigments they possess, such as chlorophyll, carotenoids, and phycoerythrin.
(2) Algae exhibit diverse tolerance to environmental conditions, such as temperature, salinity, pH, and nutrient concentration. This characteristic is important in selecting the most suitable algae for use in specific wastewater treatment systems.
(3) The growth rate and reproduction of algae significantly influence the efficiency of wastewater treatment processes. Some types of algae, like microalgae, have rapid growth rates, enabling them to treat wastewater in a short time.
(4) Algae's characteristics in absorbing pollutants, such as excess nutrients, heavy metals, and organic compounds, are crucial in the context of wastewater treatment. Some algae have high affinities for specific pollutants, making them effective bioremediation agents.
(5) Some types of algae, especially microalgae, have the potential to produce high-value products such as lipids, proteins, pigments, and polysaccharides. These products can be further processed into biofuels, animal feed, fertilizers, and chemicals.

10.2.2 Growth and Reproduction of Algae

Algae growth and reproduction have significant implications for the implementation of algae utilization in wastewater treatment. The selection of algae species with optimal growth and reproduction rates becomes a crucial factor in achieving efficient and sustainable outcomes, as described below (Sharma et al. 2021; Ziganshina et al. 2022):

(1) Processing efficiency: Algae with rapid growth rates can treat wastewater in a shorter time, leading to higher processing efficiency and enabling the system to handle larger wastewater loads. Additionally, fast algal reproduction helps maintain a sufficient algal concentration in the system, ensuring effective wastewater treatment.
(2) System scalability: Fast growth and reproduction of algae allow algae-based wastewater treatment systems to be easily scalable. Systems capable of handling larger wastewater loads are more appealing to industries and governments for adoption, as they offer more efficient and sustainable treatment solutions.
(3) Process stability: Algae that can adapt and reproduce quickly under various environmental conditions contribute to higher process stability. Stable systems are easier to operate and maintain and are more resilient to changes in operational and environmental conditions.
(4) Production of high-value biomass: Algae with rapid growth rates yield a larger biomass. This biomass can be further processed into high-value products such as biofuels, animal feed, fertilizers, and chemicals. High biomass production enhances the economic value of algae-based wastewater treatment systems and supports the transition to a circular economy.
(5) Social and community support: Algae with accelerated growth and reproduction rates can deliver a more immediate positive impact on the environment and water quality. This will increase community support for algae-based wastewater treatment technology and promote its adoption on a larger scale.
(6) Operational and maintenance costs: Rapid growth and reproduction of algae can reduce operational and maintenance costs of wastewater treatment systems. Algae that grow and reproduce quickly require less maintenance intervention and are more resilient to disturbances caused by external factors, such as changes in temperature and light conditions.

10.2.3 Algae Interaction with the Environment

The interaction of algae with the environment is crucial in influencing the implementation of algae utilization for wastewater treatment. Environmental factors significantly impact algae growth, explained as follows:

Availability of Light

Light influences the rate of photosynthesis and the growth of algae, thereby affecting the efficiency of algae-based wastewater treatment systems (Katam et al. 2022). Systems designed considering optimal light availability will yield better results in wastewater treatment. Light availability can be controlled by adjusting the pond depth, providing additional illumination, and considering factors such as light intensity, duration, and spectrum. Through the photosynthesis process, algae produce oxygen as a byproduct, enhancing water quality by increasing dissolved oxygen levels. This condition supports aquatic life and other biological processes occurring in water bodies. In the context of photosynthesis, algae also play a role in carbon dioxide (CO_2) sequestration from the environment. By means of photosynthesis, algae convert CO_2 into biomass, thereby reducing greenhouse gas emissions and contributing to mitigating the impacts of climate change.

Availability of Nutrients in Wastewater

The concentration of nutrients in wastewater, such as nitrogen and phosphorus, affects algae growth (Alazaiza et al. 2023). Algae utilize these nutrients as a food source, converting them into biomass. Optimal nutrient conditions support rapid and efficient algae growth, thereby enhancing the effectiveness of wastewater treatment systems. The optimal nitrogen and phosphorus concentrations for algae growth depend significantly on the algae species. Generally, nitrogen concentrations ranging from 10 to 60 mg/L and phosphorus level of 1–8 mg/L are considered suitable, although these requirements may vary depending on the physiological conditions of the microalgae involved.

Temperature

Algae’s ability to grow and reproduce under various environmental conditions, such as temperature and pH, impacts the effectiveness of algae-based wastewater treatment systems (Oruganti et al. 2022). Algae that tolerate environmental changes are easier to manage and can adapt to different types of wastewater. Water temperature and pH affect the rate of algae growth and metabolic activity. Each algae species has an optimal range of temperature and pH for its growth. In designing algae-based wastewater treatment systems, it is essential to consider the appropriate temperature and pH conditions suitable for the utilized algae. Generally, temperatures ranging from 20 to 30 °C are considered optimal for the growth of many microalgae species. This optimal temperature range can increase the rate of algae growth and the efficiency of algae-based wastewater treatment systems.

Temperatures above 30 °C are generally unsuitable for microalgae growth for several reasons listed below (Barten et al. 2020):

(a) Protein denaturation: High temperatures can cause protein denaturation, resulting in the alteration of protein structure and loss of function. Proteins are vital components in the metabolism and cell growth of algae, so protein denaturation will inhibit algae growth.

(b) Oxidative stress: High temperatures can increase the production of reactive oxygen species (ROS) within algae cells. Excessive ROS can cause cell damage, including structural changes to membranes, DNA damage, and oxidation of proteins and lipids. Algae have antioxidant systems to combat ROS, but if ROS production exceeds the antioxidant capacity, oxidative stress will hinder algae growth.
(c) Enzyme reaction rate changes: High temperatures can affect the rate of enzymatic reactions within algae cells. Each enzyme has an optimal temperature at which it functions most efficiently. If the temperature exceeds the optimal range, enzyme activity decreases, reducing the rate of metabolism and algae growth.
(d) Evaporation: High temperatures can increase the rate of evaporation in algae cultivation systems, leading to a reduction in water volume and nutrient concentration available to algae. Decreased water and nutrient availability will impact algae growth.

However, some references discuss the existence of thermophilic microalgae that thrive better at temperatures above 30 °C, thus potentially enhancing the efficiency of algae-based wastewater treatment systems.

Environmental pH

The optimum pH for algae growth in the context of wastewater treatment generally ranges from 7 to 9, although this may vary depending on the physiological characteristics of the algae species and the type of wastewater (Ma and Jian 2023). Environmental pH significantly influences the growth of microalgae in wastewater treatment for several reasons:

(a) The level of pH affects the solubility and availability of essential nutrients such as phosphorus, nitrogen, and metal ions in water. Some nutrients are more readily utilized by algae at specific pH levels. If the pH is unsuitable, these nutrients become less soluble and challenging for algae to absorb, thereby inhibiting their growth.
(b) Enzymes within algae cells are highly sensitive to pH changes. Each enzyme has an optimum pH at which it functions most efficiently. If the environmental pH falls outside the optimal range, enzyme activity decreases, leading to a reduction in metabolic rate and algae growth.
(c) Extreme environmental pH can cause changes in the structure and stability of algal cell membranes, which can result in cell leakage and cell death. Cell membranes also play a role in nutrient and ion transport across the membrane, so changes in membrane stability will affect algae's ability to absorb nutrients.
(d) Some algae species are more tolerant of pH fluctuations than others. Tolerant algae species may still grow under less optimal pH conditions, while more sensitive species may experience reduced growth or even die (Masojídek et al. 2021). Therefore, the suitable environmental pH for algae growth depends on the species used in the wastewater treatment system.

Chlorella vulgaris shows better growth at pH 6 compared to higher pH levels (7–9). Additionally, lipid production increases at pH 6, potentially improving the quality of algal biomass for bioenergy purposes. Generally, microalgae exhibit better growth rates at higher pH levels (approximately 7–9) in the context of wastewater treatment. However, this discovery suggests that certain microalgae species may thrive well at pH 5 and pH 6, which could enhance the efficiency of algae-based wastewater treatment systems at these pH levels.

Salinity of Wastewater

The salinity of wastewater can affect algae growth and activity (Al-Enazi 2020). Some algae species are more tolerant of high salt concentrations, while others are better suited to freshwater conditions. Some microalgae species grow better at low salinity levels, such as freshwater, while others are more tolerant of higher salinity levels, such as seawater or brackish water. Generally, low to moderate salinity (around 0.1–3% based on total dissolved solids content) is advantageous for microalgae growth in the context of algae-based wastewater treatment. Selecting the appropriate algae species that can thrive under the salinity level of the wastewater will enhance treatment efficiency.

Presence of Heavy Metals in the Environment

Algae growth is generally inhibited by high concentrations of heavy metals (Wang et al. 2022), as these metals can be toxic to algae. However, some studies indicate that low concentrations of heavy metals can act as nutrients and may affect algae growth rates. Therefore, it is essential to consider algae species that are tolerant of wastewater toxicity conditions. The ability of algae to absorb pollutants, such as excess nutrients, heavy metals, and organic compounds, is crucial in wastewater treatment. The interaction of algae with these pollutants through bioadsorption, biosorption, and biodegradation processes helps to remove pollutants from the water and improve water quality.

Interactions with Other Microorganisms or Synecology

In wastewater treatment systems, algae interact with various other microorganisms, such as bacteria, protozoa, and invertebrates. These interactions can be symbiotic, competitive, or predator–prey relationships. Some types of algae, particularly microalgae, can reduce the number of pathogens in wastewater through predation, competition, and the production of antimicrobial compounds. This helps to decrease the spread of waterborne diseases. By understanding and managing these interactions effectively, the efficiency of wastewater treatment can be enhanced (Młyński et al. 2020).

(a) Predation: Microalgae serve as a food source for other microscopic organisms known as protozoa and metazoa. These organisms prey on microalgae and pathogens present in wastewater. In this process, the number of pathogens decreases as they become prey for protozoa and metazoa. Thus, by increasing the population of microalgae in wastewater, the number of pathogens can be regulated through the microscopic food chain.

(b) Competition: Microalgae compete with pathogens and other microorganisms in wastewater for limited resources, including phosphate, nitrate, and ammonium. Microalgae can utilize these nutrients more efficiently than pathogens, limiting their growth. Moreover, microalgae can absorb heavy metals and harmful chemicals, further hindering pathogen growth.

(c) Production of antimicrobial compounds: Some microalgae species are known to produce antimicrobial compounds that inhibit pathogen growth. These compounds include aldehydes, unsaturated fatty acids, polysaccharides, and peptides. These compounds exhibit effective antimicrobial activities against various pathogens, such as bacteria, viruses, protozoa, and fungi. The production of antimicrobial compounds by microalgae can enhance the efficiency of wastewater treatment systems in reducing the number of pathogens and maintaining water quality.

Consequently, through predation, competition, and the production of antimicrobial compounds, microalgae play a significant role in reducing the number of pathogens in wastewater. The use of microalgae in wastewater treatment is not only environmentally friendly but also enhances treatment efficiency and effectiveness while reducing operational costs.

10.3 Wastewater Treatment Process with Algae

10.3.1 Principles and Mechanisms

Wastewater treatment through harnessing the metabolic activity of microalgae involves several key principles and mechanisms (Abdelfattah et al. 2023). This process is commonly known as phytoremediation or algae-based bioremediation. The principles and mechanisms involved in wastewater treatment using algae can be explained as follows: Algae are photosynthetic organisms capable of converting solar energy into chemical energy through photosynthesis. During this process, algae absorb carbon dioxide (CO_2), thereby reducing the CO_2 levels in wastewater, while releasing oxygen (O_2) into the water to aid in the oxidation and degradation of organic matter in the wastewater. High levels of dissolved oxygen are crucial for supporting the life of other aquatic organisms.

Algae require nutrients such as nitrogen (N) and phosphorus (P) for their growth and development. These nutrients are often found in high concentrations in industrial wastewater, typically present in the form of ammonia, nitrate, and phosphate. The uptake of nutrients by algae helps to reduce the excessive nutrient concentration in wastewater, thereby mitigating the potential for eutrophication upon wastewater discharge into the environment. Algae are capable of degrading and absorbing various dissolved pollutants in wastewater, such as heavy metals, pesticides, and organic compounds. This process is known as biodegradation (for pollutants broken down into simpler compounds) and bioaccumulation (for pollutants that accumulate within algae cells). Certain microalgae can degrade organic compounds present in wastewater, such as pesticides, hydrocarbons, and phenols. This process involves enzymes produced by algae that break down the organic compounds into simpler and less toxic components.

