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Tonni Agustiono Kurniawan
Abdelkader Anouzla *Editors*

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

Toward Carbon Neutrality

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Preface

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Xiamen, China — Tonni Agustiono Kurniawan, Ph.D.
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Contents

Chapter 17
Circular Economy for Biodiesel Production by Managing Wastewater Using Microalgae

Astari Minarti, Astri Rinanti, Melati Ferianita Fachrul, Tazkiaturrizki, and Ranadiya Fadhila

Abstract A circular economy is an economic concept that aims to reduce waste and pollution while maximizing the use of resources through sustainable cycles of production, consumption, and recycling. In biodiesel production, a circular economy can be applied by managing liquid waste (wastewater) produced from the production process through microalgal metabolic activities. A circular economy begins with utilizing wastewater generated from biodiesel production, which contains nutrients and other organic matter for microalgae growth. Microalgae can be cultured in closed (such as photobioreactors) or open (such as ponds) systems filled with wastewater. Naturally, microalgae will absorb nutrients such as nitrogen, phosphorus, and carbon in wastewater. This process not only cleans the wastewater, but also reduces the risk of eutrophication and algal bloom, particularly if the wastewater is discharged without treatment. By absorbing nutrients from wastewater, microalgae will grow and reproduce, producing energy-rich biomass. This biomass can then be collected and further processed to produce high-value products such as biodiesel. Microalgae biomass contains lipids (fats) that can be converted into biodiesel through extraction, transesterification, and purification. The extracted lipids are then converted into methyl esters (biodiesel) with the help of a catalyst and alcohol. After lipid extraction, the remaining biomass rich in protein and carbohydrates can be used as animal

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feed, fertilizer, or feedstock for biogas production, thereby reducing the wastage of resources. Water treated with microalgae can be further processed to reduce the remaining pollutant content, if necessary, before being discharged into the environment or reused in industrial processes. A more efficient and environmentally friendly system can be created by implementing a microalgae-based circular economy at the production and waste treatment level. This can help reduce the negative impact of biodiesel production on the environment while creating added value from the waste generated.

17.1 Introduction to the Circular Economy

17.1.1 Definition and Principles of Circular Economy

The circular economy is an economic system that aims to reduce resource wastage and minimize environmental impact by redesigning, reusing, and recycling products and materials (Morseletto 2020). The concept is an alternative to the currently dominant linear economic model based on the principle of "take, make, dispose". The circular economy combines economic, environmental, and social principles to create a more sustainable and inclusive system. Some of the basic principles in a circular economy are as follows:

(1) Design environmentally friendly products and processes by developing products and processes that can be recycled, easily separated, and minimize the use of natural resources. The goal is to reduce waste and pollution from the beginning to the end of the product life cycle.
(2) Maintenance, repair, and refurbishment concept are implemented by increasing product life with good maintenance, repair when needed, and refurbishment to maintain product quality and function.
(3) Reuse and redistribution are reusing products or their components in other processes or applications or redistributing products no longer useful to individuals or organizations in need.
(4) Recycling and upcycling involve processing waste materials to produce new materials of higher quality (upcycling) or equivalent to the original materials (recycling). The aim is to reduce the extraction of new resources and the volume of waste going into landfills.
(5) The sharing and collaboration economy encourages consumers and producers to share resources, knowledge, and infrastructure to optimize product use and reduce environmental impact.
(6) Use of renewable energy and resource efficiency by replacing fossil energy sources with renewable energy and improving resource use efficiency to reduce greenhouse gas emissions and mitigate environmental impacts.

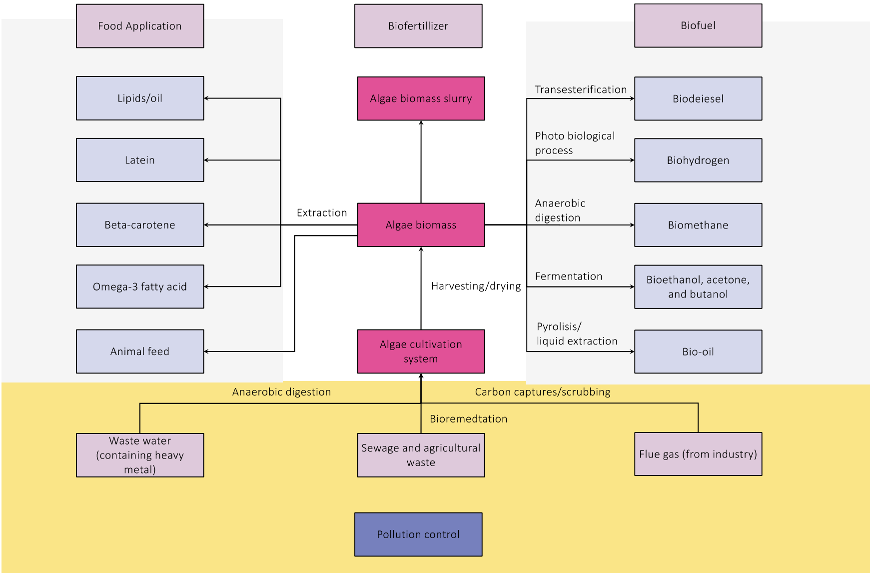

Fig. 17.1 Schematic diagram of the economic benefits of using microalgae

(7) The system approach applies circular economy principles throughout the value chain, including resource management, product design, production, distribution, consumption, and waste management. This approach helps create synergies between different sectors and stakeholders to achieve greater sustainability goals (Taelman et al. 2018), as shown in (Fig. 17.1).

