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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

Tonni Agustiono Kurniawan, Ph.D.
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Contents

Part II
Algal Management in Wastewater Treatment

Chapter 15
Addressing Algal Bloom and Other Ecological Issues Caused by Microalgae Biomass Conversion Technology

Diana Irvindiaty Hendrawan, Astri Rinanti, Melati Ferianita Fachrul, Tazkiaturrizki, Astari Minarti, Sheilla Megagupita Putri Marendra, and Luthfia Aqilah Zahra

Abstract While biomass conversion technology for microalgae has provided economic value for humans, be they in the form of biofuels, food, animal feed, and chemicals, it may also bring environmental issues through an ecological phenomenon called algal bloom. An algal bloom is the growth of microalgae that occurs very quickly and excessively in waters. This phenomenon can cause environmental problems such as decreased water quality, eutrophication, and disruption of ecosystem balance. Algal bloom can produce poisons (toxins) that are harmful to humans, animals, and ecosystems. When an algal bloom occurs, food chains are disrupted and environmental quality declines. Algal bloom can also cause an increase in nutrients, especially nitrogen and phosphorus, in the waters. Along with this increase, there is a decrease in dissolved oxygen levels, resulting in the death of fish and other aquatic organisms. Therefore, controlling the amount of nutrients that enter the waters can

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help prevent eutrophication and algal bloom. Regular monitoring of water quality and the use of advanced technology to detect signs of impending algal blooms can help reduce their impact. In addition, it is necessary to develop and apply conversion technologies that are more environmentally friendly, for example, by using algae strains that are not invasive or have less impact on the environment. Research and education are needed to understand better the mechanism of algal bloom and its impact on ecosystems and to increase public awareness about the importance of sustainable water resource management. A multidisciplinary approach involving research, technology, and collaboration between government, industry, and society is necessary to overcome algal bloom and other ecological problems caused by microalgae biomass conversion technology.

Keywords Algal bloom · Biomass conversion · Biofuels · Nutrients · Eutrophication

15.1 Introduction

15.1.1 The Potential of Microalgae Biomass as a Raw Material for Commercial Products and Its Problems

Microalgae are microscopic single-celled photosynthetic organisms living in different water types, such as freshwater, seawater, and other wet environments (Khan et al. 2018). Microalgae, also called phytoplankton, are an essential part of the food chain in aquatic ecosystems. As primary producers in the aquatic food chain, microalgae can photosynthesize, significantly contributing to the Earth's carbon cycle (Praharyawan 2021). Microalgae belong to the protists group, widely varied in shape, size, and chemical composition (Maia et al. 2020). Microalgal biomass is produced through the process of photosynthesis, which starts from the absorption of sunlight, carbon dioxide, and nutrients from water to produce energy and organic matter (Fig. 15.1). It also consists of various organic matter such as proteins, carbohydrates, lipids, pigments, and other bioactive compounds (Martins et al. 2023). Due to its rich composition and organic matter content, and high growth rate, microalgal biomass has a high potential to be used in various biotechnology applications (Khan et al. 2018). These applications include the conversion of biomass into bioenergy in solid (Osman et al. 2021), liquid, and gas forms (e.g., biodiesel, bioethanol, and biogas). Besides that, microalgae are also used in commercial products such as food ingredients, animal feed, *food supplements*, and raw materials for the cosmetic industry (Anggraeni et al. 2019).

Microalgae can be utilized as commercial feedstock products for various technical and non-technical reasons. The following are some of these technical reasons:

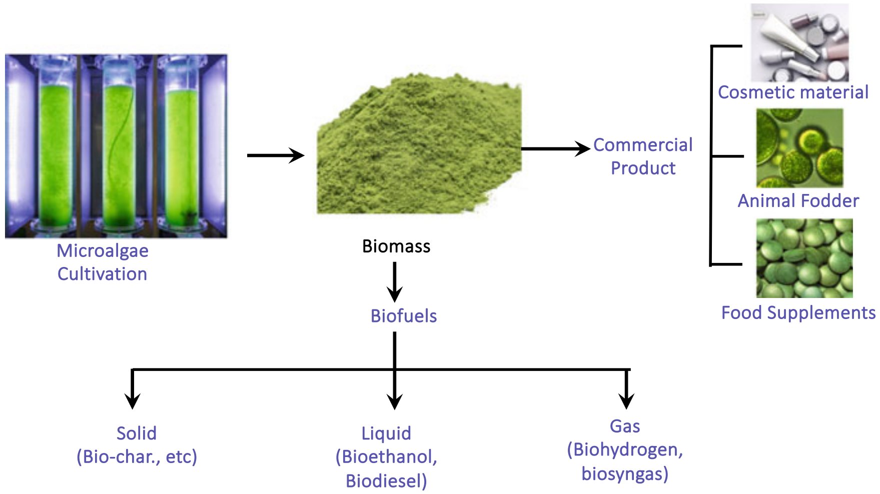

Fig. 15.1 Microalgae conversion process into biomass utilized as bioenergy and commercial products

1. Fast growth. Microalgae have a short life cycle and can reproduce rapidly. This speedy growth rate enables high biomass yields in a short time, making it an efficient and sustainable source of feedstock (Khan et al. 2018).
2. High nutrient content. Microalgae are rich in essential nutrients such as protein, omega-3 fatty acids, antioxidants, vitamins, and minerals. This high nutrient content makes them ideal for food products, beverages, and nutritional supplements (Raja et al. 2018).
3. Efficient photosynthesis. With its high photosynthetic efficiency, microalgae can produce more energy and biomass per unit area than terrestrial plants (Arenas et al. 2017). For this reason, microalgae can help reduce carbon dioxide emissions by absorbing CO_2 during photosynthesis.
4. Flexibility in habitat selection. Microalgae can grow in various environmental conditions, including freshwater, seawater, and wastewater, allowing for more diverse and sustainable use of resources.
5. Ability to produce bioactive compounds. Microalgae can produce various bioactive compounds such as carotenoids, phycobilin, fatty acids, polysaccharides, vitamins, sterols, and other biologically active molecules (Bhattacharjee 2016). These compounds have various applications in pharmaceutical products, cosmetics, and industrial needs.

In addition to the technical reasons outlined above, researchers agree that microalgae can serve as an environmentally friendly commercial feedstock. These non-technical reasons allow the utilization of microalgae to help reduce the carbon footprint and unsustainable use of natural resources. For example, using microalgae as an alternative fuel source such as biodiesel (Hossain et al. 2020) can reduce greenhouse gas emissions and dependence on fossil fuels.

Utilizing microalgae as a source of protein and nutrients can improve food security by helping to address hunger and malnutrition worldwide (Leandro et al. 2020). Microalgae can be an alternative source of nutrients that can reach areas with limitations in traditional crop production (Martins et al. 2023). Developing microalgae-based industries can create jobs and boost economies in previously underdeveloped areas, helping to reduce poverty and improve the life quality of local communities. Using microalgae in commercial products can encourage research and development of new technologies and increase public awareness of the potential for sustainable use of natural resources.

Through increasingly sophisticated conversion technologies, microalgal biomass used as feedstock can be converted into renewable energy source products, such as biogas, bioethanol, and biodiesel (Khan et al. 2018). It can also be utilized as other economically valuable products such as food, medicine, animal feed, and other chemicals. However, the development and application of biomass conversion technologies can cause several ecological problems, e.g.,

1. Large-scale microalgae cultivation that can fulfill biomass conversion needs requires enormous amounts of water and nutrients (de Carvalho et al. 2018), leading to resource competition with other human and environmental needs, such as agriculture and drinking water supply. Inefficient or unsustainable use of water resources can result in environmental problems, such as decreased water availability and changes in aquatic habitats.
2. Converting microalgal biomass to energy can produce greenhouse gas emissions, such as methane and carbon dioxide (Anwar et al. 2020). Although some of these emissions can be compensated by carbon sequestration during algal growth, the potential negative impact on climate change still needs to be considered.
3. Using fertilizers and excess nutrients in microalgae cultivation can pollute surrounding waters and trigger eutrophication and algal blooms detrimental to aquatic ecosystems (Tsikoti and Genitsaris 2021).
4. Spread of invasive microalgae. Without proper control, cultivated microalgae can spread to surrounding ecosystems, taking the place of indigenous microalgae species and potentially causing changes in community structure and ecosystem function.

15.1.2 Microalgae Biomass Conversion Process and Technology (Biofuel, Food, Animal Feed, and Chemicals)

Microalgae are microscopic photosynthetic organisms that have great potential in renewable fuel production due to their high content of lipids, carbohydrates, and proteins that can be converted into various energy products such as biodiesel, bioethanol, and biogas (Udayan et al. 2022). These fuels are considered more environmentally friendly as they reduce greenhouse gas emissions. However, the cost of

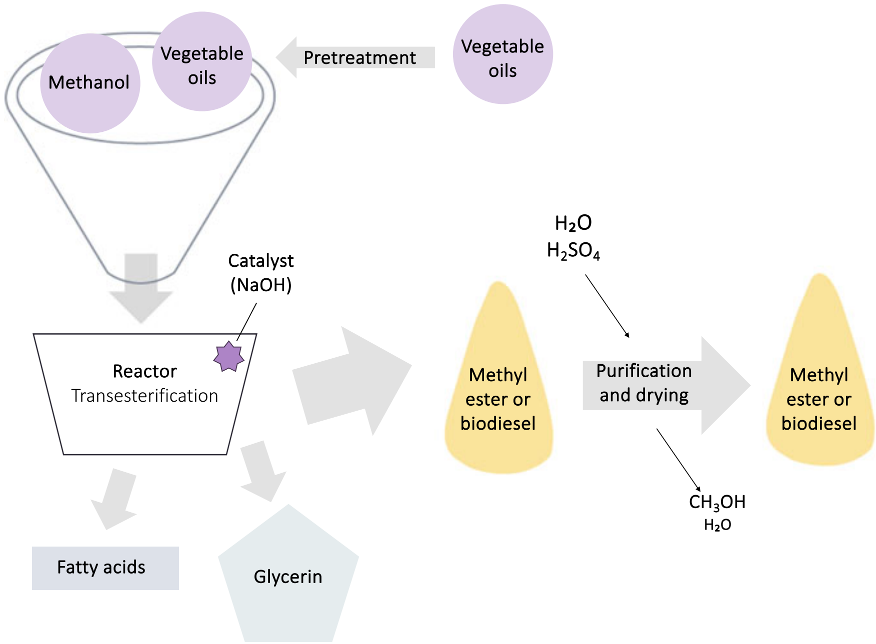

Fig. 15.2 Biodiesel production process

producing biofuels from microalgae is still high, and efficient processing technologies must be further developed. The process of converting microalgal biomass into bioenergy products involves several different steps and technologies.

Biodiesel Production

Microalgae-based biodiesel refers to biofuel produced from the conversion of lipids extracted from microalgae biomass such as (Fig. 15.2).

The microalgae used in biodiesel production are a group of microscopic photosynthetic organisms such as *Chlorella, Spirulina*, and *Nannochloropsis*. Microalgae-based biodiesel offers several advantages over biodiesel from traditional feedstocks such as palm, soybean, or castor oil. Several studies summarized in (Table 15.1) (Pal et al. 2019) show the growth media and cultivation systems used for oil-producing microalgae.

During growth, microalgae can accumulate significant amounts of lipids, reaching up to 20–50% of the algal dry weight depending on the species and cultivation conditions, as shown in (Table 15.2).

The conversion of microalgal biomass to biodiesel involves several key steps and technologies, as shown in (Fig. 15.3).

1. Microalgae cultivation. This process involves the growth and propagation of microalgae in controlled systems such as photobioreactors or open ponds.

Table 15.1 Growth media and cultivation systems used for oleaginous microalgae

Microalgae used	Media	Culture systems	Experimental conditions
Chlorella vulgaris	Modified basal medium, soy whey and thin stillage with 100 mM buffer strength	Heterotrophic growth, heterotrophic and mixotrophic batch cultivation, and mixotrophic batch cultivation	The pH of the media maintained was 5, 6, 6.8, 7.5 and 8 28 °C for 5 days
Scenedesmus obtusiusculus	Chitosan and tannin (CFL-PT) as flocculent		Salt-based medium
Chlorella vulgaris	Acetate, glucose, and glycerol	Autotrophic, heterotrophic and mixotrophic growth	150 rpm air flow rate of 200 mL/min
Scenedesmus obliquus	Secondary treated municipal wastewater and Bold's basal medium	75% wastewater (WW) + 25% Bold's Basal Medium (BBM) 100% BBM	
Chlorella pyrenoidosa II-H6	BG11, 13 days	Atmospheric and room temperature plasma technique	33 °C and 9.0
Nannochloropsis sp.	Chu 13 medium	Immobilized alginate beads in PBR	30 ± 2 °C for 7 days
Tribonema minus *Scenedesmus* sp.	BG11 medium Secondary effluent	Heterotrophic condition Heterotrophic	23 ± 1 °C
Scenedesmus obliquus SIT06	BG11	Photoautotrophic	28 °C for 10 days

Table 15.2 Several oil-producing algae and their oil content (Pal et al. 2019)

Algae	Oil content (% dry cell weight)
Botryococcus braunii	25–75
Chlorella sp.	28–31
Dunaliella sp.	23
Neochloris	35–54
Nannochloropsis sp.	31–68
Oleoabundans phaeodactylum	20–30

Microalgae will produce biomass with high lipid content suitable for biodiesel production.

2. Microalgae harvesting. After reaching the desired growth phase, the microalgal biomass is harvested by separating it from water through separation processes such as centrifugation, flocculation, or filtration (Ogbonna and Nwoba 2021).

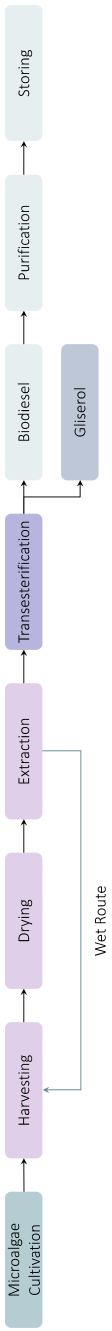

Fig. 15.3 General process of microalgae conversion to biodiesel

3. Biomass drying. The harvested microalgae biomass is then dried to reduce the moisture content. The drying process can be done by heat drying, freeze drying, or other suitable methods (Shekarabi et al. 2019).
4. Lipid extraction. The process is illustrated in (Fig. 15.4).

   After the biomass is dried, lipids are extracted from the microalgal biomass using organic solvents such as hexane, ethanol, or other methods such as supercritical or ultrasonic-assisted extraction (Ghasemi Naghdi et al. 2016).
5. Transesterification, The extracted lipids are then reacted with an alcohol (usually methanol or ethanol) in a catalyst (acidic, basic, or enzymatic) to produce methyl or ethyl esters, known as biodiesel and glycerol as a by-product. The process is illustrated in (Fig. 15.5).
6. Separation. After transesterification, the reaction mixture will contain biodiesel, glycerol, and other materials. Biodiesel and glycerol are separated through gravity separation, centrifugation, or other separation methods. The process is illustrated in (Fig. 15.6.).
7. Purification of biodiesel. The biodiesel produced may contain contaminants or residues from the production process. Purification processes such as water washing, filtration, or vacuum distillation remove contaminants and improve biodiesel quality.
8. Drying and storage of biodiesel. After purification, the biodiesel is dried to remove any moisture that may be present and stored under suitable conditions to prevent oxidation or quality changes.