Microalgae can absorb and accumulate heavy metals, such as mercury, cadmium, and lead, from wastewater (Ankit et al. 2022). This process involves adsorption, precipitation, and complexation mechanisms. The absorption of heavy metals by algae helps to reduce the concentration of these metals in wastewater, thus lowering the risk of environmental pollution. During growth and reproduction, algae form larger and denser aggregates called flocs. This process is referred to as coagulation and flocculation. Some microalgae produce extracellular polysaccharides that act as natural coagulants and flocculants. Coagulation and flocculation processes aid in the agglomeration of solid particles and colloids dissolved in wastewater, facilitating the separation of solids from the treated water.

The phase of dense algae growth helps to aggregate particles and pollutants in the wastewater, thereby facilitating solid–liquid separation. After coagulation and flocculation, algal solids and flocs containing pollutants can be separated from the wastewater through solid–liquid separation processes. This can be achieved through gravity-based methods (such as sedimentation), filtration, or centrifugation. Following solid–liquid separation, the algal biomass that has absorbed pollutants can be utilized for various purposes, such as bioenergy production (e.g., biogas or biodiesel), animal feed, fertilizers, or chemicals. The utilization of algal biomass helps to reduce environmental impacts and creates additional economic value from the wastewater treatment process.

During the wastewater treatment process, microalgae grow and produce biomass. This biomass can be further processed into high-value products, such as biofuels, animal feed, fertilizers, and chemicals. The production of biomass by algae also enhances the economic value of algae-based wastewater treatment systems. Overall, industrial wastewater treatment using algae is an environmentally-friendly approach that combines natural mechanisms with wastewater treatment technologies. In practice, microalgae-based wastewater treatment systems may involve the utilization of single algae species or consortia of algae with diverse metabolic capabilities.

10.3.2 Processing Parameters and Efficiency

Monitoring and controlling parameters are crucial to ensure the efficiency of microalgae-based wastewater treatment and to reduce negative environmental impacts. Microalgae can grow under various environmental conditions, such as changes in temperature, salinity, or water quality, and can adapt to different types of wastewaters. Several parameters affect the efficiency of microalgae-based wastewater treatment, including physical, chemical, and biological factors as listed below:

(1) Light availability: Light serves as an energy source for microalgae photosynthesis. Adequate light intensity, spectrum, and duration affect the rate of photosynthesis and algae growth, which, in turn, influences the efficiency of wastewater treatment.
(2) Temperature: Temperature affects the rate of metabolism and growth of microalgae. Each microalgae species has an optimal temperature range for growth and metabolic activity. Optimal temperature enhances the efficiency of the treatment process, while temperatures that are too high or too low can inhibit algae growth and reduce treatment efficiency. Controlling the temperature in the wastewater treatment system helps achieve higher efficiency.
(3) Nutrient availability: Nutrients including nitrogen, phosphorus, carbon, and micronutrients affect the growth and metabolic activity of microalgae. A balanced nutrient concentration ensures optimal algae growth and efficient pollutant uptake.
(4) pH of wastewater: The pH of wastewater affects the activity of enzymes and the permeability of microalgae cell membranes. Each microalgae species has an optimal pH range for growth and metabolic activity. Optimal pH ensures proper enzyme function and efficient pollutant uptake. Controlling the pH in the wastewater treatment system contributes to higher efficiency.
(5) Selection of appropriate microalgae species with favorable growth characteristics and high pollutant absorption capacity enhances the efficiency of microalgae-based wastewater treatment.
(6) Microalgae concentration in the treatment system affects the system's ability to treat pollutants (Amaro et al. 2023). An optimal concentration ensures efficient pollutant uptake and robust algae growth. The optimal microalgae concentration for wastewater treatment, ensuring efficient nutrient and heavy metal removal, falls within the range of 0.5–2 g/L. Some studies have shown that a microalgae concentration of 1 g/L can achieve high efficiency in nutrient and heavy metal uptake. Higher microalgae concentrations may enhance heavy metal and nutrient removal, but increased microalgae growth requires more energy and nutrients. Therefore, finding a balance between removal efficiency and operational costs is essential.

    Using microalgae concentrations higher than 1 g/L in wastewater treatment can offer advantages and benefits, although some considerations need to be taken into account to determine the most optimal concentration. The advantages of using microalgae concentrations higher than 1 g/L (Abdelfattah et al. 2023) include higher biomass production, which can be utilized for various applications, such as bioenergy production (biodiesel and biogas), animal feed, and biologically-based chemical products.

    However, prior to increasing microalgae concentration in wastewater treatment, population density considerations should be factored in. High population density can increase competition among microalgae for resources (nutrients and light), thereby reducing growth and removal efficiency.
(7) Adequate aeration and agitation in microalgae-based wastewater treatment systems ensure sufficient dissolved oxygen for biological oxidation processes

and maintain a homogenous distribution of algae in the system. In other words, aeration and agitation affect gas and nutrient transfer between wastewater and microalgae, as well as prevent microalgae settling in the system. Adequate aeration and agitation improve the efficiency of microalgae-based wastewater treatment (Srimongkol et al. 2022).

Thus, optimal aeration and agitation may need to be adjusted based on the physiological needs of microalgae species, the design of the photobioreactor or conventional pond system, and the specific characteristics of the wastewater. Additionally, the optimal conditions for aeration and agitation should also consider energy costs and their impact on microalgae life in the system (Valchev and Ribarova 2022).

(8) Hydraulic Retention Time (HRT) refers to the time required for wastewater to pass through the treatment system. An optimal HRT ensures sufficient contact between microalgae and pollutants, thereby enhancing removal efficiency.

10.3.3 Systems and Technology Used

Various systems and technologies can be implemented for wastewater treatment utilizing microalgae. The selection of appropriate systems and technologies for microalgae-based wastewater treatment depends on various factors (Goh et al. 2023), including wastewater characteristics, treatment objectives, climatic and geographic conditions, as well as land availability and resources. Some common alternative systems and technologies are as follows:

Ponds and Raceway Pond Systems

Ponds are open systems used for microalgae cultivation. Open ponds are the simplest cultivation system, consisting of shallow channels or ponds with water circulation to maintain even algal biomass distribution. Shallow and wide open ponds allow for good light penetration and sufficient water circulation. Generally, the optimal pond design for microalgae-based wastewater treatment will include efficient aeration and agitation systems, proper lighting, as well as optimal temperature and pH conditions. However, more detailed specifications will depend on the type of microalgae used, wastewater characteristics, and the final objectives of wastewater treatment (e.g., biofuel production, nutrient processing, or heavy metal absorption).

Raceway Pond Systems are a variation of open ponds designed to enhance water circulation and gas exchange. This system consists of U-shaped channels with paddle wheels or other mechanical devices continuously stirring the water. The raceway pond system allows for more efficient and uniform microalgae growth, enhancing the wastewater treatment capability. In general, the optimal design of ponds or raceway pond systems for microalgae-based wastewater treatment should consider aeration and agitation efficiency, light utilization, as well as ease of microalgae biomass maintenance and collection.

Although open ponds are cheaper and easier to operate and maintain compared to photobioreactor (PBR) systems, they have limited control over the environment (especially temperature and pH), making them more vulnerable to contamination and changes in environmental conditions (Li et al. 2023). Open ponds are generally used for large-scale wastewater treatment due to relatively lower construction and maintenance costs. Therefore, the design and operation of raceway pond systems need to be tailored based on the specific needs of the wastewater treatment system being used.

High-Rate Algal Pond (HRAP)

HRAP is a specialized open pond system designed for high microalgae growth rates. This system features shallow channels or ponds with strong water circulation to enhance the contact between microalgae and nutrients in the wastewater (Li et al. 2023). HRAP is commonly used for nutrient-rich wastewater treatment and biomass production. In general, the optimal design of HRAP for microalgae-based wastewater treatment should consider aeration efficiency, pond depth, light utilization, temperature control, as well as appropriate pH and nutrient concentration. The selection of suitable microalgae species and operational conditions are also crucial for achieving optimal outcomes in HRAP systems.

Algal Turf Scrubber (ATS) and Biofilm-Based System

Algal Turf Scrubber (ATS) and biofilm-based systems are two different approaches for utilizing microalgae in wastewater treatment. They share similarities and differences in terms of working principles, system design, and treatment efficiency (Reinecke et al. 2023). Both systems utilize microalgae for wastewater treatment and the removal of pollutants such as nutrients and heavy metals; both harness the microalgae's photosynthesis to convert available nutrients in wastewater into biomass, which can be further processed for various purposes such as biogas or biofuel production. In addition, both systems enable more efficient pollutant uptake compared to conventional wastewater treatment systems.

The primary differences between both systems can be explained as follows:

(1) System design: The Algal Turf Scrubber (ATS) is a system that utilizes coarse and porous substrates (such as mesh or fibers) on which microalgae grow in the form of "turf" or a thin carpet. Wastewater flows over the substrate, and microalgae absorb pollutants as they grow on it. On the other hand, biofilm-based systems involve microalgae growing as a thin layer or biofilm on suitable surfaces such as plates, rods, or spheres.

(2) Biomass maintenance and recovery: In ATS, microalgae biomass can be easily removed from the substrate through brushing or scraping, allowing periodic biomass recovery and preventing competition for space and nutrients among microalgae. In biofilm-based systems, biomass recovery may be more challenging and require more complex separation techniques, such as peeling or using enzymes to detach the biofilm from the surface.

(3) Light efficiency: ATS allows better light penetration into microalgae growing on the substrate, optimizing photosynthesis and microalgae growth. Biofilm-based systems may have limitations in light penetration, especially when the biofilm becomes thick, which can affect treatment efficiency.
(4) Resilience to disturbances: ATS tends to be more tolerant to changes in environmental conditions such as temperature, pH, and pollutant concentrations. Biofilm-based systems may be more vulnerable to such changes, which can affect microalgae growth and activity within the biofilm.
(5) Space requirement: ATS usually requires a larger area compared to biofilm-based systems due to the flowing water over the substrate. Biofilm-based systems can save space through vertical layouts or using media with complex shapes to increase the available surface area for biofilm growth.

Overall, the optimal design of ATS for microalgae-based wastewater treatment needs to consider the appropriate substrate selection, microalgae species, and operational conditions (such as lighting and aeration) (Valchev and Ribarova 2022). Wastewater treatment efficiency can also be enhanced with proper nutrient control and regular system maintenance. In the context of microalgae-based wastewater treatment, biofilm plays a significant role in pollutant removal from wastewater. Microalgae in the biofilm can take up nutrients such as phosphate and nitrogen, as well as organic compounds from wastewater and convert them into biomass. This process is known as bioremediation and can help reduce contaminants in wastewater before it is discharged into the environment or reused in industrial or agricultural processes (Ojha et al. 2021). Moreover, microalgae can produce oxygen through photosynthesis, which aids in the biological oxidation process to further break down organic compounds.

To build an optimal biofilm-based system for microalgae-based wastewater treatment, considerations include selecting appropriate substrates, effective microalgae species, optimal lighting, and proper operational conditions (such as aeration and nutrient control) need to be accounted for. The biofilm-based system offers advantages in space utilization and easier biomass separation compared to systems without biofilm. Biofilms are formed when microorganisms, like microalgae, attach to a surface and start producing extracellular polymeric substances (EPS), including proteins, polysaccharides, and nucleic acids. These EPS form a matrix that protects and supports the associated microorganisms within the biofilm. The mechanism of biofilm formation in microalgae-based wastewater treatment occurs sequentially as follows (Srimongkol et al. 2022):

(1) Initiation: Microalgae initially attach to available surfaces, such as plant stems or reactor surfaces. This initial attachment is reversible and influenced by interactions between microalgae and the surface, such as van der Waals forces, electrostatic repulsion, and hydrophobic interactions.
(2) Irreversible attachment: After the initial attachment, microalgae begin to produce EPS. This process makes the attachment irreversible and aids in biofilm growth and development.

(3) Growth and maturation: During this phase, the biofilm starts to grow and develop more complex structures. Microalgae in the biofilm acquire nutrients from wastewater and continue to reproduce. Formation of chemical and physical gradients within the biofilm allows various microorganism species, including bacteria and protozoa, to coexist and contribute to the wastewater treatment process.
(4) Dispersion: At some point, parts of the biofilm will detach from the matrix and enter the wastewater. This dispersion allows the spread of microalgae and other microorganisms, maintaining the cycle of biofilm growth.

Photobioreactor (PBR)

The photobioreactor is a closed system specifically designed for the growth of microalgae with strict environmental controls, such as temperature, pH, and illumination. In the context of wastewater treatment using microalgae, the photobioreactor provides an optimal environment for microalgae growth and maximizes their ability to remove contaminants from wastewater through photosynthesis and bioremediation, resulting in higher wastewater treatment efficiency compared to open systems.

Some advantages of photobioreactors include the ability to control environmental conditions—e.g., temperature, pH, nutrients, and light intensity—all of which are crucial for microalgae growth and activity. The concentration of microalgae can be maintained at higher levels compared to open systems, thereby enhancing wastewater treatment efficiency. Being closed and isolated from the surrounding environment, photobioreactors reduce the risk of contamination by pathogens or unwanted microorganisms. Furthermore, photobioreactors typically have smaller sizes and require less land compared to open ponds, making them more suitable for areas with limited space.

However, wastewater treatment using photobioreactors also has some disadvantages as follows:

(1) Photobioreactor requires higher initial investment costs compared to open systems (such as open ponds or flow-through systems) due to the need for more sophisticated equipment and technology.
(2) Photobioreactors generally have higher operational costs because of the strict control of environmental conditions, including temperature, pH, and light intensity. Additionally, the energy required to operate equipment, such as pumps and control systems, can increase operational costs.
(3) Although photobioreactors can achieve higher biomass concentrations, scaling up photobioreactor systems to an industrial level can be challenging. The design and operation of large-scale photobioreactors are more complex and require more resources.
(4) In photobioreactors, the risk of fouling or formation of deposits on the reactor surface is higher, subsequently reducing light efficiency and hinder microalgae growth. Regular cleaning and maintenance are required to maintain photobioreactor performance.

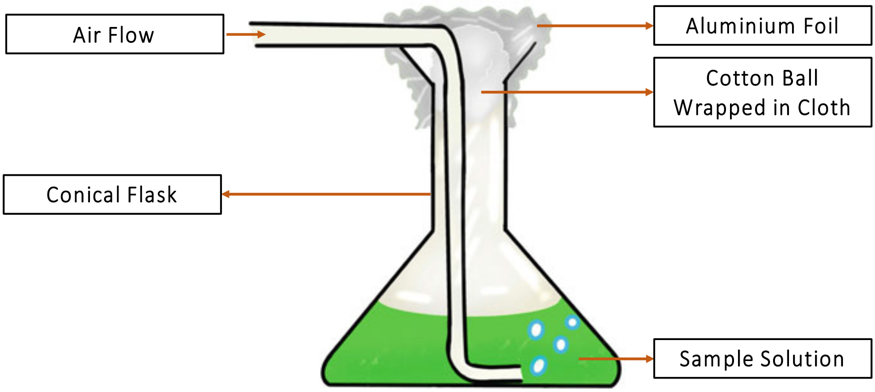

Fig. 10.3 Conical flask prototype

(5) Closed photobioreactors have limitations in gas exchange, such as oxygen and carbon dioxide, which are important for microalgae growth. Inadequate design can lead to gas accumulation, negatively affecting the microalgae activity.

Photobioreactors can be designed in the form of tubes, panels, or transparent plastic bags (Huang et al. 2017). However, the construction, investment, and maintenance costs of photobioreactors are generally higher compared to open pond systems. Various types of photobioreactors have been developed, listed as follows:

(1) Tubular photobioreactor, which is commonly used for microalgae cultivation and wastewater treatment (Egbo et al. 2018). The tubular photobioreactor consists of transparent tubes typically made of glass or plastic, in which microalgae are grown. These tubes are connected in series or parallel configurations and can have straight, spiral, or helical shapes, or even in prototype forms, as shown in Fig. 10.3 (Alazaiza et al. 2023).

Tube photobioreactor allows for efficient light penetration into the microalgae culture, which is essential for the photosynthesis process. Efficient light penetration affects the growth rate of microalgae and the efficiency of wastewater treatment. Tube photobioreactor often employs an airlift system or pumps to create circulation within the reactor. This mixing ensures even distribution of microalgae and sufficient access to nutrients, light, and CO_2 required for photosynthesis. On top of that, mixing aids in gas transfer, such as oxygen and CO_2, between the microalgae culture and the environment. In the tube photobioreactor, microalgae grow in high concentrations, enabling them to efficiently treat wastewater and reduce pollution loads.

Environmental conditions such as temperature, pH, and nutrient concentration can be easily regulated and monitored compared to open systems like open ponds. Such preferable environmental control allows for optimal microalgae growth and higher efficiency in wastewater treatment. Tube photobioreactors can be scaled up from laboratory to industrial scale, although construction and maintenance costs may be higher compared to open systems. However, the increased biomass productivity and wastewater treatment efficiency can help balance these additional costs.

(2) Flat panel photobioreactor is another type of photobioreactor used for cultivating microalgae in the context of wastewater treatment (Benner et al. 2022). This photobioreactor utilizes transparent flat plates or slightly tilted plates, allowing microalgae to grow between them. Flat panel photobioreactor provides a larger surface area for light penetration, which is crucial for microalgae photosynthesis Effective light penetration in the flat panel photobioreactor enables more efficient microalgae growth and boosts wastewater treatment efficiency.

In the flat panel photobioreactor, mixing and gas transfer between microalgae and the environment are regulated through an airlift system or gas bubble arrangement as shown in Fig. 10.4 (Benner et al. 2022). Proper mixing ensures sufficient access to nutrients, light, and CO_2 required for photosynthesis, while removing by-products such as oxygen yielded during this process.

Microalgae in the flat panel photobioreactor effectively assimilate pollutants in wastewater, including nutrients (nitrogen and phosphorus), heavy metals, and organic compounds. The high concentration of microalgae biomass in the flat panel photobioreactor enhances wastewater treatment efficiency and reduces pollution loads. Better control over environmental conditions—such as temperature, pH, and nutrient concentration—can be achieved compared to

Fig. 10.4 Gas bubble photobioreactor (Benner et al. 2022)

open systems like open ponds. This improved environmental control allows for optimal microalgae growth and higher efficiency in wastewater treatment. Flat panel photobioreactors can be scaled up from laboratory to industrial scale. However, construction and maintenance costs may be higher compared to open systems or tube photobioreactors. Scaling down and increased biomass productivity can help balance these additional costs.

Overall, flat panel photobioreactor is a suitable choice for microalgae cultivation and wastewater treatment, as it offers proper environmental control, efficient light penetration, and high treatment efficiency (Goh et al. 2023). However, it also has some limitations, such as higher costs and more complex installation compared to tube photobioreactors.

(3) Airlift photobioreactor is a system that utilizes air or gas to create circulation within the reactor. Airlift photobioreactors can take the form of tubes or flat panels. This photobioreactor operates on the principle of airlift—gas (usually air or CO_2) is injected into the bottom of the reactor, which then rises through the liquid column, generating natural circulation within the reactor. Microalgae are cultivated in a column consisting of one or several separate compartments. Airlift promotes effective mixing, gas transfer, and reduces the risk of contamination.

In the airlift photobioreactor, mixing and gas transfer between microalgae and the environment occur efficiently due to the natural circulation generated by gas injection (Cui et al. 2020). Proper mixing ensures sufficient access to nutrients, light, and CO_2 required for photosynthesis, as well as the removal of by-products such as oxygen yielded during this process.

Light penetration in the airlift photobioreactor depends on the reactor design, such as the shape and dimensions of the tube or panel. Airlift photobioreactors are generally designed with smaller diameters or thicknesses to maximize light penetration, which is crucial for microalgae growth and wastewater treatment efficiency. Microalgae in the airlift photobioreactor effectively assimilate pollutants in wastewater, including nutrients (nitrogen and phosphorus), heavy metals, and organic compounds. The high concentration of microalgae biomass in the airlift photobioreactor enhances wastewater treatment efficiency and reduces pollution loads.

Airlift photobioreactor allows for better control over environmental conditions, such as temperature, pH, and nutrient concentration, compared to open systems like open ponds. This improved environmental control allows for optimal microalgae growth and higher efficiency in wastewater treatment. Airlift photobioreactors can be scaled up from laboratory to industrial scale. Construction and maintenance costs may be lower compared to tube or flat panel photobioreactors, primarily due to the natural circulation generated by gas injection, which reduces the need for mechanical mixing equipment. Overall, airlift photobioreactor is a viable choice for microalgae cultivation and wastewater treatment, as it offers convenient environmental control, high mixing and gas transfer efficiency, as well as high treatment efficiency.

(4) Bubble column photobioreactor: This photobioreactor utilizes a transparent column filled with the culture medium (Benner et al. 2022), and air or gas is

bubbled through the bottom of the column. The resulting gas bubbles create circulation and mixing within the medium, promoting efficient microalgae growth. Bubble column photobioreactor is easy to design and has relatively low construction and maintenance costs.

Bubble column photobioreactor achieves effective mixing through the rising gas bubbles. This mixing ensures sufficient access to nutrients, light, and CO_2 required for photosynthesis; and eliminates by-products such as oxygen. Light penetration in the bubble column photobioreactor depends on the reactor design, its size, and density of the gas bubbles. In some cases, large or excessive gas bubbles may reduce light penetration, thus decreasing photosynthesis efficiency and microalgae growth.

Microalgae in the bubble column photobioreactor effectively assimilate pollutants in wastewater, including nutrients (nitrogen and phosphorus), heavy metals, and organic compounds. The high concentration of microalgae biomass in the bubble column photobioreactor enhances wastewater treatment efficiency and reduces pollution loads. Better environmental control allows for optimal microalgae growth and higher efficiency in wastewater treatment. Like other types of photobioreactors, bubble column photobioreactors can be scaled up from laboratory to industrial scale. Construction and maintenance costs may be lower compared to some other types of photobioreactors, such as tube or flat panel photobioreactors.

Airlift photobioreactor and bubble column photobioreactor are two different types of photobioreactors but share some similarities (Ding et al. 2021), which are elaborated in Table 10.1.

While both types of photobioreactors can be used for microalgae cultivation and wastewater treatment, the choice between them will depend on specific requirements, costs, and expected efficiencies in a particular application (Rinanti et al. 2014).

Table 10.1 Similarities and differences between airlift and bubble column photobioreactors

Similarities

Both belong to photobioreactors based on the principle of mixing through gas flow

Differences

Airlift photobioreactor	Bubble column photobioreactor
• This photobioreactor utilizes the airlift principle, where gas is injected into the bottom of the riser (upward column) and liquid is drawn upwards by the gas bubbles	• Bubble column photobioreactor involves gas injection into the bottom of a single liquid column, creating rising bubbles that mix its contents
• In the airlift photobioreactor, fluid circulation occurs between the riser and downcomer (downward column) due to the density difference between them	• Mixing in the bubble column photobioreactor occurs as gas bubbles rise within a single liquid column
• Airlift photobioreactor generally has a more complex design, involving multiple components such as riser, downcomer, and gas injector	• Bubble column photobioreactor has a simpler design as it only involves a single liquid column and gas injection system

Biofilm Photobioreactor

A biofilm photobioreactor is a type of photobioreactor designed to cultivate microalgae in the form of biofilms on solid surfaces within the reactor (Moreno Osorio et al. 2021). Microalgae adhere to a substrate, typically in the form of plates, threads, or other materials with a large surface area for microalgae growth. The biofilm photobioreactor offers several advantages compared to suspended liquid photobioreactors, as explained below:

(a) Allowing microalgae to grow at higher cell densities, thereby enhancing system productivity and efficiency.
(b) Providing protection for microalgae from unfavorable environmental conditions, such as temperature changes, pH variations, or fluctuations in nutrient concentrations.
(c) Enabling better control of fluid flow, as it can be independently regulated from microalgae growth.
(d) Facilitating easier biomass separation from the wastewater since microalgae grow on solid substrates rather than being dispersed in suspension.
(e) Demonstrating effectiveness in wastewater treatment, as microalgae growing in biofilms deliver higher removal efficiency of nutrients and pollutants from wastewater compared to suspended liquid systems.

However, biofilm photobioreactors also present several challenges (Guzzon et al. 2019), including:

(a) Requiring a uniform light distribution to all microalgae cells growing in the biofilm photobioreactor.
(b) Entailing more intensive maintenance compared to suspended liquid photobioreactors, including cleaning or replacing substrates covered with biofilm.
(c) Involving biofilm thickness monitoring to ensure efficient photosynthesis, as an excessively thick biofilm can hinder light penetration and lead to anaerobic conditions within the biofilm.

10.3.4 Integration of Algae Technology with Other Wastewater Treatment Technologies

The integration of algae technology with other wastewater treatment technologies can be achieved through various methods, depending on the specific objectives, characteristics of the wastewater, and operational conditions (Gururani et al. 2022). This integration allows for improved efficiency and effectiveness in wastewater treatment. Several examples of such integrations are elaborated below:

Hybrid Reactor System

The hybrid reactor system is a system that combines features and advantages from two or more different types of reactors to achieve higher efficiency and overcome the limitations of each individual system. In the context of microalgae-based wastewater treatment, the hybrid reactor system typically combines features from open ponds (algae ponds) and photobioreactors.