Bioethanol Production

Microalgae-based bioethanol is a fuel that results from converting carbohydrates contained in microalgal biomass into ethanol (Hossain et al. 2020). During growth, microalgae can accumulate significant amounts of carbohydrates, such as cellulose, hemicellulose, and amylum, which can be used as feedstock sources for bioethanol

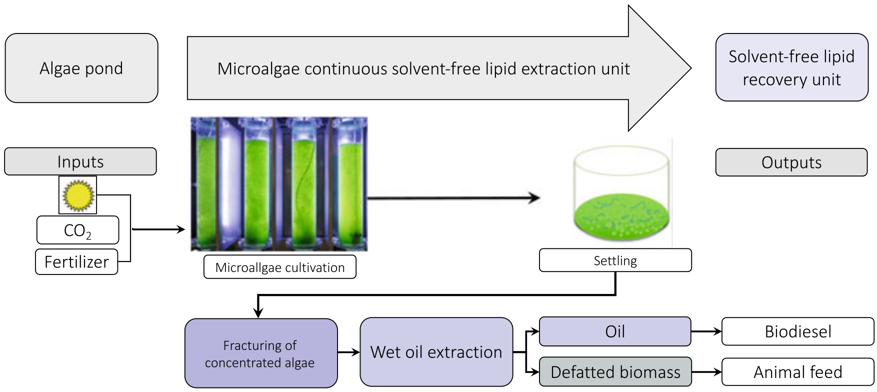

Fig. 15.4 Lipid extraction process

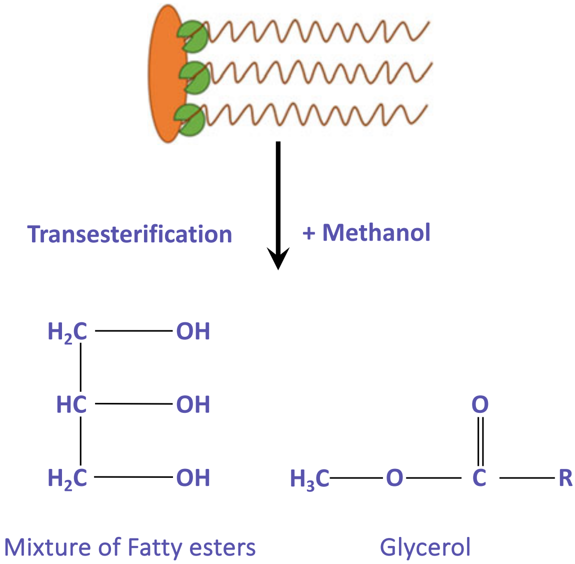

Fig. 15.5 Enzymatic transesterification to produce biodiesel and glycerol

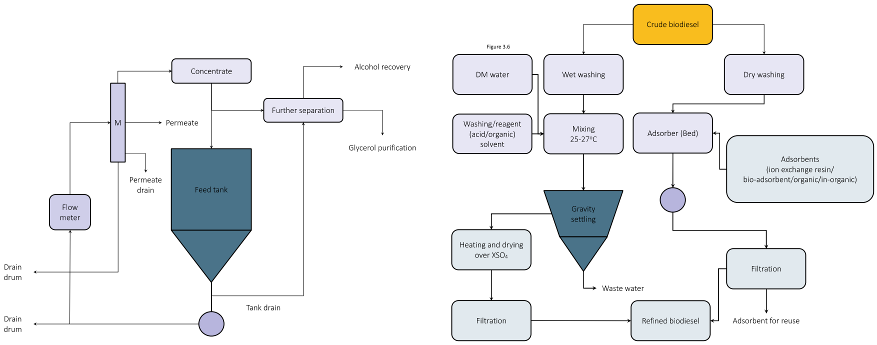

Fig. 15.6 Wet and dry biodiesel purification process

production (Khan et al. 2018). Microalgae-based bioethanol offers several advantages over bioethanol from traditional feedstocks such as sugarcane, corn, or wheat. The resulting bioethanol can be used as an environmentally friendly alternative fuel, blended with gasoline, or used purely in conventional gasoline engines (Bhan et al. 2020). Successively, the conversion of microalgal biomass into bioethanol consists of the following process steps.

1. Microalgae cultivation. Microalgae growth and propagation are carried out in controlled systems such as photobioreactors or open ponds. During growth, microalgae produce biomass with high carbohydrate content, which can be converted to bioethanol.

2. Microalgae harvesting. After reaching the desired growth phase, microalgal biomass is harvested through separation processes such as centrifugation, flocculation, or filtration to separate microalgal biomass from water and algal concentrate (Singh and Patidar 2018). Microalgal cell mass and concentration can be estimated by measuring chlorophyll content, microalgal cell number, absorbance (optical density) (Table 15.3) (Maltsev et al. 2021), dry weight, and ash-free dry weight. The most widely applied methods include flocculation, coagulation, gravity sedimentation, electricity-based processes, filtration, and centrifugation. Gravity sedimentation, flocculation, and centrifugation usually have high yields and lower costs. The harvesting process is further explained in (Fig. 15.7).
3. Pretreatment. Microalgae biomass undergoes pretreatment to destroy the cell structure and release the polysaccharides. Pretreatment methods include thermal, mechanical, chemical, or a combination of several methods, as seen in (Fig. 15.8).
4. Hydrolysis. The released polysaccharides are hydrolyzed into monosaccharides (e.g., glucose) using enzymes or chemical reagents. Enzymes that are commonly used in this process are amylase, cellulase, and xylanase (Córdova et al. 2018).

Table 15.3 Microalgae cell mass and concentration estimated by measuring chlorophyll content, microalgae cell number, absorbance (optical density)

Pigments	Absorption maxima in organic solvents, nm	Representatives
Chlorophyll *a*	420, 660	All algae
Chlorophyll *b*	435, 643	Green algae
Chlorophyll *c*	445, 625	Heterokontophyta, haptophyta, dinophyta, cryptophyta
Chlorophyll *d*	450, 690	Rodophyta, some cyanobacteria
Chlorophyll *f*	707	Some cyanobacteria
β-carotene	425, 450, 480	Most algae
α-carotene	420, 440, 470	Some algae (cryptophyta, haptophyta, dinophyta, chyrysophyceae), some cyanobacteria
Fucoxanthin	425, 450, 475	Heterokontophyta (bacillariophyceae phaeophyceae, chyrysophyceae), haptophyta
Phycoerythrin	490, 546, 576	Rodophyta, cryptophyta, cyanobacteria
Phycocyanin	618	Rodophyta, cryptophyta, cyanobacteria
Allophycocynanin	650	Rodophyta, cryptophyta, cyanobacteria

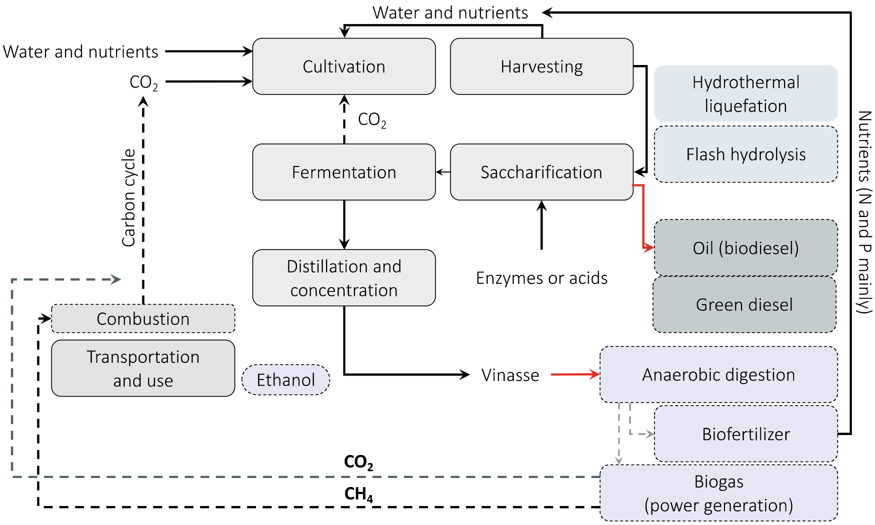

Fig. 15.7 The conversion process of microalgae to ethanol

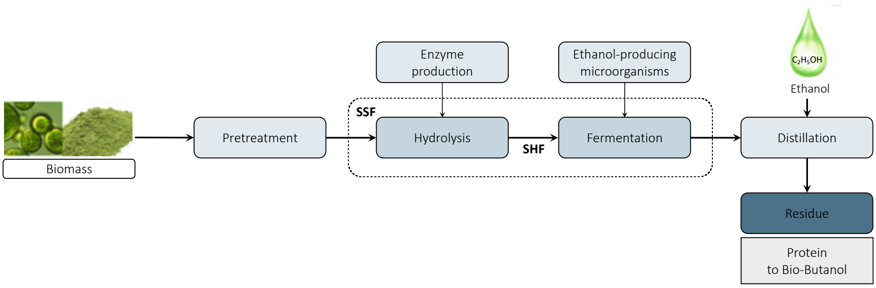

Fig. 15.8 Process flow of separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF)

5. Fermentation. Monosaccharides produced from the hydrolysis process are then fermented by microorganisms (such as *Saccharomyces cerevisiae*) to produce ethanol. Fermentation can be aerobic or anaerobic, depending on the type of microorganism used (Wongsurakul et al. 2022). The process is illustrated in (Fig. 15.9).
6. Ethanol separation. After fermentation, the resulting ethanol needs to be separated from the fermentation mixture. Separation processes include distillation, pervaporation, or extraction with solvents, which separate ethanol from water and other by-products (El-Dalatony et al. 2017).
7. Ethanol purification. Ethanol from the separation process may contain residues or contaminants (Wongsurakul et al. 2022). Purification processes such as

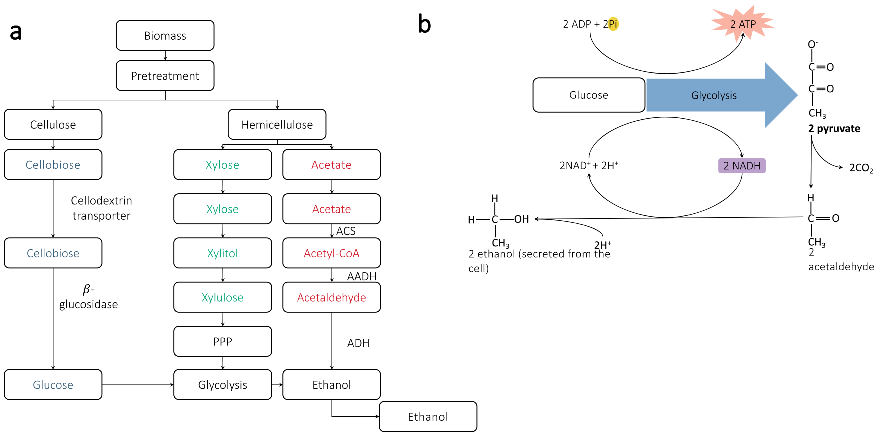

Fig. 15.9 Schematic overview of bioethanol production using cellobiose, xylose and acetic acid from microalgae biomass converted by yeast (left) and the metabolic pathways, i.e., glycolysis and fermentation (right)

azeotropic distillation, adsorption, or extraction with solvents are used to improve the quality of ethanol to the desired standard.

8. Ethanol storage. After purification, ethanol is stored under suitable conditions to prevent oxidation or quality changes. Ethanol should be stored in an airtight container and protected from direct light.

Biogas Production

Microalgae-based biogas refers to the gas produced from the anaerobic degradation of microalgae biomass (Feng et al. 2019). During growth, microalgae produce biomass containing carbohydrates, proteins, and lipids, which can be used as substrates for biogas production (Klin et al. 2020). The biogas produced consists mainly of methane (CH_4) and carbon dioxide (CO_2), as well as small amounts of other gases such as hydrogen sulfide (H_2S) and nitrogen (N_2) (Andriani et al. 2020). Biogas can be used as a renewable and environmentally friendly energy source for heating and power generation (Abanades et al. 2022), and as a vehicle fuel (Ullah Khan et al. 2017).

Microalgae-based biogas has many advantages over biogas produced from traditional feedstocks such as agricultural waste, food waste, or animal manure (Atelge et al. 2020) following are the technological steps and process of converting microalgal biomass into biogas:

1. Cultivation of microalgae. The growth and propagation of microalgae are carried out in controlled systems such as photobioreactors or open ponds (Zieliński et al. 2022). During growth, microalgae produce biomass containing carbohydrates, proteins, and lipids, which can be used as a substrate for biogas production (Sivaramakrishnan et al. 2022).

2. Microalgae harvesting. After reaching the desired growth phase, the microalgae biomass is harvested through separation processes such as centrifugation, flocculation, or filtration to separate the microalgae biomass from the water and algae concentrate (Najjar and Abu-Shamleh 2020).
3. Pretreatment. Microalgal biomass undergoes pretreatment to destroy cell structures and release intracellular components. Pretreatment methods include mechanical, physical, thermal, chemical treatments, and combination methods. The classification of pretreatment methods is shown in (Fig. 15.10).
4. Anaerobic digestion. The pretreated microalgae biomass is then fed into a biogas reactor and anaerobically degraded by microorganisms (such as methanogenic bacteria). This process produces biogas consisting of methane (CH_4), carbon dioxide (CO_2), and small amounts of other gases such as hydrogen sulfide (H_2S), nitrogen (N_2), and (NH_3) in Iron (II) oxide (Fe_2O_3) (Thanakunpaisit et al. 2017).
5. Biogas separation and purification. After anaerobic digestion, the biogas produced must be separated from the reactor mixture and cleaned from contaminants such as H_2S, CO_2, and water vapor. Separation and purification processes include absorption, scrubbing, or membrane technology, as illustrated in (Fig. 15.11).
6. Storage and use of biogas. The cleaned biogas is then stored under suitable conditions or used directly for various purposes, such as heating, power generation, and vehicle fuel (Ullah Khan et al. 2017).
7. Waste management. After the anaerobic digestion, the remaining biomass (digestate) must be managed appropriately. Digestate can be used as organic fertilizer, an additive in animal feed, or can be further processed to produce other products such as bioethanol or compost (Logan and Visvanathan 2019).

In addition, the remaining microalgal biomass can also be converted into economically valuable products such as food, medicine, animal feed, and various other chemicals.

Food and Other Chemicals

Microalgae biomass can be utilized as food ingredients. Some microalgae species, such as Spirulina (*Arthrospira platensis*) and *Chlorella*, have long been used as dietary supplements and rich sources of nutrients. Microalgae contain proteins, essential fatty acids, vitamins, minerals, and antioxidant pigments, making them nutritious food ingredients beneficial for health. Some examples of microalgae as a food source are described below:

1. Dried microalgal biomass processed into powder or tablet can be consumed as a dietary supplement to increase nutrient intake. *Spirulina* and *Chlorella* are examples of popular dietary supplements made from microalgae (Khan et al. 2018).
2. Microalgae biomass can be used as a raw material to manufacture various food products, such as bread, pasta, beverages, and snacks. Microalgae can add nutrition, color, and flavor to these food products (Pal et al. 2019).