Open ponds are a relatively simple and cost-effective system commonly used for large-scale cultivation of microalgae. However, this system has lower productivity than photobioreactors and is susceptible to contamination and environmental changes. On the other hand, photobioreactors are closed systems that offer more controlled growth conditions for microalgae, resulting in higher biomass productivity, reduced contamination risk, and better control over growth parameters. Nevertheless, photobioreactors generally have higher operational and maintenance costs compared to open ponds.

A hybrid reactor system that combines features from open ponds and photobioreactors can achieve higher efficiency in microalgae-based wastewater treatment by leveraging the advantages of both systems. For instance, microalgae can initially grow in open ponds to reduce the initial pollution load of wastewater, then be transferred to photobioreactors for further growth and more efficient nutrient processing. Hybrid reactors can also be used to produce high-value products, such as pigments or lipids for bioenergy production.

Hybrid systems also integrate microalgae-based approaches with conventional wastewater treatment technologies, such as active sludge, anaerobic, or aerobic systems. In this hybrid method, microalgae cooperate with bacteria and other microorganisms to enhance wastewater treatment efficiency. Bacteria degrade organic compounds and produce CO_2, which microalgae utilize for photosynthesis. As a result, microalgae release oxygen, which bacteria use for oxidation. This system improves wastewater treatment efficiency and generates a synergistic effect between microalgae and bacteria. Hybrid systems allow better environmental control during the initial stages and take advantage of the low maintenance costs of open ponds during the final stages, reducing operational costs and improving wastewater treatment efficiency.

In this system, microalgae are utilized alongside aerobic and anaerobic processes for wastewater treatment (Amenorfenyo et al. 2019). Microalgae can be grown in photobioreactors or open ponds and combined with conventional wastewater treatment systems, such as aerobic and anaerobic systems, after initial processing stages. In the advanced treatment stage following aerobic or anaerobic processes, the pretreated wastewater serves as a nutrient source for microalgae growth. The remaining nutrients are consumed, lowering pathogen levels. Microalgae take up the remaining nutrients and pollutants, while their photosynthesis produces oxygen to facilitate the aerobic process and reduce energy requirements for aeration. This process enhances treatment efficiency, including the reduction of excess nutrients, heavy metals, and hazardous organic compounds; leading to improved wastewater quality and enabling safe recycling or environmentally safe disposal.

Generally, literature focusing on hybrid reactor systems for microalgae-based wastewater treatment is still limited. However, by studying various existing systems (e.g., open ponds, photobioreactors, and other wastewater treatment technologies), it is expected that innovative and efficient hybrid reactor systems can be developed for microalgae-based wastewater treatment applications.

Integration with Phytoremediation Systems

The integration of a photobioreactor with a phytoremediation system can create a more efficient and effective wastewater treatment by harnessing the capabilities of microalgae and plants in removing pollutants (Cui et al. 2020). In this integrated system, wastewater is first processed through the photobioreactor containing microalgae. The microalgae will consume nutrients such as phosphates and nitrogen, as well as degrade organic compounds and produce oxygen through photosynthesis. After passing through the photobioreactor, the wastewater—which has already seen a reduction in contaminants—will be directed to the phytoremediation system.

The phytoremediation system involves the use of plants (usually aquatic plants) to remove or reduce remaining pollutants in the wastewater. The plants absorb contaminants through their roots and accumulate them in their tissues or convert them into less harmful compounds through various mechanisms, such as phytodegradation, phytostabilization, or phytovolatilization. Additionally, plants can enhance the activity of microorganisms in the root zone, known as the rhizosphere, aiding in contaminant degradation.

The integration of a photobioreactor and phytoremediation offers several advantages, including:

(1) Higher treatment efficiency: The combination of microalgae and plants allows for more efficient and effective treatment, as they can target various types of contaminants that may not be removed by a single system alone.
(2) Nutrient load reduction: By combining photobioreactors and phytoremediation, the system can be more effective in reducing nutrient concentrations such as phosphates and nitrogen, which are major contributors to eutrophication and water pollution.
(3) Sustainability: The integrated system utilizes natural processes to remove pollutants and produces biomass that can be used as an energy source or raw material for industries, such as animal feed, fertilizer, or chemicals.
(4) Flexibility: Integrated systems can be tailored to specific wastewater treatment needs and can be upgraded or modified according to changes in wastewater quality or treatment objectives.

Despite the numerous advantages, the design and operation of this integrated system require a thorough understanding of microalgae and plant biology, as well as photobioreactor and phytoremediation technologies (Benner et al. 2022). While wastewater treatment in an integrated photobioreactor and phytoremediation system has its benefits, there are also several drawbacks to consider:

(1) Investment and operational costs: Integrating photobioreactors and phytoremediation systems generally involves higher investment and operational costs compared to operating each system separately. Additional costs may include equipment, maintenance, and more complicated environmental controls.

(2) Design and operation challenges: Designing, constructing, and operating this integrated system entail a deeper understanding of both systems and how they can work efficiently and effectively together, potentially requiring more human resources and technical expertise.
(3) The potential of lower contaminant availability: In this integrated system, wastewater that has passed through the photobioreactor may already have seen significant contaminant reduction. As a result, plants in the phytoremediation system may have limited access to contaminants, diminishing the effectiveness of phytoremediation.
(4) Intensive maintenance: Involving a combination of two methods, this integrated system naturally requires more intensive maintenance. For instance, regular cleaning and upkeep are critical to sustain photobioreactor performance, while pruning plants and managing biomass may be necessary for the phytoremediation system.
(5) Scalability: Scaling up this integrated system for large-scale wastewater treatment may pose challenges due to its complexity of design and operations.

Although there are some disadvantages in utilizing an integrated photobioreactor and phytoremediation system for wastewater treatment, this technology still holds great potential in reducing pollutants and restoring water quality. In many cases, the advantages of this integrated system may outweigh its drawbacks, depending on specific wastewater treatment needs and objectives.

Integration with Coagulation-Flocculation Systems

Microalgae-based wastewater treatment integrated with coagulation and flocculation is an approach that combines biological and chemical methods to treat wastewater and remove various pollutants (Al-Jabri et al. 2021). The integrated process of wastewater treatment with coagulation and flocculation occurs as follows:

(1) In the initial stage, wastewater is directed through a photobioreactor or an open system containing microalgae. Microalgae consume nutrients (such as phosphates and nitrogen) and degrade organic compounds. During this initial process, microalgae also produce oxygen through photosynthesis, which can aid in the biological oxidation process to further break down organic compounds.
(2) After undergoing microalgae-based treatment, the wastewater is then directed to the coagulation system. In this stage, chemical coagulants (e.g., aluminum sulfate, ferric chloride, or polymers) are added to the wastewater. These coagulants react with suspended and colloidal particles in the wastewater, causing these particles to clump together into larger flocs.
(3) Flocculation follows, where the flocs formed during coagulation are agglomerated into larger and denser aggregates. This process usually involves gentle stirring or agitation of the wastewater to facilitate contact between the flocs and aid their coalescence.
(4) After flocculation, the larger and denser flocs are separated from the wastewater, either through sedimentation, flotation, or filtration. As a result, the generated outflow will have lower particle and pollutant content.

The integration of microalgae-based wastewater treatment with coagulation and flocculation offers several advantages (You et al. 2023):

(1) Higher treatment efficiency: The combination of biological and chemical processes can achieve higher treatment efficiency compared to operating each method separately, as it can remove various pollutants through different mechanisms.
(2) Nutrient load reduction: Microalgae-based treatment is effective in reducing nutrients such as phosphates and nitrogen, while coagulation and flocculation can help remove suspended and colloidal particles that may contain additional pollutants.
(3) Process stability: Combining both methods can enhance the stability of the wastewater treatment process, as the deficiency or failure of one system can be compensated by the other.

However, this integrated system still has some disadvantages, including:

(1) Investment and operational costs: Integrating microalgae-based treatment with coagulation and flocculation may involve higher investment and operational costs compared to operating each system separately. Additional costs may include equipment, chemicals, maintenance, and more complicated environmental controls.
(2) System complexity: Integrated systems are more complex and require a deeper understanding of both treatment methods, as well as knowledge of how they can work efficiently and effectively together. This may require more human resources and technical expertise.
(3) Use of chemicals: The use of chemical coagulants in the coagulation and flocculation processes can pose environmental and health concerns if not handled properly. Careful selection of chemical coagulants is vital, and appropriate management and monitoring measures are required to reduce potential negative impacts on the environment and human health.
(4) Sludge management: The coagulation and flocculation processes yield sludge as a byproduct that needs further treatment or safe disposal. Managing the sludge generated from the integrated system may be more complex due to the involvement of microalgae biomass and chemical coagulants.
(5) Scalability: Scaling up this integrated system for large-scale wastewater treatment may pose challenges due to its complexity of design and operations. Moreover, meeting the energy and chemical requirements on a larger scale may be an issue that needs to be addressed (Fudge et al. 2021).

Integration with Membrane Systems

Integrating microalgae-based approaches with membrane technologies like ultrafiltration and nanofiltration creates a more efficient and effective wastewater treatment system by harnessing the capabilities of microalgae in removing pollutants (Amenorfenyo et al. 2019), followed by further separation and purification through membrane apparatus to segregate microalgae from the treated wastewater. This process enables the collection of nutrient-rich algal biomass, which can be utilized for other purposes such as bioenergy production or animal feed.

In this integrated system, wastewater is first processed by microalgae in a photobioreactor or open system. Microalgae consume nutrients (including phosphates and nitrogen) and degrade organic compounds. After undergoing microalgae-based treatment, the wastewater with reduced contaminants is directed to the membrane system. Ultrafiltration (UF) is a filtration process that uses membranes with pore sizes ranging from 0.01 to 0.1 μm, that can effectively take out suspended particles, bacteria, and most viruses. Nanofiltration (NF) uses membranes with smaller pores, about 0.001–0.01 μm, allowing the removal of dissolved ions, small organic molecules, and most viruses.

The integration of microalgae-based wastewater treatment with membrane technologies offers several advantages:

(1) Higher treatment efficiency: The combination of microalgae and membrane technologies allows for more efficient and effective treatment, as they can target various types of contaminants that may not be removed by a single system alone.
(2) Improved water quality: Membrane technologies such as ultrafiltration and nanofiltration can produce higher-grade water quality as they effectively remove particles, bacteria, viruses, as well as most organic and inorganic contaminants.
(3) Potential for water recycling: The water generated by this integrated system can reach a sufficiently high quality for recycling and reuse in various applications, such as irrigation, cooling, or even drinking water, depending on water quality standards and additional treatments that may be required.
(4) Sustainability: The integrated system utilizes natural processes to remove pollutants and produce biomass that can be used as a source of energy or raw materials for industries, such as animal feed, fertilizers, or chemicals.

However, the integration of microalgae-based wastewater treatment with membrane technologies also has some disadvantages, including higher investment and operational costs, as well as the potential for membrane fouling by microalgae biomass or other particles. In this regard, pre-separation or additional treatment may be necessary to reduce particle load before the wastewater enters the membrane system (Goh et al. 2023).

10.4 Benefits and Potential of Algae in Wastewater Treatment

10.4.1 Absorption and Bioaccumulation of Pollutants

Utilization of microalgae offers an efficient, sustainable, and environmentally friendly solution to address water and soil pollution issues. Overall, incorporating microalgae in wastewater treatment provides various benefits, encompassing environmental, energy, and economic aspects (Goh et al. 2023). The absorption and accumulation mechanisms involved in microalgae-based wastewater treatment entail several steps, including nutrient absorption followed by biodegradation of organic pollutants, and subsequent bioaccumulation. Throughout this process, microalgae undergo photosynthesis.

(a) Nutrient absorption: Microalgae need nutrients like nitrogen and phosphorus for their growth. These nutrients are typically found in high amounts in wastewater, and microalgae have the ability to absorb them from the wastewater to support their growth and reproduction. This process aids in reducing nutrient concentrations in the wastewater, thus preventing eutrophication when the water is discharged into the environment.
(b) Biodegradation: Microalgae can also degrade some organic pollutants in wastewater, such as aromatic compounds, pesticides, and hydrocarbons. This process involves enzymes produced by microalgae to break down pollutants into simpler and less hazardous components.
(c) Bioaccumulation: Besides biodegradation, microalgae can accumulate pollutants within their cells, including heavy metals and radionuclides. This process involves the transportation of pollutants across the microalgae cell membrane and their accumulation in the cytoplasm or cell organelles. Bioaccumulation helps lower pollutant levels in wastewater but can lead to these pollutants being concentrated in microalgae biomass.
(d) Carbon dioxide fixation: Photosynthesis, occurring in microalgae, involves the utilization of carbon dioxide (CO_2) as a carbon source for biomass synthesis. Microalgae can absorb and fix CO_2 from the environment, either from the atmosphere or industrial exhaust gases, thereby reducing greenhouse gas emissions. Wastewater treatment using microalgae can help decrease CO_2 emissions while simultaneously generating biomass for various purposes, such as bioenergy production, animal feed, and fertilizer.

Several advantages and potential uses of microalgae in wastewater treatment, related to pollutant absorption and bioaccumulation in water and soil, are as follows (Abdelfattah et al. 2023):

(1) Microalgae can absorb and accumulate heavy metals, excess nutrients, and other organic pollutants found in wastewater. This process, called bioremediation, helps mitigate the negative impacts of pollution on aquatic and soil ecosystems.

(2) Certain microalgae species can degrade hazardous organic compounds and pathogens (such as pesticides and hydrocarbons) into simpler and less harmful compounds, improving the overall efficiency of the wastewater treatment system and produce cleaner effluent.
(3) Microalgae can accumulate rare metals like gold, silver, and platinum from wastewater. These metals can be recovered from microalgae biomass for industrial use.
(4) Microalgae-based wastewater treatment requires significantly less space compared to conventional methods like aerobic or anaerobic processes. This reduces pressure on land and enhances the sustainability of wastewater treatment systems. The use of microalgae in wastewater treatment is an environmentally friendly solution, as it does not produce hazardous waste and helps decrease water, soil, and air pollution. Additionally, microalgae can be cultivated in infertile or degraded land, thus avoiding competition with productive agricultural areas.

10.4.2 Production of Biomass and Renewable Energy

Microalgae-based wastewater treatment requires lower energy compared to conventional methods such as aerobic and anaerobic processes. Microalgae can grow rapidly and produce biomass rich in proteins, lipids, and carbohydrates that can be further processed for various purposes, including animal feed, organic fertilizer, cosmetics, pharmaceuticals, and nutraceuticals. This provides greater economic opportunities for industries related to microalgae. Moreover, microalgae can produce biomass as a raw material for bioenergy production (e.g., biogas, bioethanol, or biodiesel), hence reducing dependence on fossil fuels.

10.4.3 Nutrition Restoration and Reduction of Greenhouse Gas Emissions

Wastewater is often rich in nutrients derived from various sources, such as domestic, industrial, and agricultural waste. Nutrient recovery processes occur during wastewater treatment by microalgae for the following reasons (Valchev and Ribarova 2022):

(a) Nutrient absorption: Microalgae actively absorb available nutrients in wastewater, including ammonia (NH_4^+), nitrate (NO_3^-), and phosphate (PO_4^{3-}), to support their growth and diverse metabolic activities as shown in Fig. 10.5 (Gururani et al. 2022) process helps reduce nutrient concentrations in wastewater.
(b) Microalgae biomass: The nutrients taken up by microalgae from wastewater are stored in the form of cellular biomass. This microalgae biomass can be

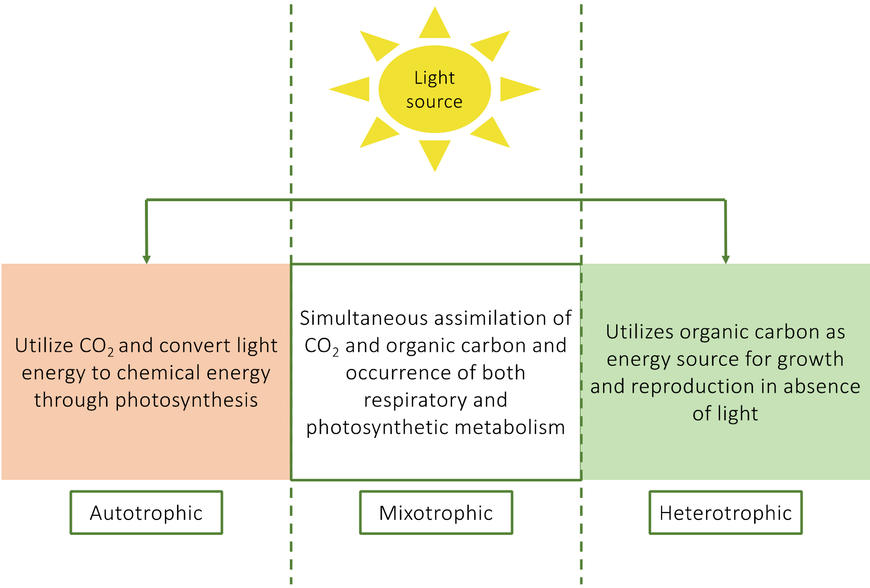

Fig. 10.5 Microalgae metabolism

utilized as nutrient-rich organic fertilizer, allowing the nutrients extracted from wastewater to be returned to the environment in a more eco-friendly form.

(c) Resource recovery: The use of microalgae in wastewater treatment not only helps reduce pollutant concentrations but also enables the recovery and recycling of valuable resources, such as nutrients. This can lessen reliance on non-renewable natural resources and enhance the sustainability of wastewater treatment systems.

(d) Mitigation of eutrophication: Eutrophication is a process where surface water bodies, such as lakes or rivers, become excessively rich in nutrients, leading to overgrowth of plants and disruptions in aquatic ecosystems. By diminishing nutrient levels in the discharged wastewater, microalgae-based wastewater treatment can help prevent eutrophication and its negative impacts on aquatic ecosystems.

Overall, nutrition restoration occurs during the wastewater treatment by microalgae due to their ability to uptake and accumulate nutrients in their biomass, thus lowering nutrient concentrations in wastewater and enabling the recovery and recycling of these valuable resources. Microalgae also play a significant role in reducing greenhouse gas (GHG) emissions during the wastewater treatment process, involving the following activities:

- Carbon dioxide (CO_2) fixation: One of the major components of greenhouse gases is CO_2. Microalgae utilize CO_2 as a carbon source during photosynthesis to form biomass. In wastewater treatment, microalgae can absorb CO_2 from both

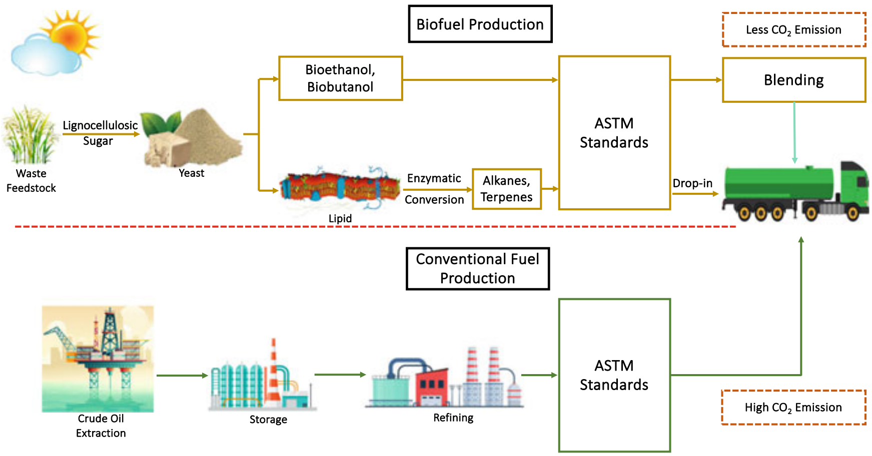

Fig. 10.6 Generation of crude oil and biofuels

the atmosphere and industrial exhaust gases. The process of CO_2 fixation by microalgae reduces the amount of CO_2 released into the atmosphere.

- Substitution of fossil energy sources: The microalgae biomass produced during wastewater treatment can be used as a renewable energy source, such as biofuel. By replacing some of the use of fossil fuels with microalgae-based biofuel, greenhouse gas emissions from fossil fuel combustion can be cut down, as portrayed in Fig. 10.6 (Malode et al. 2021).
- Methane (CH_4) emission reduction: Microalgae-based approaches can lower methane emissions yielded during conventional wastewater treatment processes, such as anaerobic digestion. Methane is a more potent greenhouse gas than CO_2. By decreasing methane production during wastewater treatment, microalgae can contribute to an overall reduction in greenhouse gas emissions.
- Utilization of microalgae biomass as fertilizer: The biomass generated from wastewater treatment with microalgae can be utilized as nutrient-rich organic fertilizer. The use of organic fertilizers can lessen reliance on synthetic chemical fertilizers—the production of which involves significant greenhouse gas emissions.

Overall, the mechanisms for decreasing greenhouse gas emissions during the wastewater treatment by microalgae involve CO_2 fixation, substitution of fossil energy sources, methane emission reduction, and the utilization of microalgae biomass as organic fertilizer. These processes help lower the carbon footprint of wastewater treatment and contribute to climate change mitigation efforts. With further research and development, microalgae can become an innovative and sustainable solution to address water and soil pollution issues. With diverse advantages and potential applications, the use of microalgae in wastewater treatment could become one of the promising future technologies to maintain ecological balance.

10.5 Economic Aspects and Cost Analysis

10.5.1 Investment and Operational Costs

The investment costs for implementing microalgae-based wastewater treatment systems can vary significantly depending on several factors and are highly determined by the scale and complexity of the project, local conditions, final objectives, and regulatory requirements, as elaborated below (Obaideen et al. 2022):

(1) Project scale: The investment costs will differ for small, medium, and large-scale projects. Small-scale projects, such as those in laboratories or research facilities, normally have lower costs compared to large-scale industrial wastewater treatment systems.
(2) Technology used: The choice of technology, such as open ponds, closed ponds, or photobioreactors, will affect the investment costs. Photobioreactors typically have higher initial costs compared to open or closed pond systems due to more advanced apparatus and more convenient environmental control.
(3) Integration with other wastewater treatment systems: If the microalgae-based approach is integrated with other wastewater treatment technologies (e.g., aerobic, anaerobic, phytoremediation, coagulation-flocculation, or membrane systems), the investment costs will vary depending on the selected methods and the level of integration.
(4) Required infrastructure: The investment costs will also depend on the infrastructure needed, such as pond construction, water treatment systems, pumping systems, and control systems.
(5) Project location: Investment costs can vary depending on the project location, including land prices, construction costs, and labor costs.

The cost components to consider when calculating investments costs are identified as follows:

(1) Initial costs required for designing and planning the microalgae-based wastewater treatment system, including feasibility studies, technical design, and environmental permits.
(2) Costs for constructing and installing the facilities for the microalgae-based wastewater treatment, such as ponds, photobioreactors, aeration systems, and other supporting infrastructure.
(3) Costs for acquiring and maintaining the microalgae used in the wastewater treatment system, including procurement, transportation, and inoculum preparation.
(4) Monitoring and evaluation: Costs needed for monitoring the performance of the microalgae-based wastewater treatment system and evaluating the achievement of environmental and economic goals, including sampling, laboratory analysis, and reporting.

In addition to the initial investment costs, it is essential to consider operational and maintenance costs. These ongoing costs are necessary to operate and maintain the microalgae-based wastewater treatment system, including energy costs, chemical expenses, equipment maintenance, and labor, as explained below:

(1) Energy costs required to operate equipment in the microalgae-based wastewater treatment system, such as pumps, aeration systems, and biomass processing apparatus—whether for living biomass only or both dead and living biomass, as depicted in Fig. 10.7 (Ojha et al. 2021). The energy required for microalgae-based systems is generally lower than conventional methods.
(2) The expenses incurred for the chemical substances needed in the wastewater treatment process, such as coagulants, flocculants, and additional nutrients that may be required to support microalgae growth.
(3) The costs associated with the labor force required to operate and maintain the microalgae-based wastewater treatment system, including salary expenses, training, and personnel management.
(4) The expenditures needed for the maintenance and repair of equipment utilized in the microalgae-based wastewater treatment system, such as photobioreactors, ponds, and solid–liquid separation devices.
(5) The expenses related to the collection, processing, and utilization of microalgae biomass generated from the wastewater treatment system, including costs for drying equipment and converting biomass into value-added products such as bioenergy or animal feed.
(6) The costs involved in periodically monitoring the performance of the microalgae-based wastewater treatment system and evaluating the achievement of environmental and economic objectives, including expenses for sample collection, laboratory analysis, and reporting.