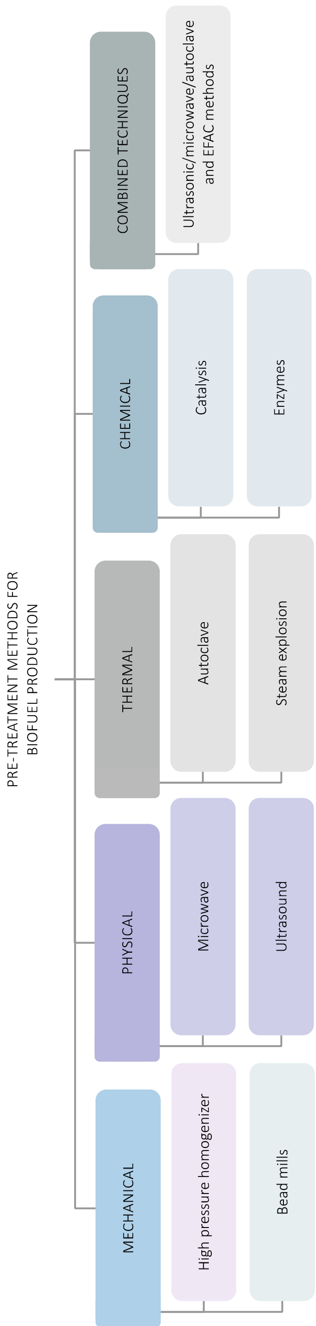

Fig. 15.10 Classification of cell pre-treatment methods

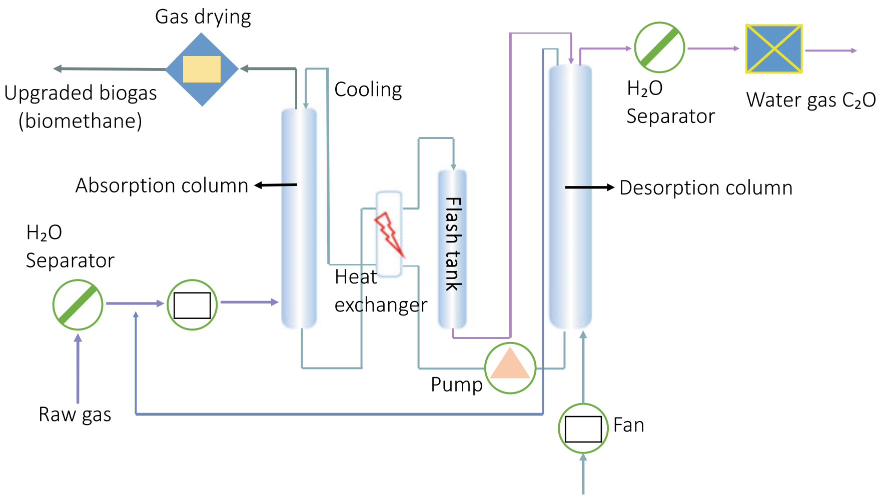

Fig. 15.11 Biogas purification by water scrubbing and organic solvent scrubbing to remove CO_2

3. The protein contained in microalgal biomass is of good quality with complete essential amino acids. Therefore, microalgae can substitute animal protein in vegetarian and vegan diets and reduce meat and animal product consumption.
4. Some microalgae species, such as *Nannochloropsis* and *Schizochytrium*, contain high omega-3 fatty acids (e.g., DHA and EPA). These fatty acids are essential for heart, brain, and immune system health. Thus, microalgal biomass can be used as an environmentally friendly and sustainable source of omega-3 fatty acids.

As a food ingredient, microalgal biomass offers advantages in terms of nutrition and sustainability, as well as the potential to reduce pressure on natural resources and the environment due to conventional food production (Liu et al. 2022). However, further research is needed for technological development supported by appropriate regulations to ensure the safety and quality of microalgae-containing food products. In addition, problems that may arise in this context include difficulties in maintaining product quality and safety and limitations in production scale (Albrektsen et al. 2022).

In addition to their potential as food raw materials, microalgae contain bioactive compounds such as carotenoids and polysaccharides that promotes skin health and beauty (Martínez-Ruiz et al. 2022). The use of microalgae for skin care products will require the development of stable and effective formulations and product safety and efficacy trials. Microalgae can also be processed into bioplastics, chemicals, and pigments. Problems using microalgae as industrial feedstock are the high production costs and complexities associated with scaling up mass-scale production.

Animal Feed

Microalgae biomass can be converted into feed for various types of livestock, e.g.,

- Poultry such as chickens, turkeys, ducks, and other birds can consume microalgae feed mainly due to their high protein and omega-3 fatty acid content can help improve meat and egg quality and support poultry growth and overall health.
- The use of microalgae in fish feed has become an important area of research, especially to replace or reduce the use of unsustainable fishmeal (Nagappan et al. 2021). Microalgae are rich in protein, omega-3 fatty acids, and pigments such as astaxanthin, which are essential for fish growth and health, as well as attractive colors in ornamental fish.
- Microalgae can also be used as feed for shrimp and mollusks, such as clams and oysters. Microalgae contain nutrients essential for these aquaculture species' growth and reproduction (Maizatul et al. 2017).
- Cattle, goats, sheep, and other ruminants can consume microalgae feed. Although microalgae will not replace grass or silage completely, they can be used as a supplement to protein and other nutrients to improve livestock health and productivity (Souza et al. 2021).
- Microalgae can be used as an additional source of protein and nutrients in pig feed. Using microalgae in pig feed can help improve meat quality and overall animal health.
- Rabbits and other herbivorous animals can also consume feed containing microalgae. The protein and other nutrients found in microalgae can support rabbit growth and health.

Overall, microalgal biomass has the potential to be a sustainable and nutritious feed source for various livestock species. However, proper feed formulation and further research on the optimal dosage and long-term effects of microalgae in animal feed are still needed to maximize its benefits (Nagappan et al. 2021). The technology and process of converting microalgal biomass into animal feed involve several important steps, starting from microalgae cultivation as in (Fig. 15.12) to the final processing into ready-to-use feed. The following are the general steps used in the process.

1. Microalgae cultivation. Microalgae are cultivated in closed systems (e.g., photobioreactors) or open systems (e.g., ponds or raceway ponds) under optimal conditions, such as sufficient lighting, temperature, pH, and nutrients. The selection of suitable microalgae species is also important, especially species that have a high content of protein, fatty acids, and other nutrients and are suitable for livestock needs.
2. Harvesting microalgae. After reaching the desired density, microalgae are harvested from the cultivation system using centrifugation, filtration, or flocculation methods. The aim is to separate the microalgae cells from the water and concentrate the microalgae biomass.
3. Biomass drying. The harvested microalgae biomass is then dried to reduce the moisture content. Hot air drying, spray drying, or freeze drying are commonly

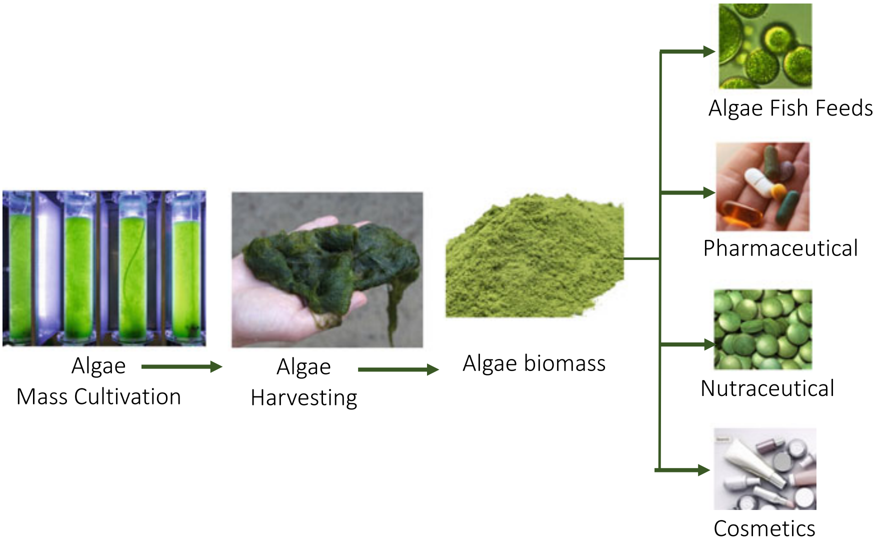

Fig. 15.12 Schematic diagram of the microalgae cultivation process (Yaakob et al. 2021)

used methods. Drying will help preserve the nutrients in the microalgae and facilitate storage and transportation (Vilatte et al. 2023).

4. Processing and nutrient extraction. Dried microalgal biomass can be further processed to extract desired nutrients, such as proteins, fatty acids, and pigments. The extraction process involves mechanical methods, such as solvent extraction or enzymatic methods. However, this stage may not always be necessary, depending on the animal feed application and the microalgae species used.
5. Animal feed formulation. After processing, the microalgal biomass or nutrient extracts can be mixed with other feed ingredients to create a balanced feed formulation that meets the nutritional needs of the livestock. This formulation will be customized according to the livestock species, age, and production goals (e.g., growth, reproduction, or egg production).
6. Pelletization. Feed formulations can be converted into pellets through pelletization to facilitate feeding. Pelletization helps to reduce nutrient losses during storage and feeding and improves feed consumption and digestion by livestock (Mores et al. 2020).

These technologies and processes can convert microalgal biomass into nutritious and sustainable animal feed. In general, the utilization of microalgae biomass into products of economic value still faces the following obstacles:

1. High production cost. Developing more efficient and energy-saving technologies is needed to reduce the cost of microalgae biomass production.
2. Limited availability of resources. Factors such as sunlight, temperature, and nutrients affect microalgae growth. The availability of optimal conditions for large-scale microalgae growth can be challenging (Chowdury et al. 2020).

3. Regulatory barriers. The use of microalgae in food, cosmetic or pharmaceutical products requires approval from a competent authority, such as the FDA or EFSA. This approval process can require significant time and resources (Ferreira de Oliveira and Bragotto 2022).

In addition to the three major problems mentioned above, the underlying problem of massive microalgal biomass production raises serious environmental issues, such as the potential for algal bloom, which needs to be addressed in an integrated and comprehensive manner because it has the potential to cause prolonged ecosystem imbalance (Sarker and Kaparaju 2023).Microalgae biomass conversion technology does not directly cause algal bloom. However, increasing microalgae production on a large scale can increase the risk of algal bloom if not appropriately managed. Here are some factors that may contribute to the risk of algal bloom:

1. Large-scale microalgae cultivation requires adequate intake of nutrients, such as phosphate and nitrogen, for optimal growth. If the nutrients provided exceed the microalgae's needs, the excess nutrients can pollute the surrounding waters and cause algal blooms, negatively affecting the aquatic ecosystem (Yaakob et al. 2021).
2. If not appropriately managed, Microalgae cultivation in open conditions, such as ponds or lakes, can increase the risk of algal blooms. For example, if an open cultivation system develops a leak or is contaminated by wild microalgae, this can lead to an overgrowth of algae in the surrounding waters.
3. Various microalgae species can be used in biofuel production. Some species may be more tolerant of extreme environmental conditions or more adaptable. If such species "leak" into the natural environment, they may dominate the local ecosystem and cause algal blooms (Patwardhan et al. 2022).

15.2 Algal Bloom and Its Impact on the Environment

15.2.1 Causes and Mechanism of Algal Bloom

An algal bloom is a phenomenon that occurs when the microalgae population in an aquatic ecosystem increases rapidly, resulting in a significant increase in phytoplankton biomass. The increase in biomass can alter the physical and chemical characteristics of the ecosystem (Song and Lv 2023). Algal blooms can result from natural or anthropogenic factors, such as increased nutrients (e.g., phosphorus and nitrogen), favorable temperatures, optimal light conditions, and water flow. Some factors causing algal bloom are:

1. Nutrient overload. High concentrations of nutrients, especially phosphorus and nitrogen in the water, can trigger massive microalgae growth. The source of these nutrients can come from industrial, agricultural, and urban waste discharges (e.g., fertilizers, livestock waste, and detergents) that pollute waters through surface

runoff, soil erosion, and infiltration into groundwater (Irfeey et al. 2023). Excess nutrients provide food for microalgae, which allows microalgae to thrive.

2. Water temperature. Warmer water temperatures, especially in spring and summer, often favor microalgae growth. Hot summers or temperature changes due to climate change can lead to increased water temperatures, which in turn can increase the risk of algal blooms.
3. Light conditions. Microalgae require light for photosynthesis. Availability of sufficient light or increased light intensity can trigger microalgal growth (Irfeey et al. 2023).
4. Hydrodynamic conditions. Changes in currents, flow velocity, and stagnant water layers can affect the distribution of nutrients and oxygen in the water (Nzayisenga et al. 2020). Slow or stagnant water flow can result in nutrient accumulation, creating favorable conditions for microalgae growth. In addition, reduced water flow due to water use or weather changes can also affect nutrient concentrations and microalgal growth.
5. The process that causes water layers to separate based on temperature and density, known as stratification, can also affect microalgae growth. When water layers separate, nutrients trapped in the lower layers may not be able to mix with the oxygenated upper layers, leading to excessive microalgae growth in the upper layers.

The mechanism of algal bloom involves an interaction between factors that create optimal conditions for microalgal growth. The process includes:

1. Increased nutrients. Algal blooms usually start when environmental conditions favor microalgal growth, such as excess nutrients (primarily nitrogen and phosphorus), optimal temperature and light, and changes in water flow. The high availability of nutrients in water provides an abundant food source for microalgae, promoting rapid microalgae growth and reproduction.
2. Microalgae growth. Under favorable conditions, microalgae begin to reproduce faster, too much to be controlled by their natural consumers (e.g., zooplankton) (Nagappan et al. 2021). This condition results in exponentially increasing microalgae populations.
3. Biomass accumulation. As the microalgae population continues to grow, the microalgae biomass also increases. Microalgae begin to form algal bloom, indicated by discoloration of the water surface, reduced water clarity, or the formation of a thick layer of floating microalgae. The algal bloom causes an increase in turbidity, which affects light penetration and photosynthetic activity (Udayan et al. 2022).
4. Ecosystem disruption. Prolonged and intensive algal blooms can result in chemical and biological changes in waters, such as decreased dissolved oxygen, toxin production, and changes in the composition of the aquatic organism community.
5. Algal blooms usually end when nutrients that support microalgal growth are depleted, or environmental conditions become less favorable, such as a drop in temperature or a change in water flow. At this point, the microalgae population will decline, and the aquatic ecosystem will return to its previous state. However,

microalgae that die and are decomposed by bacteria can cause hypoxia or oxygen deficiency in the water (Khan et al. 2018). This condition significantly affects the survival of other aquatic organisms, causing fish mortality which has a long-term adverse effect on the balance of the ecosystem.