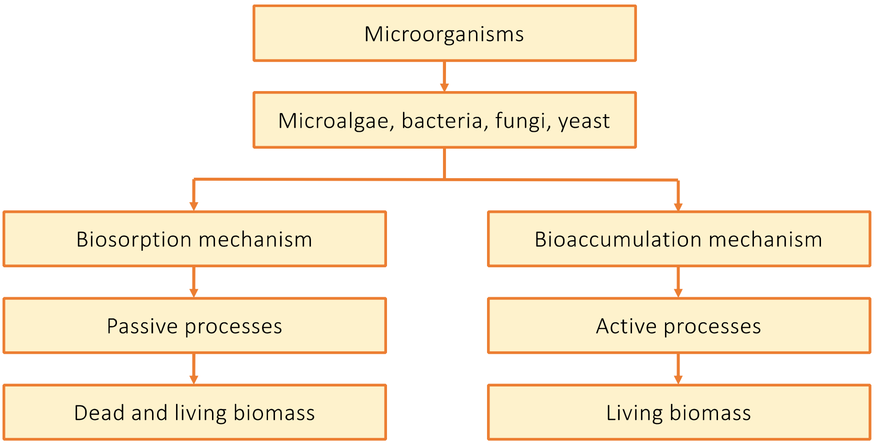

Fig. 10.7 Dead and living biomass

Due to the multitude of factors affecting investment costs, it is challenging to provide precise figures for the implementation expenses of microalgae-based wastewater treatment systems. However, some studies indicate that the cost of treating wastewater with microalgae ranges between $0.10 and $0.50 per cubic meter of water processed. These costs will vary depending on the aspects mentioned above. To obtain a more accurate cost estimate, it is advisable to conduct a feasibility study that takes into account the specific factors of the planned project and to consult with experts and suppliers of microalgae-based wastewater treatment technology.

10.5.2 Assessment of Economics and Processing Scale

The economic study related to the project scale when implementing microalgae-based approaches involves analyzing the costs and benefits associated with various aspects of the wastewater treatment system (Srimongkol et al. 2022), including investment, operational, and maintenance costs, as well as the potential revenue from the products generated. Several factors that need to be considered in the economic study are as follows:

(1) Treatment scale: The scope of microalgae-based wastewater treatment can range from small-scale systems (e.g., domestic or small industrial wastewater treatment) to large-scale systems (e.g., urban or large industrial wastewater treatment). The investment and operational costs will vary depending on the project magnitude, and economies of scale may apply, where the cost per unit of treatment decreases along with the increasing processing capacity. Small-scale systems may have lower investment costs, but the operational cost per unit volume of treated wastewater may be higher compared to large-scale systems. Large-scale systems can achieve economies of scale in operational costs but may require a higher initial investment.

(2) Technology used: The technology employed in the microalgae-based wastewater treatment system, such as open ponds, photobioreactors, or a combination with other treatment technologies, will determine the investment, operational, and maintenance costs. Photobioreactors are generally more expensive in terms of investment but can yield higher microalgae growth rates and removal efficiency. Advanced technologies may offer higher efficiency and better control over environmental conditions, but they may also have higher initial costs.

(3) Wastewater quality: The quality of the influent will affect the operational costs and efficiency of the microalgae-based treatment system (Al-Jabri et al. 2021). Wastewater with higher pollutant concentrations may require higher processing costs, but it can also provide a richer nutrient source for microalgae—which, in turn, can increase biomass productivity and the revenue potential from the products generated.

(4) Treatment objectives: The aims of the wastewater treatment system, such as achieving emission standards or utilizing the resources contained in the wastewater (e.g., nutrients or energy), will impact the economic costs and benefits of the microalgae-based wastewater treatment system.
(5) Products generated: The commodities obtained from the microalgae-based wastewater treatment system, such as biomass, bioenergy, or animal feed, have economic value that can help cover the investment and operational costs of the treatment system. The economic study should consider the revenue potential from the products generated, as well as the market and prices for these products.
(6) Government subsidies and incentives: In some cases, the government may offer incentives or subsidies for microalgae-based wastewater treatment, especially if the system helps achieve environmental or sustainability targets. These incentives can help reduce investment and operational costs, thus enhancing the economic feasibility of the treatment system.

A comprehensive economic study will aid in assessing the feasibility and potential success of the microalgae-based wastewater treatment system within a specific context. Cost–benefit analysis, sensitivity analysis, and feasibility studies can help identify the most economical and sustainable treatment solutions for a particular project, as portrayed in Fig. 10.8 (Srimongkol et al. 2022).

(1) Cost–benefit analysis is a systematic process used to compare the costs and benefits associated with a microalgae-based wastewater treatment project. Its purpose is to determine whether the project provides positive value to investors and/or the community. In other words, cost–benefit analysis aims to identify solutions that offer the highest benefit relative to the incurred costs. The analyzed expenses

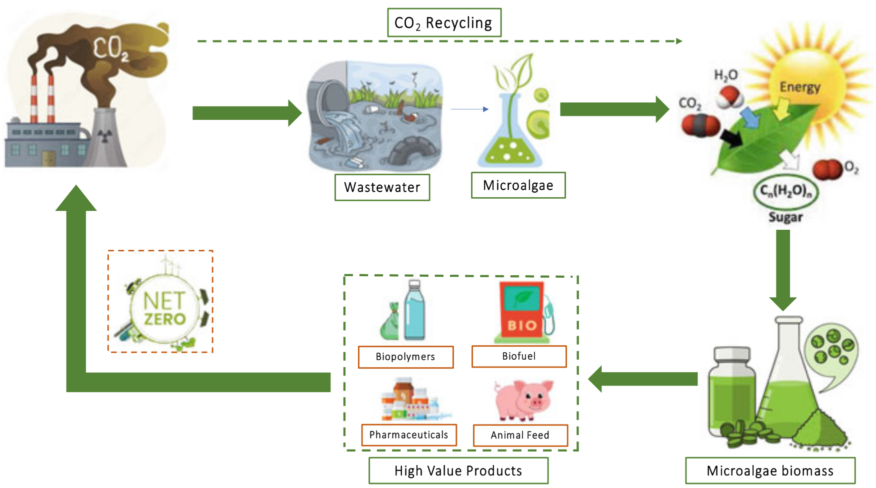

Fig. 10.8 Biorefinery economic model

include investment, operational, and maintenance costs, while the benefits encompass improvements in water quality, greenhouse gas emission reduction, and the potential utilization of by-products such as microalgae biomass. Cost–benefit analysis helps identify the most economical treatment options and indicates whether the project is economically viable.

(2) Sensitivity analysis is a process to test how changes in variables or assumptions used in the cost–benefit analysis can influence the results. These variables may include, for example, investment costs, energy prices, by-product prices, and processing efficiency. Sensitivity analysis assists in determining critical variables that affect the success of the microalgae-based wastewater treatment and can help optimize the system's design and operation. It also identifies the key factors with the most significant influence on the project's economic outcomes and demonstrates the project's susceptibility to changes in market conditions or technological advancements.

(3) Feasibility study is a comprehensive evaluation that covers the technical, economic, environmental, and social aspects of a microalgae-based wastewater treatment project. It aims to determine whether the project is feasible and can be implemented under specific conditions. The feasibility study includes cost–benefit analysis and sensitivity analysis, as well as an evaluation of the technology used, wastewater quality, regulatory requirements, financial analysis, and the project's environmental and social impacts. The feasibility study helps identify the most sustainable and viable treatment solutions for the specific needs of a project.

By employing these three tools, decision-makers can better understand the potential and risks associated with the microalgae-based wastewater treatment project, as well as identify the most economical and sustainable treatment solutions for specific requirements (Srimongkol et al. 2022). Furthermore, these analyses can assist in proposing the project to investors or other supporting parties, and aid in planning and implementing the wastewater treatment project.

10.5.3 Product Marketing Potential and Sources of Income

The implementation of microalgae utilization for wastewater treatment not only improves water quality but also generates diverse products and sources of income. The potential products and revenue sources that can be derived from microalgae-based wastewater treatment are as follows:

Bioenergy Production

Microalgae biomass generated from wastewater treatment can be converted into various types of bioenergy, e.g., biogas, biodiesel, or bioethanol. In this context, the produced bioenergy can be sold in the energy market or used internally to reduce energy costs of the treatment system (Malode et al. 2021).

The choice between using fossil energy (such as kerosene) and biogas for household needs depends on several factors, such as energy availability, cost, environmental impact, and practicality. These aspects affect the revenue potential of biogas produced from microalgae feedstock. The following considerations need to be taken into account when choosing between kerosene and biogas for household needs:

(a) Availability and sustainability: Kerosene is a non-renewable fossil energy source, hence its availability is limited. In contrast, biogas is a renewable energy source produced from the degradation of organic materials (e.g., household waste, animal manure, and plants).
(b) Cost: Fossil fuel costs (such as kerosene) often tend to be more stable and cheaper in certain regions, especially in oil-producing countries. However, biogas can be a cheaper alternative if there is existing infrastructure for biogas production and distribution, particularly in rural areas or places where kerosene is difficult to access or expensive.
(c) Environmental impact: Biogas has a lower environmental impact compared to kerosene. It produces less greenhouse gas emissions and reduces reliance on fossil energy. Moreover, biogas produced from organic waste helps to manage waste effectively and decrease environmental pollution.
(d) Practicality: The use of kerosene for household needs is generally easier and more practical due to the already established infrastructure in many areas. On the other hand, the use of biogas entails more complex production and storage systems. However, in some countries, especially in rural areas, small-scale biogas systems have become practical and efficient solutions to meet household energy needs.

The relative benefits of using kerosene or biogas for household purposes depend on local situations and conditions. Over the long haul, transitioning to biogas may be more advantageous in terms of environmental sustainability and resource management. However, in the short run, kerosene might be more practical and cost-effective in certain regions. Therefore, it is crucial to consider these factors before deciding on the most beneficial energy source for household needs (Bušić et al. 2018). Similarly, the choice between fossil fuels (such as gasoline and diesel) and biodiesel for transportation fuel depends on several factors, including energy availability, cost, environmental impact, and vehicle performance. Some considerations regarding the selection of gasoline, diesel, or biodiesel—affecting the potential income from biodiesel produced by microalgae—are as follows:

(a) Availability and sustainability: Gasoline and diesel are non-renewable fossil fuel sources, leading to limited availability. On the other hand, biodiesel is derived from renewable microalgae, making it a sustainable energy source.
(b) Cost: The cost of gasoline and diesel fuel is often more stable and can be cheaper in some regions, particularly in oil-producing countries. However, biodiesel prices may vary depending on feedstock prices and production scale. In certain countries, government incentives can make biodiesel prices more competitive.
(c) Environmental impact: Biodiesel has a lower environmental impact compared to gasoline and diesel. It yields less greenhouse gas emissions and reduces

dependence on fossil fuels. Moreover, using biodiesel can help mitigate air pollution from particulate emissions and volatile organic compounds.

(d) Vehicle performance: Biodiesel has better lubricating properties than gasoline and diesel, decreasing friction and wear in engines. However, biodiesel has a slightly lower energy value than gasoline and diesel, which may result in a tad higher fuel consumption. Most modern vehicles can operate with a biodiesel blend of up to 20% (B20) without significant engine modifications. Some vehicles are even specifically designed to run on pure biodiesel (B100).

Based on the above description, the potential income from bioenergy production using microalgae biomass derived from wastewater treatment relies on several factors, such as production scale, conversion efficiency, and the market price of bioenergy products. The following are some factors influencing the potential income from microalgae-based bioenergy production:

(a) Microalgae biomass concentration: The productivity of microalgae in wastewater treatment systems affects the amount of biomass available for conversion into bioenergy. Higher biomass concentration leads to greater bioenergy production potential.
(b) Conversion efficiency: The process of converting microalgae biomass into bioenergy has varying efficiencies depending on the technology used. Higher efficiency results in more bioenergy per unit biomass, thus increasing the income potential.
(c) Market price of bioenergy: The income potential from bioenergy production heavily relies on the market price of bioenergy products (e.g., biogas, biodiesel, or bioethanol). This price is affected by economic factors and policies, including demand and supply, government incentives, and environmental regulations.
(d) Production costs: When calculating the income potential, it is crucial to consider bioenergy production costs, including operational and maintenance costs of wastewater treatment systems, biomass conversion costs, and byproduct processing costs.

Given the variability in these factors, it is difficult to provide specific income figures for bioenergy production derived from microalgae-based wastewater treatment. Nonetheless, the potential for income growth can be fostered by improving system efficiency, conducting research and development of innovative conversion technologies, and implementing supportive and favorable policies.