15.2.2 The Impact of Algal Blooms on Water Quality, Ecosystems, and Human Health

Algal bloom can negatively impact water quality, which in turn can affect ecosystems, aquatic life, and human water use. The negative impacts of algal bloom on water quality are described below:

1. Decrease in dissolved oxygen. When the microalgae in an algal bloom die and begin to decompose, the decomposition process consumes dissolved oxygen in the water. This condition can lead to hypoxia or oxygen deprivation, harming the lives of aquatic organisms such as fish and invertebrates.
2. Increased turbidity. Algal blooms can cause an increase in water turbidity, which reduces light penetration and affects photosynthetic activity. High turbidity can also impair visibility for aquatic organisms and reduce water aesthetics (Nasution et al. 2021).
3. Toxin production. Some microalgae involved in algal blooms can produce harmful toxins to aquatic life, humans, and animals. These toxins can contaminate waters and cause poisoning if accumulated in the food chain or exposed through direct contact with contaminated water.
4. Water discoloration. Algal blooms often change the color of the water to green, red, brown, or even purplish-blue. This discoloration is caused by pigments in the microalgae cells and can detract from the water's aesthetics and signal a decline in water quality (Sun et al. 2023).
5. Odor and taste. Algal blooms can cause changes in the odor and taste of water, especially when microalgae begin to die and decompose (Ballah et al. 2019). These unpleasant odors and tastes can affect the quality of drinking water, swimming pools, and recreational waters and reduce the aesthetic value and attractiveness of water.
6. Water treatment disruption. Algal blooms can disrupt drinking water treatment processes, such as coagulation, filtration, and disinfection. High microalgae concentrations and toxin production can cause disruption to water treatment and increase treatment costs.

Algal blooms also pose many negative impacts on human health, especially when the blooms involve toxin-producing types of microalgae, namely:

1. Food poisoning. Toxins produced by some microalgae, such as cyanobacteria, can accumulate in the tissues of aquatic organisms such as fish and shellfish. Consumption of seafood contaminated with these toxins can cause food

poisoning with symptoms such as nausea, vomiting, diarrhea, headaches, and in severe cases, liver or kidney damage (Vilariño et al. 2018).

2. Respiratory distress. Some toxins produced by microalgae, such as brevetoxin produced by Karenia brevis, can irritate the human respiratory tract when inhaled (Ransom Hardison et al. 2019). This can cause symptoms such as coughing, sneezing, nasal congestion, and difficulty breathing, especially in individuals with respiratory diseases such as asthma or chronic obstructive pulmonary disease (COPD).
3. Skin and eye irritation. Direct contact with water containing toxins from algal blooms can irritate the skin, eyes, and mucous membranes. Possible symptoms include rash, itching, redness, swelling, and red or watery eyes.
4. Nervous system disorders. Some toxins produced by microalgae, such as anatoxin-a (Plata-Calzado et al. 2022) produced by some species of Cyanobacteria, can affect the human nervous system. Exposure to these toxins can cause symptoms such as muscle weakness, tingling, numbness, seizures, and in severe cases, paralysis or death.

The risk of negative impacts of algal bloom on human health can be prevented by doing several things, for example:

1. Avoid direct contact with water containing algal blooms, such as swimming, diving, or other water activities.
2. Do not consume seafood from waters experiencing algal blooms or suspected of containing toxins (Costa et al. 2021).
3. Follow the advice and warnings of local health authorities regarding the presence of algal bloom and the associated potential health risks.
4. Report the presence of algal bloom to local environmental authorities so that they can take necessary prevention and control measures.

15.2.3 Case Studies of Algal Bloom

The following are several case studies of algal blooms that occurred around the world in the past 10 years and their negative impacts:

- Galicia, Spain (2020). Algal blooms involving dinoflagellates in Galician coastal waters resulted in the closure of the shellfish fishing industry and significant economic impacts (Karlson et al. 2021).
- Lake St. Clair, Michigan, USA (2020). An algal bloom involving cyanobacteria in Lake St. Clair resulted in the closure of several recreational areas and a drinking water quality advisory. Negative impacts include health threats to residents and visitors and disruptions to tourism.
- India (2019). Algal blooms in India's coastal waters, especially in the Kerala region, have resulted in declining fish populations and negative impacts on the fishing industry and ecosystem.

- Utah, USA (2019). An algal bloom involving cyanobacteria in Utah Lake led to health warnings and the closure of several recreational areas. Negative impacts include health threats to residents and visitors and disruptions to tourism and water activities.
- New South Wales, Australia (2019). The algal bloom in the Darling River resulted in a mass die-off of fish, particularly Murray cod, an endangered species. Negative impacts include economic losses to the fishing industry and threats to the survival of fish species.
- Oregon, USA (2018). An algal bloom involving cyanobacteria in Detroit Lake, Oregon, led to the closure of several recreational areas and warnings regarding drinking water quality. Negative impacts include health threats to residents and visitors and disruptions to tourism.
- Lake Okeechobee, Florida, USA (2018). An algal bloom involving cyanobacteria in Lake Okeechobee caused a decline in water quality and negative impacts on the ecosystem and the fishing and tourism industries.
- Florida, USA (2016 and 2018). Algal blooms involving cyanobacteria and *Karenia brevis* (red tide) resulted in mass deaths of fish and other marine life, including dolphins, sea turtles, and manatees. These events also negatively impact tourism and the fishing industry.
- Lake Victoria, Africa (2017). An algal bloom involving cyanobacteria in Lake Victoria resulted in health threats to residents who depend on the lake for drinking water and fishing, as well as negative impacts on fish life and the ecosystem.

Meanwhile, several water bodies in Indonesia have experienced algal blooms, e.g.,

- Jatiluhur Reservoir in West Java, a source of raw water for Jakarta and surrounding areas, has experienced algal blooms resulting in water quality problems, including unpleasant odor and taste in drinking water.
- Kedung Ombo Reservoir in Central Java has also experienced algal bloom, resulting in a decline in water quality and negative impacts on ecosystems and fisheries.
- Rawa Pening in Central Java is one of the natural lakes that has experienced algal bloom, causing water discoloration and quality degradation, directly impacting fish life and ecosystems.
- Lake Maninjau in West Sumatra has experienced algal bloom, which resulted in a decline in water quality and negative impacts on fish life and ecosystems as well as tourism.
- Lake Matano in South Sulawesi has experienced an algal bloom that resulted in a decline in water quality and negative impacts on fish life and ecosystems.
- Jakarta Bay in DKI Jakarta has caused a decline in water quality and disruption to ecosystem life and fisheries.

15.3 Other Ecological Problems Caused by Microalgae Biomass Conversion Technology

15.3.1 Eutrophication

Microalgae biomass conversion technology involves using algae as an energy and fuel source. When microalgal biomass is mass-produced for conversion into such energy or fuel, it usually utilizes a growth medium containing high nutrients, such as nitrogen and phosphate fertilizers. When mass production is done in an open system (e.g., pond) and the growth medium is not adequately controlled, unused nutrients can flow out of the system and enter the surrounding environment (van der Wiel et al. 2019). This situation further caused increasing nutrient concentrations in the water, triggering undesirable algal blooms and eventually leading to eutrophication.

Another example is microalgae biomass treated in a closed system that uses wastewater as a growth medium. Suppose the wastewater contains high nutrients, such as nitrogen and phosphorus. In that case, these nutrients will enter the microalgae growth system and trigger unwanted algae growth, which can cause eutrophication. Based on this description, eutrophication can be defined as the process of increasing nutrient concentration, especially phosphorus and nitrogen, in a water body such as a lake, river, or ocean. These nutrients come from various sources, such as agricultural and domestic waste and industrial pollutants. This nutrient increase leads to excessive growth of phytoplankton, mainly algae, which can cause drastic changes in the aquatic ecosystem.

Eutrophication can cause various negative impacts, such as algal bloom, the formation of hypoxia (oxygen deprivation conditions) or dead zones (Sidabutar et al. 2021) and food chain disruption that causes ecological imbalance. Microalgae biomass conversion technology should be used carefully to avoid eutrophication and use appropriate and effective growth systems. In addition, waste treatment must also be appropriately managed to minimize negative impacts on the surrounding environment.

15.3.2 Disruption to Ecosystems and Food Chains

Algal blooms or explosions of wild algal populations can cause disruptions in food chains and imbalances in aquatic ecosystems (Kazmi et al. 2022). The stages of food chain disruption due to algal bloom in waters include the following:

1. An algal bloom occurs when the number of wild algae populations increases significantly over a short period. This can be triggered by increased levels of nutrients in the water, such as nitrogen and phosphorus, the primary food sources for algae.

2. Furthermore, algal blooms can cause a decrease in water quality because wild algae require large amounts of oxygen for growth. As a result, oxygen levels in the water will decrease and cause the death of aquatic organisms that need oxygen to survive. Excessive algae growth can damage aquatic ecosystems and decrease the dissolved oxygen that eventually leads to the death of fish and other organisms.
3. Some types of wild algae can produce harmful toxins to animals and humans. When algal blooms occur, the amount of wild algae that produce toxins also increases. This can threaten the health of fish, shrimp, other aquatic organisms, and humans who consume such seafood. Fish or birds that consume organisms contaminated by wild algal toxins can experience nervous system disorders, organ damage, and death. Because of this, the population of organisms at higher levels of the food chain will be reduced.

   Some types of toxin-producing algae can produce compounds that can kill zooplankton. These zooplankton are the first consumers in the aquatic food chain (Talib et al. 2022) and if their numbers are reduced, then populations of organisms at higher levels of the food chain will be affected. Some types of toxin-producing algae that can kill zooplankton include:

   (a) Dinoflagellates are a group of marine algae known for their ability to produce saxitoxin toxins that can affect aquatic organisms and humans. The toxin can kill zooplankton and affect human and animal health.
   (b) Diatoms. Some species of diatoms produce the toxin domoic acid, which can cause suffocation in fish and seabirds that consume contaminated organisms.
   (c) Cyanobacteria, or blue-green algae, are a group of algae commonly found in freshwater and seawater. Some species of cyanobacteria produce a toxin called microcystin, which can affect human and animal health and kill zooplankton.
   (d) Prymnesiophyta is a group of unicellular algae that produce bioluminescent toxins, which can cause injury to the cells of affected organisms (Núñez-Pons et al. 2018). *Prymnesium parvum* is an algal species found in fresh and saltwater. *Prymnesiophyceae* produce prorocentrolid and prymnesin toxins that can kill zooplankton and other aquatic organisms.
   (e) Coccolithophore. Some coccolithophore species produce toxic emitters that can affect human and animal health and kill zooplankton (Moore 2021).
   (f) *Alexandrium* spp. is a group of marine algae commonly found in warm waters. Some species of Alexandrium spp. produce toxins known as saxitoxins, which can affect zooplankton and other aquatic organisms.
   (g) *Karenia brevis* is a species of marine algae that can produce a toxin known as brevetoxin. This toxin can affect zooplankton and other aquatic organisms and cause poisoning in humans who consume contaminated fish or shellfish.

       If the zooplankton population decreases, the food available to fish as the second consumer in the food chain will also decrease. This can affect the fish population and cause an imbalance in the food chain. Ultimately, algal blooms can disrupt the aquatic food chain because increasing wild algal populations can affect the number and diversity of other organisms.

4. In addition, algal blooms can trigger the growth of invasive organisms, such as sea moss or wild corals, which can disrupt food chains and damage ecosystems (Fig. 15.13).

Invasive organisms are "new" species that did not exist before and quickly establish themselves in an algal bloom environment. Some examples of invasive organisms related to algal blooms include:

- *Caulerpa taxifolia* is an invasive sea lichen native to the Caribbean. The species has a rapid growth rate and outcompete the indigenous species, spreading into the Mediterranean Sea, and is now disrupting ecosystems and inhibiting coral reef growth.

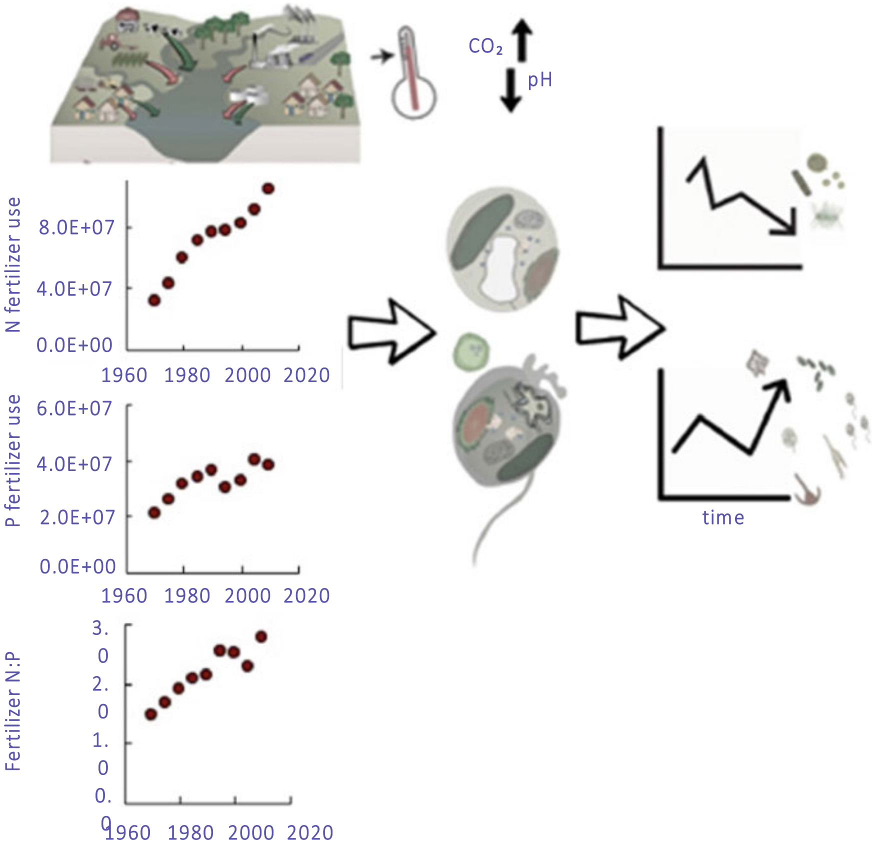

Fig. 15.13 The concept of aquatic ecosystem disturbance caused by algae blooming

- *Sargassum muticum* is a type of invasive brown algae that can grow in various conditions and disrupt coastal ecosystems, including coral reefs.
- Zebra Mussel *(Dreissena polymorpha)*: Although not algae, the zebra mussel is highly invasive and disrupts the aquatic food chain. It filters food particles from water that would otherwise be a food source for indigenous species.
- *Ostreopsis ovata* is a type of dinoflagellate that can cause toxic algal blooms. The toxin produced by this organism can harm marine life and humans.
- *Pfiesteria piscicida* is a type of dinoflagellate that can produce harmful toxins that affect fish and other organisms in the food chain.
- *Didymosphenia geminata* (Didymo) is also known as "rock slime": This freshwater alga has become invasive in many places, including New Zealand and North America forming thick algal blooms and disrupting the habitat of fish and other organisms in rivers and lakes.
- Lionfish (*Pterois volitans*), a venomous fish as an indigenous predator from the Pacific Ocean, has spread to the Caribbean and Atlantic Seas rapidly and massively. Lionfish feed on various fish and invertebrates, disrupting local food chains.

The growth of invasive organisms can disrupt food chains, damage ecosystems by competing with indigenous organisms in the ecosystem, and affect food availability for consumers at higher levels of the food chain (Emery-Butcher et al. 2020). The growth of invasive organisms can disrupt food chains and damage ecosystems as follows:

- Invasive organisms often have a competitive advantage in a new environment. These organisms may defend themselves through faster growth or have better self-defense systems than native organisms (Parr and Bishop 2022). This can result in a decrease in the population of native organisms, affecting the food chain.
- Invasive organisms can disrupt food chains by potentially feeding on foods generally eaten by indigenous organisms. This can reduce food availability for consumers at higher levels of the food chain.
- Invasive organisms can become prey for new predators that have no natural enemies in the new environment. On the other hand, invasive organisms can prey on indigenous species in the ecosystem. This can lead to a decline in the population of indigenous species and affect the entire food chain above due to predator–prey changes.
- Some invasive organisms can produce toxic or chemical substances that harm native organisms and other animals in the environment. These toxic substances cause new diseases in the ecosystem, which can affect the population of indigenous organisms, disrupting the balance of the food chain and destroying the balance of the ecosystem.
- Some invasive organisms, such as sea moss or wild coral, can rapidly grow and cover large areas. This can damage the physical structure of ecosystems, such as coral reefs or mangrove forests, which are habitats for many organisms and play a crucial role in the food chain.

15.3.3 Pollution of Water and Soil Due to Production Waste

As explained earlier, some algae species can produce toxins that are harmful to humans and animals. If wild algae grow excessively, the increased toxin levels can pollute waters, ultimately threatening the health of humans and living creatures along the food chain.

In addition to water pollution, microalgae biomass production has the potential to pollute the soil. Land pollution due to microalgae biomass production waste can occur when the waste generated from the microalgae biomass conversion process is not adequately managed. Microalgae biomass conversion technology uses microalgae as a renewable energy source, such as biofuels, chemicals, and other products. Some commonly used processes in microalgal biomass conversion include lipid extraction, fermentation, pyrolysis, and gasification. Solid and liquid wastes can be generated during these processes, which can contaminate the soil if not appropriately managed.

There are several ways that microalgae biomass production waste can contaminate soil:

1. Solid waste. After lipid extraction or other conversion processes, the remaining biomass is usually rich in nutrients and organic matter. However, if these solid wastes are carelessly disposed of on the ground, the nutrients can contaminate the soil and groundwater, causing pollution and eutrophication.
2. Liquid waste. The microalgae biomass conversion process often generates liquid waste containing chemicals and nutrients. If these wastes are not adequately treated before being discharged into the environment, they can pollute soil and groundwater and damage the surrounding ecosystem.
3. Chemicals. During the microalgae biomass conversion process, chemicals such as solvents, catalysts, and acids may be used. If these chemicals are not handled and disposed of properly, they can contaminate soil and groundwater and threaten human health and the environment.

Several management strategies to reduce the impact of soil pollution due to microalgae biomass production waste should be taken, for example:

1. Properly treat solid and liquid waste before disposal into the environment, for example, by composting, drying, or utilizing waste as fertilizer or animal feed (Ayilara et al. 2020).
2. Utilizing environmentally friendly and biodegradable chemicals in microalgae biomass conversion processes can reduce the potential for soil pollution. Selecting appropriate chemicals will depend on the specific microalgae biomass conversion process and operational conditions (Rinanti and Purwadi, 2019).

   Some recommended chemicals in the microalgae biomass conversion process are:

   (a) Enzymes such as cellulase, hemicellulase, and protease can be used to pretest and hydrolyze microalgae biomass. These enzymes are efficient and environmentally friendly biological catalysts and are biodegradable.

(b) Citric acid is a weak organic acid that can be used in lipid extraction and pretreatment of microalgae biomass. Citric acid is biodegradable and has a lower environmental impact than strong acids such as sulfuric acid or hydrochloric acid.
(c) Acetic acid is an organic acid that can be used in the pretreatment process of microalgae biomass. It is biodegradable and more environmentally friendly than strong inorganic acids.
(d) Oxalic acid is an organic acid that can be used to extract lipids from microalgal biomass. Oxalic acid is biodegradable and has a lower environmental impact than other strong acids.
(e) Sodium hydroxide (NaOH) is a base that can be used in the pretreatment process of microalgae biomass. Although NaOH is not a completely environmentally friendly chemical, its environmental impact can be minimized in the right concentration and with good waste management.
(f) Sodium bicarbonate ($NaHCO_3$) is the sodium salt of carbonic acid, which can be used in microalgal biomass's precipitation and flocculation process. Sodium bicarbonate is a biodegradable chemical and has a low environmental impact.

3. Regularly monitoring and controlling waste and chemical emissions in the microalgae biomass production process can help identify and address potential pollution problems before they become significant (Ali et al. 2022). Some of the things that can be done include:

(a) Monitor the quality of water used in the microalgae production process, including nutrient and pollutant content. Water containing excess nutrients or pollutants can increase the risk of algal blooms and environmental pollution.
(b) Monitor and control chemical consumption in the production process. Prioritize using environmentally friendly and biodegradable chemicals to reduce environmental impact and the risk of algal blooms.
(c) Ensure that the wastewater treatment system from the microalgae production process effectively reduces emissions of waste and pollutants to the environment, including regular monitoring of wastewater quality and treatment effectiveness.
(d) Regularly monitor the density and quality of microalgae biomass in the production system to ensure the process is running optimally and reduce the risk of algae bloom.
(e) Monitor the contamination in microalgae production systems caused by pathogenic microorganisms or potentially toxic algae species. Contamination can increase the risk of algal blooms and environmental pollution.
(f) Implement good management and operating practices to reduce the risk of algal bloom and environmental pollution, including optimizing microalgae growth conditions, controlling environmental factors such as temperature and lighting, and conducting regular equipment maintenance and sanitation.

(g) Ensure personnel in the microalgae biomass production process have adequate knowledge and training on algal bloom and environmental pollution control.
(h) Cooperate with authorities and communities in algal bloom and environmental pollution control efforts, including reporting algal bloom incidents or potential environmental problems to the appropriate authorities.

4. Optimize the production and conversion of microalgal biomass to reduce the amount of waste generated and ensure resources are used efficiently and sustainably.

15.4 Strategies to Deal with Algal Blooms and Other Ecological Problems

15.4.1 Management of Nutrients and Reduction of Pollutants in the Waters

Nutrient management and pollutant reduction in water is one of the crucial strategies for addressing algal blooms and other ecological problems. Excess nutrients, such as nitrogen and phosphorus, are often the leading cause of algal blooms and eutrophication. Pollution by other pollutants, such as chemicals and heavy metals, can also disrupt aquatic ecosystems. Here are some ways to manage nutrients and reduce pollutants in water:

1. Source control of pollutants by reducing the introduction of nutrients and pollutants into waters through regulation and control of industry, agriculture, and domestic waste disposal. This may include more efficient use of fertilizers, treatment of wastewater before discharge, and application of green technologies in industry. Some regions have established nutrient management, including imposing restrictions on using phosphate in detergents and fertilizers, as phosphate is a key nutrient promoting algae growth.
2. *Wetland* restoration and establishing vegetative buffer zones along the banks of rivers or lakes can help absorb nutrients and pollutants to avoid algal blooms in waterways. Restoring buffer zones involves maintaining riparian plants, swamps, and mangroves, which can absorb nutrients and pollutants before they reach the water. Buffer zones can also reduce erosion and sedimentation, which can affect water quality.
3. Implementation of Bioremediation Technology, specifically phytoremediation utilizing plants and/or microorganisms, to reduce and even remove pollutants from the environment. For example, some types of algae and plants can be used to absorb excess nutrients from water, preventing algal blooms.
4. Water flow management by using water flow management techniques, such as retention ponds, dams, and infiltration wells, to reduce the flow of water containing nutrients and pollutants into the waters.

5. Water quality monitoring by regularly monitoring water quality to identify sources of nutrients and pollutants and measuring the effectiveness of the management strategies implemented.
6. Educate the public to be more aware of the impacts of nutrients and pollutants on waters and ways to reduce these impacts, such as reducing fertilizer and pesticide use, managing household waste, and reporting pollution. This includes raising awareness about the importance of good waste management and sustainable agricultural practices.
7. Encourage research and development of new technologies or generate innovations to reduce nutrients and pollutants in waters and improve understanding of the relationship between nutrients, pollutants, and algal blooms.
8. Promote cooperation between government, industry, environmental groups, and communities to address water nutrient and pollutant issues.
9. Encourage the central and local governments to develop and implement effective regulations and policies to control pollution and reduce algal blooms.

By implementing these strategies, hopefully, the water's nutrients and pollutants can be controlled, which will help prevent algal blooms and address other ecological concerns. Effective and sustainable management of water bodies is essential for maintaining ecosystem balance and human well-being. Effective management strategies usually involve a combination of the various approaches mentioned above. The appropriate strategy usually varies depending on the specific ecosystem and pollution source (Imai et al. 2021; Rohmah et al. 2018).

15.4.2 Monitoring and Early Detection of Algal Blooms

Monitoring and early detection of algal blooms are essential in managing and addressing associated ecological issues. Early detection of algal blooms allows ecosystem authorities and managers to respond faster and reduce environmental and human health impacts. The following are some methods and strategies that can be used for monitoring and early detection of algal blooms (Binding et al. 2021):

1. Water Sampling and Analysis. Periodic sampling of water from aquatic systems and analysis of nutrient content, such as nitrogen and phosphorus, as well as algae with the potential to form blooms, is essential. Laboratory methods such as morphological analysis with various microscopes, liquid chromatography analysis, and spectroscopic techniques can be used to identify and quantify the concentration of algae in water samples.
2. Satellite Monitoring and Aerial Imagery (*Remote Sensing*). Using *remote sensing* technologies, such as satellite or *drone* sensing, can help monitor algal blooms from a distance. This technology is beneficial for monitoring large or inaccessible areas. Satellite imagery can identify changes in water color that indicate the presence of algal blooms. The images and data collected can be used to identify

areas of high algal activity and monitor the changing waters and the distribution of algal blooms over time.

3. Biosensors. A biosensor is a device that uses organisms or biological components to detect the presence of a specific material. Biosensors are designed to detect certain types of algae or toxins produced by algae and thus can be used for early detection of algal blooms. Biosensors can also be devices to measure chlorophyll fluorescence, aiding in the early detection of algal blooms. Biosensors can be placed in aquatic systems and provide real-time data on conditions that may favor algal blooms.
4. Monitor the presence of vulnerable species. Susceptible species to algal blooms, such as some fish and mollusks, can be monitored as indicators of ecosystem health and the potential for algal blooms. Different types of fish can be affected by algal blooms, and the specific susceptibility of fish can depend on several factors, including the type of algae involved, the type of toxin produced, and the characteristics of the fish species. Some fish species that are more susceptible to algal blooms and can be used as indicators of potential blooms are:

   (a) Prey fish, such as pike, bass, and tuna, can be particularly vulnerable to algal blooms because they are at the top of the food chain. If toxin-producing algae cause algal blooms, the toxins can build up in the food chain and reach high concentrations in predatory fish.
   (b) Fish that live in shallow waters, such as trout and salmon, can be particularly vulnerable to algal blooms. Salmon (*Salmo salar* and *Oncorhynchus* sp.) are sensitive to changes in water quality and the presence of toxins produced by some algae. Decreases in salmon larval populations or survival can indicate algal blooms. Trout (*Salmo trutta* and *Oncorhynchus mykiss*) are also susceptible to changes in water quality and dissolved oxygen levels. Trout can indicate algal blooms that are occurring or will occur, especially in fresh waters such as lakes and rivers.
   (c) Plankton-eating fish, such as herring and anchovy, can be vulnerable to algal blooms as toxin-producing algae can form part of their diet. Herring (*Clupea harengus*) are particularly sensitive to changes in water quality, especially low dissolved oxygen, which is often associated with algal blooms. Mass mortality of herring can indicate algal blooms that are occurring or about to occur.
   (d) Menhaden (*Brevoortia* sp.) is a small pelagic species highly susceptible to hypoxic conditions (low dissolved oxygen) caused by algal blooms. High mortality of menhaden can be an early sign of algal blooms.
   (e) Mullet (*Mugil* sp.) is a species sensitive to changes in water quality, including hypoxic conditions and the presence of toxins some algae produce. Declines in mullet populations or mass mortality can be indicative of algal blooms.
   (f) Monitoring these fish species and other species susceptible to algal blooms can help identify changes in water quality and provide early signs of blooms. However, note that mass fish mortality or population declines can be caused by other factors such as disease, pollution, or habitat changes. Therefore,

observations of vulnerable fish species should be combined with other detection and monitoring methods to identify algal blooms effectively.

5. Predictive Models. The development of predictive models that consider environmental factors such as temperature, humidity, rainfall, and nutrient concentrations can assist in identifying conditions that favor algal blooms. Based on historical data and current environmental conditions, computer models can be used to predict when and where algal blooms might occur. For example, models can use water temperature, salinity, and nutrient concentration data to predict the risk of algal blooms, allowing ecosystem managers to take action before algal blooms occur.
6. Inter-Agency Cooperation. Collaboration between research institutions, governments, and environmental organizations enables the exchange of data and information on algal blooms and the conditions that support blooms. This cooperation also enables effective coordination of actions to reduce the impact of algal blooms on the environment and human health.
7. Community Participation. Involving the community in monitoring algal blooms through citizen watch programs or reporting incidents of algal blooms is expected to aid in the early detection and response to this problem. Communities are trained to identify changes in water properties such as color, texture, or unusual odors. In addition, communities can also play a role in preventing algal blooms by reducing pollution and keeping the environment clean.

In order to manage and address algal blooms and other ecological issues, a combination of these multiple monitoring and early detection methods, along with nutrient management and pollutant reduction strategies, will be essential.

15.4.3 Use of Environmentally Friendly Technology in Microalgae Biomass Conversion

Using environmentally friendly technologies in microalgae biomass conversion can help reduce the negative environmental impacts that trigger algal blooms. Although green technology in microalgae biomass conversion does not directly play a role in monitoring and early detection of algal blooms, it can provide benefits in reducing the risk of algal blooms (Zabochnicka et al. 2022). Such green technologies in microalgae biomass conversion, such as using more efficient extraction methods, separation technologies that minimize the use of hazardous chemicals, and using biodegradable green chemicals, can help reduce the amount of waste and pollutants produced. Proper waste management is essential to prevent environmental pollution in the microalgae biomass conversion process. Environmentally friendly technologies can involve the treatment of solid and liquid wastes before disposal, such as composting, drying, or utilizing wastes as fertilizer or animal feed.

Efficient energy use in microalgal biomass conversion can reduce energy consumption and greenhouse gas emissions. This can help reduce broader environmental impacts and, indirectly, the risk of algal blooms associated with climate change (Zieliński et al. 2023). Sustainable resource use can be pursued by optimizing the production and conversion of microalgal biomass to reduce the amount of waste produced, which can help prevent environmental problems such as algal blooms. Overall, although green technologies in microalgal biomass conversion do not directly play a role in monitoring and early detection of algal blooms, they can help reduce the environmental impacts that trigger algal blooms. By reducing risks and negative environmental impacts, these green technologies can contribute to the prevention and management of algal blooms.