Livestock Feed

Microalgae biomass is rich in protein, fatty acids, and other beneficial nutrients for livestock (Bušić et al. 2018; Lamminen 2021). After undergoing drying and processing, microalgae biomass can be sold as livestock feed for the farming industry. The income derived from microalgae-based livestock feed business in the farming industry depends significantly on various factors as listed below:

(1) Production scale: Larger microalgae production scale can decrease production costs per unit and increase revenue. Production efficiency also influences the costs and the generated income.
(2) Selling price: The selling price of microalgae-based livestock feed depends on market conditions, demand, and competition with other livestock feed products. Competitive pricing can help boost sales and revenue.
(3) Production costs: Microalgae production costs include energy, water, nutrient inputs, maintenance, and equipment expenses. Lowering production costs will raise the profits from the livestock feed business (Chanana et al. 2023). Energy is required to operate photobioreactors, pumps, heating or cooling systems, lighting systems (if used), and other instruments. Energy costs will depend on local electricity tariffs and equipment efficiency. Water is a crucial component in microalgae cultivation, and its cost will be determined by the water source, required treatment, and local water prices. Equipment and infrastructure costs include photobioreactors, lighting systems, pumps, control systems, tanks, and other facilities requisite for *Chlorella* production. These expenses will vary depending on the production scale and technology used. Labor is required to operate and maintain the system, perform quality control, and carry out other tasks related to *Chlorella* production. These costs will depend on the number of workers and wage rates at the location. Following the *Chlorella* growth, processing costs are indispensable, including separation, drying, and packaging costs to manufacture the final sellable product.
(4) Nutritional value: The nutrient content of microalgae (e.g., protein, essential fatty acids, and vitamins) can affect product appeal and boost selling prices.

- Microalgae typically contain a high amount of protein, around 40–70% of their dry weight, making them valuable as a protein source in livestock feed. Products with higher protein content are usually priced higher.
- Some microalgae types, such as *Nannochloropsis* and *Schizochytrium*, are rich in omega-3 fatty acids like DHA and EPA, which are highly valuable in the fish and shrimp feed industries.
- Certain microalgae species, including *Spirulina* and *Haematococcus*, contain pigments like phycocyanin and astaxanthin, which have high commercial value and can elevate the selling price of products.

Estimated selling prices of livestock feed products based on their nutritional value are as follows:

- *Chlorella* is one of the most commonly used microalgae in livestock feed due to its high protein content (around 50–60%) and essential fatty acids. Its selling price ranges from $10 to $25 per kilogram, depending on quality and nutrient content.
- *Spirulina* has an incredibly high protein content (around 60–70%) and is rich in vitamins, minerals, and essential fatty acids. Its selling price ranges from $15 to $40 per kilogram, depending on quality and nutrient content.

- *Haematococcus pluvialis* contains astaxanthin, a powerful antioxidant with numerous health and nutritional benefits. The selling price of *Haematococcus pluvialis* is usually higher than other microalgae types and can reach $100 per kilogram or more, depending on the astaxanthin content and product quality.
- *Nannochloropsis* has a high protein content (around 50%) and is rich in omega-3 fatty acids. Its selling price ranges from $10 to $25 per kilogram, depending on quality and nutrient content.

(5) Marketing and distribution: Effective marketing strategies and a wide distribution network can help increase sales and revenue for microalgae-based livestock feed businesses.

(6) Regulation and quality standards: Complying with existing regulations and quality standards for livestock feed can impact manufacturing costs and product acceptance in the market. In general, the selling price of microalgae-based livestock feed ranges from $5 to $15 per kilogram or more, depending on quality and nutritional composition of the product.

Nutritional Supplements

Microalgae contain abundant essential nutrients, such as omega-3 fatty acids, proteins, vitamins, and minerals (Koyande et al. 2019). Following the extraction and purification processes, these nutrients can be marketed as dietary supplements or used as raw materials in the food and beverage industry.

Raw Materials for Industries

Microalgae serve as a source of various bioactive compounds with commercial value, as they have significant potential as raw materials in the pharmaceutical, cosmetic, and chemical industries. Some commercially valuable bioactive compounds are as follows:

(a) Astaxanthin is a carotenoid pigment found in microalgae like *Haematococcus pluvialis*. It possesses powerful antioxidant properties and has been utilized in dietary supplements, skincare products, and cosmetics.

(b) Phycocyanin is a blue-green pigment found in *Spirulina* (*Arthrospira platensis*). It exhibits antioxidant, anti-inflammatory, and immunomodulatory properties and finds applications in the pharmaceutical, food, and cosmetic industries.

(c) Phycobiliproteins are pigments found in *Cyanobacteria* and *Rhodophyta* (red algae), such as phycoerythrin and allophycocyanin. They are used as natural colorants, fluorophores, and diagnostic markers in the pharmaceutical and biotechnology industries.

(d) Certain microalgae produce polysaccharides that act as antioxidants, antitumor, antiviral, and anti-inflammatory agents. Examples include polysaccharides from *Porphyridium* sp., *Chlorella* sp., and *Dunaliella* sp.

(e) Some microalgae types, such as *Nannochloropsis* and *Schizochytrium*, yield omega-3 fatty acids like DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid). These fatty acids offer wide-ranging health benefits and are used in the pharmaceutical, nutraceutical, and food industries.
(f) Certain microalgae, like *Dinoflagellates*, generate toxins that can be used in pharmaceutical and biomedical research. Examples of these toxins include okadaic acid and brevetoxins.
(g) Several microalgae produce peptides that function as antimicrobial, antitumor, and antioxidant agents. These peptides can be isolated and utilized in pharmaceutical and biotechnology research.

Water Quality Improvement

Microalgae-based wastewater treatment can produce cleaner water that meets the water quality standards set by the government. In some cases (Goh et al. 2023), the treated water can be reused for irrigation, cooling water, or other industrial processes, thus decreasing operational costs in an industry.

(a) Irrigation: Water treated by microalgae typically contains fewer pollutants and excess nutrients, making it safe for agricultural irrigation. The use of treated water can alleviate pressure on freshwater sources and contribute to the preservation of water resources.
(b) Cooling water: In industrial processes, cooling water is used to regulate the temperature of machines or manufacturing operations. Water treated by microalgae can be used as cooling water due to its reduced pollutant content and improved quality.
(c) Other industrial processes: Water treated by microalgae can be employed in various industrial processes, such as chemical, oil and gas, food and beverage, or pharmaceutical productions. The use of treated water can abate the demand for fresh water and help cut down natural resource consumption.
(d) Fisheries and aquaculture: Water treated by microalgae can also be used in fisheries and aquaculture systems. Cleaner water can elevate the environmental quality for fish and other organisms, hence improving productivity and animal welfare.
(e) Water storage and sustainable water resources: Water treated by microalgae can be stored in reservoirs or artificial lakes to ensure water resource availability in the future. Treated water can also replenish groundwater or reduce pressure on existing freshwater sources.

The use of microalgae-treated wastewater in various applications not only helps lower the consumption of freshwater resources but also generates additional income for wastewater treatment system stakeholders.

Carbon Emission Credit Sales

The use of microalgae in wastewater treatment can diminish greenhouse gas emissions through CO_2 absorption and eco-friendly bioenergy production. In this context, companies implementing microalgae-based wastewater treatment systems can earn carbon emission credits that can be sold in the carbon market or used to meet emission reduction targets. To maximize income from microalgae utilization in wastewater treatment, it is crucial to identify the most promising products and markets, as well as optimize the manufacturing and treatment processes of microalgae biomass. Effective marketing strategies and collaboration with related industries can also help enhance the economic value of microalgae-based wastewater treatment systems.

10.6 Social and Policy Aspects

10.6.1 Community Awareness and Acceptance

The implementation of microalgae utilization for wastewater treatment indeed requires awareness, acceptance, and active participation from the community. Society needs to comprehend the negative impacts of wastewater on the environment and human health. By increasing awareness of the importance of wastewater treatment (You et al. 2023), the community will be more inclined to support microalgae-based solutions. For widespread adoption of microalgae-based approaches, the public must understand and embrace this technology. Educating the community about the benefits and sustainability of this solution will help them accept it as a viable alternative to conventional wastewater treatment methods. The community also needs to actively engage in the wastewater treatment process using microalgae, e.g., participating in local wastewater treatment initiatives, supporting research and development of microalgae technology, and adopting environmentally friendly practices to reduce water pollution.

The application of microalgae-based approaches requires collaboration between the government, industry, research institutions, and the community. Society is obliged to support government policies that promote the use of microalgae in wastewater treatment and collaborate with industries to develop effective and economical solutions.

To ensure the successful implementation of microalgae technology, education and training must be provided to the community. This will help them understand the mechanism and how to manage microalgae-based wastewater treatment systems. The public can participate in small-scale wastewater treatment projects that use microalgae, such as in residential areas, offices, or agriculture. Such involvement will promote this technology at the local level and create more sustainable solutions for waste management. With community awareness, acceptance, and active participation in the use of microalgae for wastewater treatment, the implementation of this technology will be more effective and efficient, thereby reducing the negative impact of wastewater on the environment and human health.

10.6.2 Policies and Regulations Supporting the Use of Algae

Policies and regulations supporting the use of algae as agents in wastewater treatment vary between different countries and regions. Some common policies and regulations frequently encountered include (Amaro et al. 2023):

(1) Environmental policies: These policies encourage the use of environmentally friendly technologies to reduce water pollution and protect water resources. The use of algae as agents in wastewater treatment aligns with environmental policies.

(2) Wastewater regulations: These regulations establish standards for wastewater quality that industries and wastewater treatment facilities must meet. Algae can help achieve these standards as they are effective in absorbing and removing specific pollutants in wastewater.

(3) Subsidies and incentives: Governments often provide subsidies and incentives to industries and wastewater treatment facilities that employ environmentally friendly technologies, including algae utilization. These incentives may include tax reductions, financial assistance, or technical support. The Government of the Republic of Indonesia has taken steps to support industries and wastewater treatment facilities that adopt eco-friendly methods, including algae usage. Examples of incentives and subsidies provided are:

    (a) Tax reductions on:

    - Value-added tax (VAT) covered by the government for environmentally friendly equipment and technologies, including algae-based wastewater treatment systems.
    - Corporate income tax exemption or abatement for companies investing in environmentally friendly technologies, such as algae-based wastewater treatment.

    (b) Financial assistance:

    - Soft loans with low-interest rates for companies interested in adopting environmentally friendly technologies in wastewater treatment.
    - Provision of research grants and development assistance for projects using algae technology in wastewater treatment.
    - Subsidies for companies generating renewable energy from algae biomass yielded during wastewater treatment.

    (c) Technical support:

    - Training and workshops for industry workers on the implementation of environmentally friendly technologies, including algae-based wastewater treatment.
    - Consultation facilities and technical support from the government or research institutions to assist companies in adopting and optimizing algae-based technologies.

- Collaboration among companies, government, and research institutions in the development and enhancement of algae-based wastewater treatment technologies.

These policies and incentives aim to encourage companies and wastewater treatment facilities to adopt eco-friendly technologies, including algae utilization, to achieve desired environmental and sustainability goals. However, it is essential to note that the provided policies and incentives may change over time, depending on government priorities and economic conditions. Therefore, it is crucial to continually monitor the latest developments in policies and incentives offered by the Government of the Republic of Indonesia.

(4) Research and development policies: Governments and research institutions in various countries may have policies to support studies and development of innovative technologies in wastewater treatment, including the use of algae. These policies may include research funding allocations, government-industry partnerships, and international collaborations.

(5) Education and training policies: The algae-based approach to wastewater treatment requires specialized knowledge and skills. Hence, policies on education and training supporting the development of human resources in this field will be a vital aspect to promote algae utilization.

(6) Industrial regulations and standards: Some industries that generate wastewater may be required to comply with specific standards and regulations encompassing the use of environmentally friendly technologies, including algae-based wastewater treatment.

10.6.3 Partnerships and Collaborations Between Government, Industry, and Society

By fostering effective partnerships and collaborations between the government, industry, and society, the implementation of microalgae utilization in wastewater treatment can be facilitated, leading to broader environmental, economic, and social benefits (Srimongkol et al. 2022). Several strategies to promote effective partnerships and collaborations include the following:

(1) The government can develop policies and regulations that support the use of microalgae in wastewater treatment, such as stringent water quality standards, tax incentives or subsidies, as well as research and development support for eco-friendly technologies.

(2) The government needs to take an active role in providing the necessary infrastructure and technical support to facilitate the adoption of microalgae-based technologies in wastewater treatment. This may involve constructing wastewater treatment facilities, providing equipment, and offering technical support for system maintenance and operations.

(3) Collaboration between the government, industry, and research institutions is pivotal to develop efficient, effective, and economical microalgae-based wastewater treatment methods. Research efforts can focus on optimizing microalgae growth, improving photobioreactor or pond technologies, as well as processing and utilizing by-products. Government and industry can support research and development through funding, resources, and technical assistance.

(4) The government, industry, and educational institutions can collaborate to devise training and education programs in order to amplify the grasp of the benefits and technologies of microalgae-based approaches. Such training can help build local capacity in designing, operating, and maintaining microalgae-based wastewater treatment systems. Educating the public and industries involved in microalgae-based technologies is essential to improve understanding and technical capacity for implementing wastewater treatment systems. The government and educational institutions can cooperate to provide training programs, facilities, resources, and technical support.

(5) The government, industry, and society need to work together to promote the use of microalgae-based technologies in wastewater treatment. Marketing and promotional strategies may include public awareness campaigns, supporting the marketing of by-products, and recognizing best practices. Partnerships between the government, industry, and society can help identify business opportunities, reduce risks, and create synergies in resource management (Srimongkol et al. 2022).