15.4.4 Restoration of Ecosystems Affected by Algal Blooms

Restoration of ecosystems affected by algal blooms involves a series of actions to restore environmental conditions and ecological balance (Sukenik & Kaplan 2021).

1. Eliminate algal blooms. The first step in ecosystem restoration is to eliminate existing algal blooms. This can be done by using environmentally friendly algaecide exposures, mechanical controls such as screening or physically removing algae, or using organisms that prey on algae, such as phytoplankton-eating fish or mussels.
2. Increase oxygen. Algal blooms can cause a decrease in oxygen levels in water, which negatively affects aquatic life. Aeration or other technologies that increase oxygen content in water can help restore optimal environmental conditions.
3. Habitat restoration by replacing dead vegetation or removing toxin-laden sediments to help restore damaged ecosystems. This includes restoration of wetlands, vegetative buffer zones, and damaged river or lake bed substrates.
4. Nutrient management by reducing nutrient inputs into aquatic systems affected by algal blooms is a significant effort to prevent recurrence. It is the control of pollutant sources such as industrial, agricultural, and domestic effluents, as well as the use of improved sewage treatment technologies and more sustainable agricultural practices.
5. Once restoration measures are taken, ongoing monitoring and evaluation are required to ensure the success of the restoration efforts. This includes monitoring water quality, algae population density, and overall ecosystem health.
6. In some cases, restoring fish populations affected by algal blooms may be necessary, for example, by releasing fish caught from elsewhere or a hatchery program to help increase the hard-hit fish population.
7. Community education and engagement about algal blooms and their impacts on ecosystems can help prevent blooms as a long-term restoration effort. Education

programs can include information campaigns, training, and developing awareness of the importance of good waste management and sustainable agricultural practices.

15.5 Circular Economy and Wastewater Management

15.5.1 The Circular Economy Concept and Its Application

The Circular Economy concept is an approach that aims to reduce resource waste and pollution and promote environmental sustainability through the efficient design of products, processes, and systems. It encompasses the principles of "reduce, reuse, recycle" and replaces the "take, make, dispose" paradigm commonly found in linear economies (Kirchherr et al. 2023). In the context of wastewater management and microalgae biomass conversion, the application of the circular economy concept can include various strategies, such as using wastewater as a nutrient source for microalgae growth: Wastewater rich in nutrients, such as nitrogen and phosphorus, can be used to grow microalgae. This way, wastewater is treated and simultaneously provides the necessary nutrient source for microalgae, reducing the need for artificial fertilizers.

After the microalgae biomass conversion process, the remaining water can be further treated to recover nutrients or other chemical compounds that can be used in other processes, such as agriculture or industry. In order to optimize resource use and reduce the environmental footprint, wastewater treatment systems can be combined with microalgae biomass conversion technologies. This enables pollution reduction, resource recovery, and the production of valuable raw materials, such as bioenergy or other high-value products. Microalgae biomass conversion processes often produce by-products that can be used for other purposes, such as animal feed, fertilizer, or raw materials for the chemical industry. Utilizing these by-products reduces resource wastage and creates added value from the production process.

In applying the circular economy concept, developing technologies that can be adapted and improved to meet changing needs and incorporate innovations must be considered. The application of the circular economy concept in wastewater management and microalgae biomass conversion can help create a system that is more environmentally friendly and efficient in resource use. This will support environmental and economic sustainability in the long run.

15.5.2 The Use of Microalgae to Treat Wastewater

Microalgae biomass conversion technology produces commercial products and leaves liquid and solid waste from the production process. Utilizing microalgae to treat wastewater is one example of applying the circular economy concept in wastewater management. Microalgae are photosynthetic microorganisms that can absorb nutrients, such as nitrogen and phosphorus, and organic chemicals from wastewater. This process helps reduce the levels of pollutants in wastewater and simultaneously supports the growth of microalgae (Abdelfattah et al. 2023). The following are some aspects related to the utilization of microalgae in wastewater treatment:

1. Bioremediation. Microalgae play a role in wastewater bioremediation by absorbing excess nutrients (such as nitrates and phosphates) and reducing organic matter levels that can cause pollution. This process helps prevent eutrophication and algal blooms in natural waters.
2. Biomass production. Microalgae growth supported by nutrients from wastewater produces biomass that can be converted into various high-value products, such as bioenergy (biodiesel, biogas, or bioethanol), animal feed, fertilizer, and industrial chemicals.
3. Integrated wastewater treatment. The utilization of microalgae in wastewater treatment can be combined with other treatment technologies, such as aerobic or anaerobic systems, to achieve more efficient and effective treatment levels. This integration allows for more optimized resource use and reduced environmental footprint.
4. Resource recovery. After a wastewater treatment process with microalgae, the remaining water can be further treated to recover resources such as nutrients, water, or other chemical compounds that can be used in other processes, such as agriculture or industry.
5. Education and community engagement. Utilizing microalgae in wastewater treatment can also be used as an educational tool and community involvement in environmental sustainability. The community can be involved in monitoring water quality and maintaining treatment systems that use microalgae.

15.5.3 Case Studies and Best Practices in Wastewater Treatment Using Microalgae

Several projects in Europe have successfully applied wastewater treatment technology using microalgae to produce renewable energy, high-value products, and recover resources (You et al. 2023), namely:

1. The All-gas project in Spain is one of the industrial-scale projects developed by Aqualia, a leading water utility company in Spain. The project focuses on using microalgae to treat wastewater and produce biogas as a renewable energy source. The project successfully combines wastewater treatment with renewable energy production and reduces greenhouse gas emissions. The All-gas project: The most significant wastewater to biofuel facility using algae.

2. The EU INCOVER project is a research initiative funded by the European Union under the Horizon 2020 program. The project includes developing and demonstrating three innovative microalgae-based solutions for wastewater treatment, including biomass production as a renewable energy source, nutrient recovery, and wastewater treatment for irrigation. The INCOVER project demonstrates the potential use of microalgae in integrated and sustainable wastewater treatment systems.
3. The BIOFAT (Biorefinery for Food, Fuel, and Materials) project in the European Union is a research project funded by the European Union under the FP7 program. The project aims to develop an integrated microalgae biorefinery process to produce various high-value products from wastewater, such as biodiesel, chemicals, and fertilizers. The project successfully demonstrated pilot and commercial-scale wastewater treatment using microalgae as a renewable source of energy and chemicals.

15.6 Policy, Regulation, and International Cooperation

15.6.1 Policies and Regulations that Support Algal Bloom Control and the Use of Environmentally Friendly Technologies

Policies and regulations that support the control of algal blooms and the use of environmentally friendly technologies are essential to prevent and manage the negative impacts of algal blooms on ecosystems and human health. Below are some policies and regulations that can help achieve this goal (Rashidi et al. 2021):

1. **Wastewater Management Policies** include policies to limit the amount of nutrients entering aquatic systems through human activities such as agriculture, industry, and domestic sewage, in an effort to reduce the risk of algal blooms. Regulations governing the use of fertilizers, implementation of sustainable agricultural practices, and adequate treatment of effluents can contribute to the control of algal blooms. Here are some international and national regulations governing nutrient restrictions:

    (a) The European Union's Water Framework Directive (WFD) (2000/60/EC), is the legal framework governing the management of water resources in EU member states. The WFD includes restrictions on nutrients, including nitrogen and phosphorus, coming from agriculture, industry, and domestic sewage. Other aspects addressed in the WFD include assessment methodologies, implementation challenges, and integration with other environmental frameworks (de Carvalho et al. 2018).

(b) The European Union's Urban Wastewater Treatment Directive (UWWTD) (91/271/EEC) regulates the collection, treatment, and discharge of municipal wastewater, including restrictions on pollutants that can cause algal blooms.
(c) The United States Clean Water Act (CWA) is a law that aims to restore and maintain the physical, chemical, and biological integrity of the nation's waters. The CWA includes requirements to reduce the amount of nutrients entering waters through restrictions on Total Maximum Daily Loads (TMDLs). In addition, the CWA also regulates the National Pollutant Discharge Elimination System (NPDES) which requires facilities that discharge wastewater to be licensed and meet certain emission standards.
(d) Nutrient Management Regulations in Canada are federal and provincial regulations that govern the management of nutrients in agricultural, industrial, and domestic waste activities. Some provinces such as Ontario have specific regulations called the Nutrient Management Act, which govern the use and handling of nutrients in the agricultural and industrial sectors.
(e) Australia's National Environment Protection (Assessment of Site Contamination) Measure is a regulation governing the assessment and remediation of site contamination, including the limitation of nutrients from human activities such as agriculture, industry, and domestic waste. Australia also has The Australian Guidelines for Water Recycling (AGWR), Water Act 2007 and Australia's National Water Quality Management Strategy (NWQMS). These three regulations generally provide a national framework for efficient and environmentally friendly wastewater management, including the reduction of pollutants that can trigger algal blooms.
(f) Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. 68 Year 2016 on Wastewater Quality Standard is a regulation governing the limitation of nutrients in wastewater originating from various sources, including agriculture, industry, and domestic waste.
(g) Hong Kong's Water Pollution Control Ordinance (WPCO) regulates wastewater management to reduce water pollution and potential algae blooms. The WPCO covers technical requirements for wastewater treatment facilities, water pollution control, such as the implementation of water quality standards, discharge permits, and enforcement. These regulations aim to reduce the negative impacts of water pollution on the environment, human health, and aquatic life.
(h) China's Environmental Protection Law is a law that regulates wastewater management and the discharge of pollutants into waters, including requirements for environmental licensing and efficient and environmentally friendly wastewater management.
(i) Various water quality standards have been developed around the world to help prevent and control algal blooms. Environmental Quality Standards (EQS) in various countries regulate the amount of nutrients allowed in surface water and wastewater to prevent and control algal blooms. These standards can be used as a basis for monitoring and enforcement.

The standards normally include the parameters of nutrient concentration, algae density, and toxicity levels. EQS vary depending on the country and local regulations (Leverett et al. 2021). The following are some examples of water quality standards adopted by several countries and international organizations:

i. The European Union—Water Framework Directive (WFD) and Environmental Quality Standards Directive (EQSD) are standards covering the parameters of nutrient concentration, phytoplankton density (including algae), and toxicity levels set to achieve the goal of good ecological status in surface waters.
ii. The US Environmental Protection Agency (EPA) established the United States—National Recommended Water Quality Criteria (NRWQC) which contains criteria for the concentration of nutrients such as nitrogen and phosphorus, as well as the toxicity of chemicals that may contribute to causing algal blooms.
iii. Australia—The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG) are guidelines that provide information on nutrient concentrations, algal densities, and toxicity that are considered safe for various water uses, such as drinking water supply, ecosystem protection, and recreation.
iv. Canada—The Canadian Water Quality Guidelines for the Protection of Aquatic Life (CWQG) contain criteria for nutrient concentrations, algal densities, and toxicity that are considered safe to protect aquatic life.
v. World Health Organization (WHO)—Guidelines for Drinking-water Quality (GDWQ) is a WHO Guideline that contains information on drinking water quality parameters, including nutrient concentrations, algae density, and toxicity levels considered safe for human health.

Each country may have its own water quality standards that include the parameters of nutrient concentration, algae density, and toxicity levels. These standards are usually implemented by national or local environmental authorities. In Indonesia, water quality standards covering the parameters of nutrient concentration, algal density (Leverett et al. 2021) and toxicity levels to help prevent and control algal blooms can be found in the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. 68 Year 2016 on Wastewater Quality Standards (Permen LHK 68/2016). It regulates the quality of wastewater that is allowed to be discharged into the environment, including limits on nutrient concentrations and toxicity levels that are considered safe for ecosystems and human health. While algae density may not specifically be regulated in the above regulation, water quality criteria that include nutrient concentrations and toxicity levels indirectly help prevent and control algae blooms by reducing the influx of nutrients and other pollutants that can trigger algae growth.

2. Energy and Industrial Policies are expected to support the development and use of environmentally friendly technologies in the energy and industrial sectors, such as tax incentives and research funds to help reduce negative environmental impacts that can trigger algal blooms. Here are some examples of relevant energy and industrial policies:

   (a) The European Union—Renewable Energy Directive (RED) and Energy Efficiency Directive (EED), is the European Union's Green Energy Policy that sets renewable energy and energy efficiency targets for EU member states. It supports the development and adoption of green technologies in the energy and industrial sectors through tax incentives for companies using green energy technologies, financial support schemes, and research funds for the development of new technologies.
   (b) The Renewable Portfolio Standard (RPS) in the United States is a policy that requires power companies to supply a portion of their energy from renewable sources. It encourages the use of green technologies and can help reduce negative impacts on the environment.
   (c) United States—The Production Tax Credit (PTC) and Investment Tax Credit (ITC) are federal tax incentives aimed at supporting the development and adoption of renewable energy and energy efficiency technologies in the energy and industrial sectors.
   (d) China—The 13th Five-Year Plan for Energy Development is a plan that includes targets for the development and use of renewable energy, energy efficiency, and green technologies in the energy and industrial sectors. It includes tax incentives, research funds, and other policy support.
   (e) India—National Solar Mission and National Wind Energy Mission, are part of India's energy policy to reduce dependence on fossil energy and promote the use of renewable energy. The policy includes tax incentives, financial support schemes, and research funds for the development of green technologies in the energy and industrial sectors.
   (f) Germany—Energiewende (Energy Transition) is Germany's highly ambitious energy policy, which aims to reduce greenhouse gas emissions and increase the use of renewable energy. It includes tax incentives, research funds, and other policy support for the development of green technologies in the energy and industrial sectors.
   (g) The Australian Renewable Energy Target (RET) is an Australian government policy designed to increase energy production from renewable sources. The policy includes tax incentives and research funding for companies that develop and use green technologies.
   (h) Feed-in Tariffs (FiTs) and Power Purchase Agreements (PPAs) in various countries are policy instruments used to encourage renewable energy development. These policies guarantee certain payments to renewable energy producers, which helps make the technology more economical and encourages its implementation.

(i) Indonesia—The National Energy General Plan (RUEN) is Indonesia's energy policy that includes targets for the development and use of renewable energy and energy efficiency in the energy and industrial sectors. The policy includes tax incentives, research funding, and other policy support. Indonesia's Renewable Energy Law No. 30 of 2007 establishes the legal framework for renewable energy development in Indonesia, which includes tax incentives and research funds for companies using environmentally friendly technologies.

3. Effective monitoring and enforcement are necessary to ensure regulatory compliance, as well as strict enforcement of violations to control algal blooms.
4. Community education and engagement is expected to increase public awareness about algal blooms, their impacts, and how to prevent them, helping to encourage more environmentally friendly behavior and support existing policies and regulations.
5. As the sources of pollutants and algal blooms are often transboundary, there is a need for international cooperation in developing and implementing effective policies and regulations. This cooperation can include information and knowledge sharing, technical support, and policy coordination between countries.

By combining these various policies and regulations, governments and international organizations can collaborate to control algal blooms and support the use of green technologies in various sectors. This will help protect the ecosystem.

15.6.2 International Initiatives and Cooperation in Tackling Algal Blooms and Ecological Problems

The following are some of the international initiatives and cooperation in addressing algal blooms and ecological problems (Kumar et al. 2021):

1. The Global Water Partnership (GWP) is an international network established in 1996 by the World Bank, Sweden, and the United Nations through the United Nations Development Programme (UNDP) (https://www.gwp.org/en/About-GWP/). GWP aims to support sustainable water resources management and create partnership-based solutions worldwide. GWP works with governments, international organizations, academic institutions, and the private sector to develop and promote Integrated Water Resources Management (IWRM) principles to address water-related challenges at global, regional, and national levels. GWP does not specifically targ*et al*gal blooms but, through initiatives and activities in sustainable water management, indirectly helps reduce the risk of algal blooms. Here are some examples of GWP activities related to water management and their impact on algal blooms:

   (a) Integrated Water Resources Management (IWRM). GWP strongly supports the concept of IWRM, which is a holistic approach to managing water resources. Through IWRM, GWP helps countries develop policies and practices to reduce human activities' negative impacts on water resources, including pollution that can cause algal blooms.

(b) The GWP Water, Climate, and Development Program (WACDEP) is a program designed to integrate climate change in water resources planning and management in Africa. Through WACDEP, GWP works with governments and local partners to reduce the impacts of climate change on water resources, including algal blooms exacerbated by climate change.

(c) GWP-Caribbean is a regional partner of GWP that aims to address water management challenges in the Caribbean. GWP-Caribbean has taken steps to reduce the risk of algal blooms, such as through the development of early warning and monitoring systems.

(d) Water Stewardship and Industry Partnerships is GWP's private sector partner to promote sustainable water management, including efforts to reduce industrial pollution that can cause algal blooms.

(e) GWP supports training and capacity building for water management professionals, including those working in water pollution control and algal blooms.

Although GWP does not explicitly focus on algal blooms, their activities in sustainable water management and mitigation of climate change impacts indirectly help reduce the risk of algal blooms. By working closely with government, private sector, and local partners, GWP helps build awareness and capacity to effectively manage water resources and reduce negative impacts on the environment.

2. The UNESCO Intergovernmental Oceanographic Commission (IOC) (https://ioc.unesco.org/about-ioc) is a commission under UNESCO that was established in 1960. The IOC aims to enhance international coordination and cooperation in research and management of marine resources. Through programs and projects focusing on ocean science, water management and disaster mitigation, the IOC contributes to the development of national knowledge and capacities to address challenges related to climate change, water sustainability, and food and water security. The IOC also plays an important role in early warning systems for tsunamis and other maritime disasters, and in the development and implementation of international policies and strategies for sustainable management of marine resources and disaster risk reduction. The IOC has developed programs such as the Global Harmful Algal Bloom (HAB) which aims to improve global understanding of the harmful algal bloom phenomenon and help countries identify, monitor, and mitigate the impacts of algal blooms on ecosystems and human health. Here are some of the main activities carried out by the Global HAB Program:

(a) The Global HAB Program supports research and monitoring of harmful algal blooms around the world. The program helps countries develop and implement effective monitoring technologies, such as the use of satellites, remote sensing, and early warning systems. This enables early detection of algal blooms and a faster response to mitigate their impacts.

(b) The Global HAB Program organizes various trainings, workshops, and courses to increase countries' capacity to manage and mitigate algal blooms. The program helps water management professionals, scientists and policy makers improve their knowledge and skills in tackling harmful algal blooms.

(c) The Global HAB Program facilitates the exchange of information and knowledge between countries affected by algal blooms. The program supports the development of global and regional networks, such as the Harmful Algal Bloom Information System (HABISYS) and the Northwest Pacific Action Plan (NOWPAP), which enable collaboration and information exchange between experts and institutions working on algal blooms.

(d) The Global HAB Program recognizes the importance of community engagement in reducing the impacts of algal blooms. The program works with local communities, coastal groups, and fishers to raise awareness about algal blooms and develop effective adaptation and mitigation strategies.

(e) The Global HAB Program helps countries develop effective policies to reduce the impacts of algal blooms on ecosystems and human health. The program provides guidance and recommendations to policymakers on how to reduce inputs of nutrients and other pollutants that can cause algal blooms and how to manage and mitigate the impacts of algal blooms that have already occurred.

2. The United Nations Environment Programme (UNEP) is a UN agency that focuses on environmental protection and sustainable development (https://www.unep.org/about-unep). The organization, founded in 1972, focuses on protecting the environment and empowering people to implement sustainable development. UNEP works to provide leadership and foster partnerships in caring for the environment by inspiring, informing, and empowering nations and communities to improve their quality of life without compromising future generations. UNEP has implemented various initiatives and programs to address global environmental issues, including water pollution and algal blooms. Here are some examples of activities undertaken by UNEP:

   (a) The Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) is a global initiative that aims to address marine pollution from land-based activities, including pollution that can cause algal blooms. UNEP works with governments, international organizations, and the private sector to develop and implement pollution reduction strategies.

   (b) UNEP Freshwater Strategy. The strategy is designed to improve the management of freshwater resources and reduce water pollution. Through this strategy, UNEP helps countries develop effective policies and practices to reduce water pollution and its impacts on ecosystems, including algal blooms.

(c) The World Water Assessment Programme (WWAP) is a program led by UNESCO and implemented by UNEP, which specifically evaluates the state of water resources around the world. WWAP produces the World Water Development Report, which includes information on water pollution and algal blooms and strategies to address them.
(d) UNEP has developed guidelines and a framework for sustainable nutrient management, which aims to reduce the impact of excess nutrients, such as nitrogen and phosphorus, on the environment. These excess nutrients can cause algal blooms and result in negative impacts on ecosystems and human health.
(e) The Partnership for Clean Fuels and Vehicles (PCFV) is a global initiative led by UNEP that aims to reduce emissions and air pollution from vehicles. While the main focus of PCFV is air pollution, reducing emissions can also reduce the deposition of nutrients and pollutants from the atmosphere into waters, thereby helping to reduce the risk of algal blooms.
(f) UNEP works with various international organizations, governments, and the private sector to address environmental issues, including water pollution and algal blooms. UNEP also supports the establishment of networks and platforms for countries to share knowledge and experience in managing environmental issues.

Through these activities, UNEP helps countries identify and address water pollution and algal blooms and other environmental problems. UNEP emphasizes an integrated, multi-sectoral approach to achieve sustainable environmental management and reduce the risk of algal blooms.

4. HELCOM (Baltic Marine Environment Protection Commission) https://helcom.fi/about-us/

   HELCOM (Baltic Marine Environment Protection Commission), or Helsinki Commission, is a regional environmental organization formed by the countries around the Baltic Sea and the European Union. The main objective of HELCOM is to protect the Baltic marine environment from all sources of pollution by coordinating the necessary actions by the member states. HELCOM was established in 1974 under the Convention on the Protection of the Marine Environment of the Baltic Region (Helsinki Convention). The Convention was revised in 1992 to accommodate political and environmental changes in the region. HELCOM member states cooperate in the monitoring, assessing, and managing the Baltic marine environment, and develop recommendations and environmental protection measures, including efforts to control algal blooms through nutrient load reduction and environmental monitoring.
5. OSPAR Commission (Oslo-Paris Commission) https://www.ospar.org/about is a regional environmental organization established in 1992 to protect and preserve the marine environment of the Northeast Atlantic and North Sea. The OSPAR Commission is the result of the merger of the Oslo Convention of 1972, which deals with waste disposal at sea, and the Paris Convention of 1974, which deals with marine pollution from land-based sources. OSPAR has 15 member states and

the European Union, which work together to control and reduce marine pollution, protect marine biodiversity and ecosystems, and monitor and assess the quality of the marine environment. The Commission develops strategies, recommendations and environmental management measures that are adopted by member states. Cooperation among member states within the OSPAR Commission plays an important role in improving the quality of the marine environment and ensuring the sustainability of ecosystems in the Northeast Atlantic and North Sea. OSPAR is an intergovernmental cooperation mechanism that aims to protect the marine environment of the Northeast Atlantic and North Sea including reducing pollution from various sources, which can cause algal blooms.

6. The International Nitrogen Initiative (INI) https://www.initrogen.org/about is a global program focused on understanding and addressing the impacts of the nitrogen cycle on the environment, economy, and human health. INI was established in 2003 as a result of recommendations from the Scientific Committee on Problems of the Environment (SCOPE) and operates under the auspices of Future Earth and the International Union of Nutritional Sciences (IUNS). INI's goal is to optimize nitrogen use in agricultural and industrial systems and reduce unwanted nitrogen emissions that can lead to climate change, air pollution, water quality degradation and biodiversity loss. INI achieves this goal through research, education, and policy development involving scientists, policy makers, and other stakeholders. INI has several regional centers responsible for coordinating activities in different regions around the world, including North America, Latin America, Europe, Africa, and Asia. The initiative supports international cooperation and multidisciplinary research aimed at effectively and sustainably addressing nitrogen issues is an international program that aims to optimize the use of nitrogen in agricultural and industrial systems, while reducing the negative impacts of nitrogen on the environment and human health by reducing the excessive influx of nutrients into aquatic systems, which can lead to algal blooms (McLellan et al. 2018). Here are some of the efforts made by THIS to prevent algal blooms:

   (a) Research and understanding. INI supports and facilitates research on the nitrogen cycle and its impact on the environment, including algal blooms. This research helps improve understanding of how excess nitrogen triggers algal blooms and how to reduce their impact.
   (b) Sustainable nutrient management. INI develops and promotes sustainable nutrient management practices, such as efficient fertilizer use and precision farming systems. These practices help reduce excess nutrient inputs to waters, thereby reducing the risk of algal blooms.
   (c) Policy and recommendations. INI provides guidance and recommendations to policy and decision makers on how to reduce the impact of excess nitrogen on the environment, including algal blooms. INI seeks to influence policy and practice at national and international levels to reduce nitrogen pollution.
   (d) Building Capacity and Education. INI seeks to increase the capacity and knowledge of experts, practitioners, and policymakers in effectively

managing nitrogen and reducing environmental impacts, including algal blooms. INI organizes workshops, trainings, and conferences to promote the exchange of knowledge and experience in the field of nitrogen management.

(e) Partnerships and collaboration. INI works closely with various international organizations, governments, the private sector, and research institutions to address the issue of excess nitrogen and its impact on the environment. INI helps coordinate and integrate efforts across different sectors and countries to reduce the impacts of excess nitrogen, including algal blooms.

Through these efforts, the International Nitrogen Initiative (INI) seeks to reduce the negative impact of excess nitrogen on the environment and prevent algal blooms.

7. Ramsar Convention on Wetlands. This convention is an intergovernmental agreement that aims to conserve and use wetlands wisely. The convention includes efforts to control algal blooms through nutrient source management and environmental monitoring (Xu et al. 2019). Although the main focus of the convention is wetland conservation, some efforts have been made to control algal blooms in the context of wetlands. Below are some examples of the Ramsar Convention on Wetlands' efforts to control algal blooms:

   (a) Sustainable wetland management. The Convention encourages sustainable and wise management of wetlands, which can help reduce the flow of nutrients into waters and reduce the risk of algal blooms. This management includes erosion control, ecosystem restoration, and efficient use of water resources.
   (b) The Ramsar Convention supports research and monitoring of wetland ecosystems, including water quality and the occurrence of algal blooms. A better understanding of the processes and factors that influence algal blooms in wetland ecosystems can help inform effective management strategies.
   (c) The convention seeks to raise public awareness about the importance of wetlands and the impact of algal blooms on ecosystems and human health. This includes extension and information campaigns on how to reduce the flow of nutrients and pollutants into wetlands and waters.
   (d) The Ramsar Convention provides guidelines and recommendations for member states on effective and sustainable wetland management. This includes policies and practices that can reduce the risk of algal blooms, such as pollutant control and nutrient management.
   (e) The Convention promotes international cooperation in the conservation and wise use of wetlands. Through the exchange of information, knowledge and best practices, countries can learn from each other on how to control algal blooms and protect wetland ecosystems.

International cooperation on algal blooms and other ecological issues is an important aspect of global efforts to protect the environment and biodiversity. Through these initiatives, countries can share information, resources, and best practices to address common environmental problems.

15.6.3 The Role of Government, Industry, and Society in Overcoming the Algal Bloom Problem

Addressing algal blooms requires an integrated and collaborative effort between government, industry, and society (Stauffer et al. 2019). Governments are urged to develop and implement regulations and policies that limit the release of nutrients and pollutants into waters; increase monitoring and research on algal blooms to better understand their causes, impacts and control. In addition, the government is expected to provide support and resources for efficient and environmentally friendly wastewater management and treatment. Collaboration and coordination between various government agencies in addressing the problem of algal blooms is also highly desirable. Public education and outreach campaigns on the importance of protecting water resources and reducing pollution need to be initiated by the government.

Industry is expected to adopt environmentally friendly technologies and practices that reduce the release of nutrients and pollutants into waters; implement effective environmental management systems to reduce operational impacts on aquatic ecosystems; invest in research and development of technologies that can help reduce algal blooms and their impacts. Industry needs to actively cooperate with governments and communities in a joint effort to address algal blooms and conduct transparent and accountable reporting on company environmental impacts and algal bloom reduction efforts.

In addition to the government and industry, the public is also expected to increase awareness and knowledge about algal blooms and their impact on the environment and human health. Other things that communities need to do are to reduce the use of chemical fertilizers and pesticides in agriculture and plantations and implement sustainable agricultural practices; reduce water pollution from domestic waste, such as ensuring good septic systems and reducing the use of phosphate detergents. In addition, the community needs to monitor and report algal blooms to the authorities and encourage effective control measures. Finally, communities need to participate in initiatives and activities that aim to protect and maintain the quality of water resources.

15.7 Research and Innovation of Environmentally Friendly Conversion Technology

15.7.1 Recent Research on Treating Algal Blooms and Other Ecological Problems

Here are some examples of collaborative research initiatives between universities, research centers, and industry that focus on the circular economy and wastewater management using microalgae:

1. AlgaePARC (Algae Production and Research Center) is managed by Wageningen University & Research, the Netherlands. AlgaePARC is a research center that combines expertise from academia, industry, and government to develop efficient and sustainable microalgae biomass production technologies. Researchers at AlgaePARC work on the development and optimization of microalgae cultivation systems, such as photobioreactors, open ponds, and systems that combine various technologies. The goal is to increase the efficiency and reduce the cost of microalgae production. AlgaePARC also focuses on improving photosynthetic efficiency, nutrient use, and microalgae growth by optimizing environmental conditions such as Light (Oostlander et al. 2020), temperature, and nutrients. Researchers at AlgaePARC study various microalgae species to determine the most suitable species for specific applications, such as the production of chemicals, feedstuffs, and bioenergy. To improve the productivity and resilience of microalgae species, researchers at AlgaePARC use conventional breeding techniques and genetic engineering. AlgaePARC also focuses on developing efficient processing technologies for the extraction of high-value products from microalgae, such as lipids, proteins, and carbohydrates. In addition, they are also examining ways to recover nutrients from waste streams and use them for microalgae growth. The development of mathematical models and life cycle analyses were also conducted to assess the environmental and economic impacts of microalgae production systems and identify opportunities for improvement.
2. Bielefeld University and Karlsruhe Institute of Technology, Germany—Project "MicroAlgae". This project is a collaboration between Bielefeld University, Karlsruhe Institute of Technology, and industrial partners to develop an innovative photobioreactor technology capable of treating wastewater and producing microalgae biomass for biodiesel production. The aim of the project is to reduce greenhouse gas emissions and produce high-value by-products from microalgae biomass.
3. Arizona State University—Arizona Center for Algae Technology and Innovation (AzCATI) is a collaboration between Arizona State University and industry partners to develop environmentally friendly and economical microalgae biomass production technologies and processes. AzCATI collaborates with industry and academic partners to accelerate research and development of microalgae technology and facilitate the transfer of technology and knowledge to the industrial sector. AzCATI provides education and training to students, researchers, and industry professionals on microalgae technology and its applications in various sectors (Khavari et al. 2021). AzCATI focuses on wastewater management, increasing microalgae productivity, and converting biomass into biodiesel and other value-added products. AzCATI also provides support and services to startups and companies interested in developing microalgae-based technologies or products, including access to research facilities, equipment, and technical expertise.
4. National University of Singapore (NUS)—Environmental Research Institute (NERI). NERI collaborates with industry and academic partners to develop wastewater treatment technologies using microalgae, with the aim of producing

microalgal biomass that can be converted into biodiesel and high-value by-products. The initiative aims to reduce water pollution and optimally utilize resources.
5. BioGAS + Project (European Union). The BioGAS + project is a consortium of universities, research centers and companies working together to develop innovative technologies for producing biogas from wastewater enriched with microalgae. In addition to producing biogas, the project also creates high-value by-products from the microalgae biomass, such as animal feed and fertilizer.