(6) The government and financial institutions can provide financial support in the form of loans, grants, or incentives to companies implementing microalgae-based wastewater treatment systems. This financial aid can help lower initial investment costs and accelerate the adoption of this technology.

(7) Society can play an active role in supporting the implementation of microalgae utilization in wastewater treatment, for example, by participating in water resource management programs or local environmental initiatives. Increased awareness and support from the public for this technology will help hasten its adoption and success in wastewater treatment.

Collaboration between diverse industries (e.g., wastewater treatment, agriculture, energy, and pharmaceuticals) can help create synergies and efficiencies in resource utilization and usage of by-products derived from microalgae-based wastewater treatment systems.

10.7 Case Studies and Real Applications

10.7.1 Experience and Lessons from Implementation in Different Countries

Various countries in Asia have implemented the utilization of microalgae in wastewater treatment. Many lessons and experiences can be drawn from the use of microalgae-based approaches, as described below (Geremia et al. 2021):

(1) India: Microalgae utilization in wastewater treatment has been a subject of research in India. Several studies have demonstrated the effectiveness of microalgae in reducing pollutants such as nitrogen, phosphorus, and heavy metals. Lessons learned from India include the importance of research and development to optimize microalgae-based technologies and identify competent local microalgae species for wastewater treatment.
(2) China: As a country with large-scale industries, China has experienced increased water pollution due to industrial and agricultural activities. Microalgae utilization for wastewater treatment has been a focus of research and implementation in various regions. China has invested significant resources in the research and development of microalgae-based technologies for wastewater treatment and bioenergy production (Goh et al. 2023). Lessons learned from China highlight the prominence of collaboration between the government, industry, and research institutions in developing and adopting microalgae-based wastewater treatment technologies.
(3) Taiwan: Taiwan has employed microalgae for wastewater treatment in the fisheries sector, producing clean water for reuse in aquaculture and mitigating environmental impacts. Lessons learned from Taiwan emphasize the utilization of microalgae in specific sectors, such as fisheries, and the integration of wastewater treatment technologies with relevant industries.
(4) Indonesia: Several small-scale studies and implementations have been conducted in Indonesia to utilize microalgae in domestic and industrial wastewater treatment. Lessons learned from Indonesia underscore the importance of developing technologies suitable for local conditions and specific needs in wastewater treatment (Gómez-Sanabria et al. 2020).

In Europe, the utilization of microalgae in wastewater treatment has also been adopted and implemented in various research and pilot projects in the following countries:

(1) Spain: Spain has carried out several studies and projects related to microalgae use in wastewater treatment, particularly in the fisheries and agriculture sectors. One of the paramount lessons learned from Spain is the importance of cross-sector collaboration in developing innovative solutions harnessing microalgae to address water pollution issues.

(2) Netherlands: The Netherlands has numerous projects and initiatives focusing on using microalgae for wastewater treatment and producing high-value products like bioenergy and nutritional supplements (Watanabe and Isdepsky 2021). Lessons from the Netherlands emphasize the significance of research and development to enhance the efficiency and economics of microalgae-based approaches.
(3) Germany: Germany has invested considerable resources in research and development of microalgae-based technologies, including their use in wastewater treatment (You et al. 2023). Lessons learned from Germany highlight the importance of government support in the form of policies, regulations, and incentives to promote the adoption of environmentally-friendly technologies.
(4) France: France has implemented various research and pilot projects focusing on microalgae use in wastewater treatment, especially in agriculture and industry. Lessons from France emphasize the integration of microalgae-based approaches with conventional wastewater treatment methods to create efficient and sustainable solutions.
(5) United Kingdom (UK): The UK has undertaken several research and projects exploring microalgae utilization in wastewater treatment. One of the notable projects involves using photobioreactors harnessing microalgae to reduce greenhouse gas emissions and produce high-value products from wastewater.
(6) Italy: Italy has conducted various research and pilot projects related to microalgae use in wastewater treatment, particularly in the fisheries and industry sectors. Italy has experimented with integrated wastewater treatment systems combining microalgae and conventional technologies to create efficient and sustainable solutions.
(7) Sweden: Sweden has invested in research and development of microalgae-based methods for wastewater treatment and bioenergy production. One of the noteworthy projects involves using microalgae to treat wastewater from the pulp and paper industry.
(8) Norway: Norway has also adopted microalgae-based technologies in wastewater treatment, especially in the fisheries and aquaculture sectors. One of the eminent projects involves using microalgae to treat wastewater from the fisheries industry and produce high-value products such as protein and omega-3 fatty acids.
(9) Denmark: Denmark has carried out research and projects exploring microalgae use in wastewater treatment, particularly in agriculture and industry sectors. Examples of renowned projects include using microalgae to treat wastewater from farms and produce high-value products such as animal feed and bioenergy.

Some countries in Africa and America have also adopted and implemented microalgae utilization in wastewater treatment (Mohsenpour et al. 2021). Here are a couple of instances:

(1) South Africa: South Africa has undertaken several research and projects exploring microalgae use in wastewater treatment, particularly in agriculture and industry sectors. Microalgae are used to treat wastewater from farms and industries to produce high-value products such as animal feed and bioenergy.

(2) Nigeria: Nigeria has experimented with microalgae-based technologies in wastewater treatment, especially in the fisheries and aquaculture sectors. Microalgae are used to treat wastewater from the fisheries industry and produce high-value products such as protein and omega-3 fatty acids.
(3) Egypt: Egypt has conducted research on the utilization of microalgae for wastewater treatment in the agriculture and industry sectors. One of the acclaimed projects involves using microalgae to treat wastewater from the textile industry and produce high-value products such as bioenergy.
(4) United States (USA): The USA has invested in research and development of microalgae-based technologies for wastewater treatment and bioenergy production. Some projects have incorporated microalgae to treat wastewater from farms and industries to generate high-value products such as animal feed and bioenergy.
(5) Canada: Canada has also adopted microalgae-based approaches in wastewater treatment, principally in the fisheries and aquaculture sectors. One of the remarkable projects involves using microalgae to treat wastewater from the fisheries industry and yield high-value products such as protein and omega-3 fatty acids.
(6) Brazil: Brazil has carried out research and projects exploring microalgae use in wastewater treatment, particularly in agriculture and industry sectors. Examples of projects include using microalgae to treat wastewater from farms and produce high-value products such as animal feed and bioenergy.

From the experiences of these countries, several common lessons can be drawn, including:

(1) The importance of research and development to identify effective local microalgae species and optimize microalgae-based approaches in wastewater treatment.
(2) The significance of policies and regulations that support the use of microalgae-based methods in wastewater treatment, including government incentives to promote environmentally-friendly technology adoption.
(3) The importance of collaboration between the government, industry, and research institutions in developing and adopting microalgae-based wastewater treatment systems.
(4) The utilization of microalgae in specific sectors, such as fisheries and agriculture, to mitigate environmental impacts and create business opportunities.
(5) The development of technologies tailored to local conditions and specific needs in wastewater treatment.

10.7.2 Success Factors and Constraints in Implementation

Aspects contributing to the successful implementation of microalgae utilization in wastewater treatment include (Mohsenpour et al. 2021):

(1) Research and development: Continuously advancing knowledge and technology through research and development efforts will optimize microalgae-based operations, boost efficiency, and lessen costs.
(2) Government support: Policymaking, regulations, and incentives aid from the government play a crucial role in encouraging the adoption of microalgae-based technologies in wastewater treatment.
(3) Cross-sector collaboration: Collaboration among the government, industry, and research institutions facilitates the dissemination of technology, funding, and development of the necessary infrastructure.
(4) Education and training: Raising awareness and understanding of the benefits and potential of microalgae in wastewater treatment will help promote this technology across various sectors.
(5) Technology integration: Integrating microalgae-based approaches with conventional wastewater treatment methods can create more efficient and sustainable solutions.

Furthermore, the following primary challenges have been identified in implementing microalgae utilization in wastewater treatment:

(1) Investment costs: The expenses entailed in establishing infrastructure and acquiring necessary equipment for microalgae-based wastewater treatment systems can be a hindrance, particularly for developing countries or small and medium-sized industries.
(2) Operational costs: Although operational costs may diminish over time along with improved efficiency, they can still be a constraint for some management parties.
(3) Limited knowledge and advanced technology: The lack of understanding and the modern instruments required to utilize microalgae in wastewater treatment may restrict the adoption and effectiveness of this method.
(4) Variability in wastewater quality: The considerable variation in wastewater quality, particularly concerning nutrient content and pollutants, can influence the efficiency and effectiveness of microalgae-based wastewater treatment.
(5) Scaling up the technology: Developing and optimizing microalgae-based wastewater treatment systems for larger scales can be a challenge, notably in controlling microalgae growth conditions and managing the waste.

10.7.3 Recommendations and Strategies for Further Development

The following strategies are recommended to further develop the implementation of microalgae-based wastewater (Srimongkol et al. 2022):

(1) Focus on research and development: Research efforts should prioritize improving efficiency, lowering costs, and optimizing microalgae-based

approaches, including studies on the most effective microalgae species, optimal growth conditions, and high-value product extraction methods.

(2) Government support: The government needs to provide favorable policy support, such as fiscal incentives, subsidies, or regulations encouraging the adoption of microalgae-based technologies in wastewater treatment.
(3) Enhanced collaboration: Strengthen the partnership and cooperation between the government, industry, and research institutions to expedite technology dissemination, financing, and necessary infrastructure development.
(4) Community empowerment: Conduct education and training campaigns to raise awareness and understanding of the benefits and potential of microalgae utilization in wastewater treatment.
(5) Technology integration: Combine microalgae-based approaches with conventional wastewater treatment methods to create more efficient and sustainable solutions, including integrated systems incorporating wastewater treatment with renewable energy production and by-product utilization.
(6) Scalability and adaptability: Develop and optimize microalgae-based wastewater treatment systems for larger scales and different types of waste water, including designing modular and flexible schemes adaptable to various conditions and needs.
(7) Market and product development: Increase the added value of products derived from microalgae-based wastewater treatment (e.g., animal feed, bioenergy, and chemicals) by expanding new markets and applications.
(8) Regular evaluation and monitoring: Periodically assess the performance of microalgae-based wastewater treatment systems to identify areas for improvement and ensure the technology's long-term sustainability.
(9) Knowledge exchange: Facilitate the exchange of knowledge and experiences between countries and sectors that have successfully implemented microalgae utilization in wastewater treatment, thus enhancing technology effectiveness and accelerating global adoption.
(10) Community engagement: Involve the community in decision-making processes and the implementation of microalgae-based wastewater treatment to foster social support and ensure project sustainability in the long run.

10.8 Challenges and Future Prospects

The following challenges and prospects in several studies regarding the development of microalgae approaches need to be addressed to enhance efficiency and innovation in wastewater treatment (Srimongkol et al. 2022):

(1) Microalgae species selection: Research should focus on identifying the most efficient microalgae species for pollutant and nutrient removal from wastewater, with high potential for biomass production and valuable product generation.

(2) Growth conditions optimization: Investigate optimal growth conditions for microalgae (e.g., temperature, pH, light intensity, and nutrient concentration) to increase wastewater treatment efficiency and biomass production.
(3) Photobioreactor design optimization: Improve photobioreactor design to enhance light utilization, microalgae growth, as well as ease control of growth conditions and wastewater treatment.
(4) Microalgae separation and product recovery: Research and develop efficient and energy-saving methods for microalgae separation from wastewater and recovery of high-value products (e.g., proteins, fatty acids, pigments, and bioenergy).
(5) Co-cultivation technology: Combine microalgae with other organisms, such as bacteria or fungi, to boost wastewater treatment efficiency and high-value product generation.
(6) By-products valorization: Develop methods to convert by-products from microalgae-based wastewater treatment into valuable commodities like bioenergy, fertilizers, or chemicals.
(7) Integration with other technologies: Incorporate microalgae-based approaches with conventional wastewater treatment or renewable energy systems to create more efficient and sustainable solutions.
(8) Mathematical modeling: Employ mathematical modeling and computer simulations to optimize the design of microalgae-based wastewater treatment systems and predict its performance under various operating conditions.
(9) Monitoring and control technology: Devise real-time monitoring and control technologies for microalgae-based wastewater treatment systems to maximize efficiency and lower operational costs.
(10) Scalability and adaptability: Inspect and construct microalgae-based water treatment systems that can be adapted and scaled up for various types of wastewater and operational scales to allow broad applications across different sectors and environments.

Through research and development in microalgae technology, we can improve efficiency and innovation in wastewater treatment (You et al. 2023), opening up opportunities for new applications and high-value products derived from microalgae.

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