By involving various stakeholders in collaborative research initiatives, the process of discovering and developing new technologies becomes more efficient, and research results can be applied more quickly on an industrial scale.

15.7.2 Microalgae Biomass Conversion Technology Innovations That are Environmentally Friendly (Microwave Pyrolysis, Fermentation Processes for Bioethanol Production, Integration of Photobioreactor Technology (PBR) With Wastewater Treatment Systems)

Some environmentally friendly microalgae biomass conversion technology innovations include:

Lipid Extraction Technology with Green Solvents

The use of green solvents, such as peracetic acid or terpenes, can replace conventional, potentially hazardous organic solvents in the process of lipid extraction from microalgae. This technology enables a more environmentally friendly and safe lipid extraction. Lipid extraction technology with green solvents, such as peracetic acid or terpenes, is an innovative microalgal biomass conversion technology that is environmentally friendly for several reasons

1. Green solvents such as peracetic acid or terpenes are more environmentally friendly compared to conventional solvents, such as hexane or chloroform. Green solvents have lower environmental impact, are biodegradable, and have low potential toxicity.
2. Lipid extraction technology using green solvents offers higher extraction efficiency compared to conventional methods. This helps to increase production yield and reduce resource consumption in the microalgae biomass conversion process.
3. The lipid extraction process with green solvents produces less waste than conventional methods. This waste reduction contributes to the sustainability of the industry and reduces environmental impact.

4. The use of green solvents in the lipid extraction process has the potential to produce better quality products, such as lipids with higher purity or products with more stable characteristics. This can increase the commercial value of the product and expand its applications.
5. Green solvents are generally safer to use in industrial processes and have lower risks to human health. This can reduce the risk of occupational accidents and improve safety for workers involved in the lipid extraction process.

The process of lipid extraction with green solvents proceeds in stages as follows (Zieliński et al. 2022):

1. Microalgae cells are crushed or treated with mechanical, chemical, or enzymatic methods to break the cell wall and release the lipids inside.
2. After cell destruction, the cellular solids are separated from the solution to isolate the desired lipids.
3. Extraction of lipids with green solvents involves mixing a lipid solution with a green solvent, such as peracetic acid or terpenes, which will solubilize the lipids and separate them from other components in the solution.
4. After extraction, the lipid-solvent mixture is separated from the aqueous phase and other insoluble components through processes such as centrifugation, decantation, or filtration.
5. The extracted lipids are then separated from the solvent through evaporation, distillation, or other techniques, resulting in pure lipids ready for use.

Lipid Extraction Technology by Supercritical Method

This process has advantages such as low use of chemical solvents and shorter extraction time. Supercritical lipid extraction technology is an innovative microalgae biomass conversion technology that is environmentally friendly for several reasons (Saini et al. 2021).

1. Use of supercritical solvents. Supercritical methods often use supercritical CO_2 ($scCO_2$) as a solvent. CO_2 is a relatively non-toxic, non-flammable, and non-reactive solvent, making it safer and environmentally friendly compared to conventional organic solvents.
2. Extraction efficiency. The lipid extraction process by supercritical methods offers high extraction efficiency and good selectivity. This means that more lipids can be extracted from microalgal biomass by this method compared to conventional methods.
3. Waste reduction. In the supercritical extraction process, the amount of waste generated is usually lower than in conventional methods. In addition, the CO2 used as a solvent can be recycled and reused in the extraction process, reducing emissions and environmental impact.
4. Product quality: Supercritical methods produce lipids with higher purity and better quality, as the process is more selective in removing lipids from microalgal biomass. This increases the commercial value of the product and expands its applications.

5. Safety and health: Compared to conventional organic solvents, supercritical CO_2 is safer to use in industrial processes and has a lower risk to human health.

How does supercritical lipid extraction technology work? Here are some steps to perform lipid extraction by supercritical method

1. Biomass preparation. The dried and crushed microalgae biomass was placed in an extraction chamber.
2. Supercritical condition setting. CO_2 is compressed and heated to reach supercritical conditions (pressure and temperature above the critical point of CO_2). At this condition, CO_2 has unique solvent properties and is effective for dissolving lipids.
3. Lipid extraction. Supercritical CO_2 is flowed through an extraction chamber containing microalgae biomass. Lipids dissolve in the supercritical CO_2 and are carried out of the extraction chamber.
4. Lipid separation. After going through the extraction chamber, the mixture of supercritical CO_2 and lipids is flowed into the separation chamber, and then the pressure and temperature are reduced. The CO_2 will return to gas and the lipids will separate, resulting in pure lipids ready for use.
5. CO_2 recycling. The CO_2 separated from the lipids is then recycled and reused in the extraction process, reducing emissions and environmental impact.

Hydrothermal Technology

Hydrothermal conversion processes such as hydrothermal liquefaction and hydrothermal gasification are innovative microalgal biomass conversion technologies that are environmentally friendly (Grande et al. 2021) due to the following:

1. Through a hydrothermal conversion process microalgal biomass is converted into liquid or gaseous fuels that are biodegradable and sustainable. This means that in the event of a spill or leak, the environmental impact will be much lower than with fossil fuels. Hydrothermal technology also has the potential to reduce negative environmental impacts by reducing the amount of solid residue, producing cleaner energy, and promoting energy sustainability.
2. Hydrothermal liquefaction and hydrothermal gasification are efficient processes that convert microalgal biomass under high pressure and temperature conditions without the need for a pre-drying step. This reduces energy costs and makes the process more environmentally friendly.
3. The use of fuels produced from microalgal biomass can help diversify energy sources and reduce dependence on fossil fuels, which will have a positive impact on the environment and energy sustainability.

Utilization of Microalgal Biomass for Biogas Production

Microalgal biomass can be used as a substrate in anaerobic processes, such as anaerobic fermentation or anaerobic digestion, to produce biogas. The biogas produced can be used as fuel or converted into electricity and heat. The utilization of anaerobic digestion of microalgae is an important step to make microalgae-based biodiesel production more sustainable. In this study, the authors evaluated the anaerobic digestion of microalgae and assessed its potential to improve the sustainability of microalgae-based biodiesel production. This study focused on exploring the energy potential in the microalgal biomass remaining after lipid extraction for biodiesel production. Anaerobic digestion of microalgal biomass can produce biogas, which is a mixture of methane (CH_4) and carbon dioxide (CO_2) and other components in small amounts. This process can improve the sustainability of biodiesel production from microalgae by reducing environmental impacts and creating an additional energy source. The authors also discuss various factors that affect the efficiency of the anaerobic digestion process, such as microalgal biomass composition, process conditions, and pre-processing techniques used before anaerobic digestion. In addition, the authors identify future research areas that can improve the efficiency and sustainability of microalgae-based biodiesel production.

Microwave Pyrolysis

Microwave pyrolysis technology is a thermochemical process that converts microalgae biomass into solid, liquid, and gaseous fuels under low oxygen conditions (Zhou and Hu 2020). Microwave pyrolysis has advantages, such as higher energy efficiency and shorter process time. This process is considered an environmentally friendly microalgae biomass conversion technological innovation for several reasons:

1. Pyrolysis is a thermochemical process that occurs under low oxygen conditions, thereby reducing emissions of greenhouse gases such as carbon dioxide (CO_2) and oxides of nitrogen (NO_x) generated during the conversion process.
2. Microwave pyrolysis uses microwaves to generate heat, which improves energy efficiency and reduces energy consumption during the conversion process. This reduces the carbon footprint derived from this pyrolysis process and makes it more environmentally friendly.
3. Just like the hydrothermal conversion process, the use of microalgae biomass in microwave pyrolysis technology allows the utilization of a sustainable and fast-growing biomass source, without competing with agricultural land or food needs.
4. Microwave pyrolysis technology produces solid (biochar), liquid (bio-oil), and gas (biogas) products that can be used as fuel or feedstock for the chemical industry. These products are of high quality and can replace fossil fuels, thereby reducing environmental impact.
5. As with hydrothermal conversion, microalgal biomass absorbs CO_2 during growth, thus helping to reduce greenhouse gas emissions. The use of fuel produced from microwave pyrolysis technology will also reduce CO_2 emissions resulting from fossil fuel combustion (Megia et al. 2021; Rinanti and Purwadi 2018).
6. By producing solid, liquid, and gaseous fuels, microwave pyrolysis technology helps diversify energy sources and reduce dependence on fossil fuels.

Fermentation Process for Bioethanol Production

Microalgae can be fermented to produce bioethanol, an environmentally friendly alternative fuel. Carbohydrates in microalgae biomass are broken down or converted into simple sugars which are then fermented into ethanol. The fermentation process for bioethanol production from microalgae biomass is considered an environmentally friendly biomass conversion technology innovation for several reasons:

1. A sustainable source of biomass. Microalgae is a fast-growing and renewable biomass source. Compared to terrestrial crops, microalgae have higher productivity and do not require large areas of agricultural land, so they do not compete with land requirements for food production.
2. CO_2 sequestration. During growth, microalgae absorb CO_2 from the atmosphere, thus helping to reduce greenhouse gas emissions. In addition, bioethanol produced from the fermentation of microalgae biomass will reduce CO_2 emissions resulting from the combustion of fossil fuels.
3. Renewable fuel. Bioethanol is a renewable fuel that can be used as an alternative or blend with gasoline, thereby reducing dependence on fossil fuels and the environmental impacts associated with them.
4. Biodegradability. Bioethanol is more biodegradable in the environment than fossil fuels, so it has a lower environmental impact in the event of a spill or leak.
5. Reduction of pollutant emissions. Bioethanol produces lower emissions of some air pollutants, such as sulfur dioxide (SO_2) and particulates, compared to gasoline. This can help reduce air pollution and improve air quality.
6. Waste utilization. Fermentation processes for bioethanol production from microalgae can utilize microalgae biomass waste generated from other processes, such as lipid extraction for biodiesel production. By utilizing this waste, the fermentation process helps to reduce waste and make it more environmentally friendly.

Therefore, the fermentation process for bioethanol production is considered an innovative microalgal biomass conversion technology that is environmentally friendly because it utilizes a sustainable and fast-growing biomass source (Rozina et al. 2022), produces renewable fuels with lower environmental impact, and reduces greenhouse gas emissions. The use of bioethanol can also help diversify energy sources and reduce dependence on fossil fuels (Juliarnita et al. 2018).

Integration of Photobioreactor (PBR) Technology with Wastewater Treatment Systems

Specially designed photobioreactors can be used to treat wastewater by utilizing microalgae. This technology helps to reduce water pollution and utilize the nutrients contained in wastewater for microalgae growth and biomass production as in (Fig. 15.14).

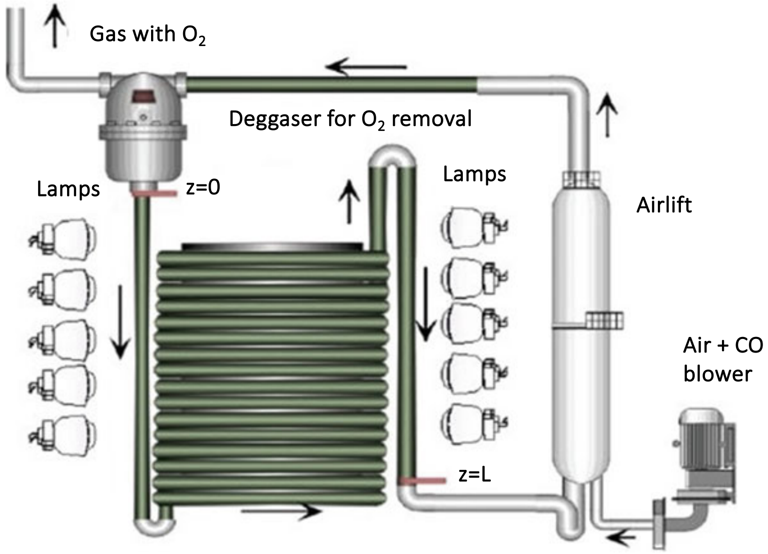

Fig. 15.14 The tubular photobioreactor (PBR)

The integration of photobioreactor (PBR) technology with wastewater treatment systems is considered an environmentally friendly conversion technology innovation for several reasons:

1. Photobioreactors integrated with wastewater treatment systems allow microalgae to grow in wastewater, helping to treat the water and reduce pollution. Microalgae can remove excess nutrients such as phosphate and nitrogen from wastewater, thereby reducing eutrophication and disruption of aquatic ecosystems.
2. During growth, microalgae in the photobioreactor absorb CO_2 from the atmosphere and from industrial emissions associated with wastewater treatment systems. This helps reduce greenhouse gas emissions and associated environmental impacts.
3. Microalgae grown in photobioreactors are a fast-growing and renewable source of biomass (Egbo et al. 2018). The use of microalgae as feedstock to produce fuels and other products may reduce dependence on non-renewable natural resources and help realizing a circular economy.
4. Photobioreactors can be placed in various scales and shapes, allowing flexible placement and efficient space utilization. In addition, photobioreactors integrated with wastewater treatment systems utilize existing resources, such as wastewater and CO_2 emissions, to produce microalgal biomass.
5. The microalgal biomass produced from the photobioreactor can be converted into various products, such as bioethanol, biodiesel, biogas, or other chemicals, which can replace fossil fuels and help diversify energy sources.

6. By utilizing microalgae to remove nutrients and contaminants from wastewater, the cost of wastewater treatment can be reduced, making the system more environmentally friendly and economical.

In summary, integrating photobioreactor technology with wastewater treatment systems is an environmentally friendly conversion technology innovation because it helps reduce water pollution and greenhouse gas emissions, utilize sustainable biomass sources, and improve space and resource efficiency. By developing and adopting environmentally friendly microalgae biomass conversion technology innovations, industries can actively reduce negative impacts on the environment and create more sustainable processes.

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