By adopting the circular economy principles, companies, governments, and individuals can reduce their environmental footprint, save costs, and create added value for society and the environment.

17.1.2 The Benefits and Sustainability of the Circular Economy

The circular economy offers many benefits and sustainability that can change how we produce, use, and manage resources (Barros et al. 2021). Here are some of the benefits and sustainability aspects of the circular economy:

(1) Waste and pollution reduction. The redesign of products and processes to reduce waste and pollution from the outset, as well as an emphasis on recycling and upcycling, reduces the amount of waste going into landfills and minimizes pollutant emissions to the environment.

(2) Resource efficiency. The circular economy encourages more efficient use of resources, such as renewable energy and the reuse of materials. This reduces pressure on natural resources and helps keep resources available for future generations.
(3) Reduce greenhouse gas emissions. By reducing energy and material consumption and increasing efficiency in resource use, the circular economy can reduce greenhouse gas emissions that contribute to climate change.
(4) Economic sustainability. The circular economy promotes sustainable economic growth by creating new jobs and industries focusing on recycling, remanufacturing, and efficient resource management.
(5) Innovation and competitiveness. The circular economy spurs innovation in product design, technology, and business models, thereby improving the competitiveness of companies and promoting economic growth.
(6) Social well-being. Reducing waste and pollution, and using resources more efficiently, can improve the quality of life and public health, especially in communities vulnerable to a linear economy's negative impacts.
(7) Environmental sustainability. The circular economy helps maintain the balance of nature and biodiversity by reducing pressure on ecosystems and mitigating the negative impacts of resource extraction, production, and consumption.
(8) System resilience. The circular economy builds resilience in economic and environmental systems by reducing dependence on finite natural resources, reducing risks related to resource prices, and increasing the ability to handle change and disruption.

By applying the circular economy principles, we can create a more sustainable and inclusive system that benefits individuals and the environment (Velenturf and Purnell 2021). These economic, social, and environmental benefits will help ensure long-term sustainability and well-being for future generations.

17.1.3 Circular Economy Applications in the Renewable Energy Industry

The renewable energy industry has great potential to adopt and integrate circular economy principles. Here are some applications of the circular economy in the renewable energy industry:

(1) Design and manufacture of renewable energy equipment. Develop equipment such as solar panels, wind turbines, and energy storage systems that are easily recyclable, use environmentally friendly materials, and have a longer lifespan (Massoud et al. 2023). This may include modularity in design, selection of recyclable materials, and planning for repair, maintenance, and dismantling.
(2) Equipment maintenance and repair. Conduct regular maintenance and repairs on renewable energy equipment to extend its lifespan and reduce the need

for equipment replacement. This includes performance monitoring, preventive maintenance, and timely repair interventions.

(3) Recycling and waste management. Implement efficient recycling and waste management systems for renewable energy equipment that has reached the end of its useful life. For example, old solar panels can be recycled to obtain raw materials such as silicon, metal, and glass, which can then be used to make new panels (Chowdhury et al. 2020).

(4) Integrated energy systems. Integrate various renewable energy sources, such as solar, wind, and hydro, in a flexible and coordinated energy system (Manousakis et al. 2023). This creates synergy and efficiency and ensures a stable and sustainable energy supply.

(5) Service-based business model. Adopt business models emphasizing providing renewable energy services rather than selling energy equipment. These models, such as Energy-as-a-Service (EaaS), encourage manufacturers and service providers to take responsibility for equipment maintenance, repair, and recycling, thus reducing the burden on end-users and promoting resource efficiency (Islam et al. 2022).

(6) Collaboration and sharing economy. Build platforms and networks that enable companies, governments, and communities to share renewable energy knowledge, resources, and infrastructure (Sutherland and Jarrahi 2018). This collaboration could include partnerships for technology development, integrated planning, or shared use of infrastructure such as power grids.

By integrating the principles of the circular economy in the renewable energy industry, we can create an energy system that is more efficient, sustainable, and resilient to resource price fluctuations and changing environmental conditions. This will help accelerate the transition to a greener energy system and support sustainability goals.

17.2 Biodiesel and Microalgae Biomass Conversion Technology

17.2.1 Definition and Characteristics of Biodiesel

Biodiesel is an alternative fuel from renewable feedstocks such as vegetable oils, animal fats, and used cooking oil (Neupane 2023). Biodiesel is a form of bioenergy that has similar properties and characteristics to petroleum-derived diesel, but is more environmentally friendly and, therefore, sustainable. Biodiesel is commonly used as a fuel for diesel engines in the transportation and industrial sectors. Characteristics of biodiesel include:

(1) Renewable feedstock sources. Biodiesel is produced from renewable feedstocks such as vegetable oils (e.g. palm oil, soybean oil, and rapeseed oil) and animal fats. These feedstocks can be sourced locally and replanted after harvesting, which means a more stable and sustainable supply than petroleum.
(2) High biodegradability. Biodiesel is more biodegradable in the environment compared to conventional diesel. This means that biodiesel spills tend to have a lower environmental impact than fossil fuel spills.
(3) Lower greenhouse gas emissions. The use of biodiesel results in lower greenhouse gas emissions, especially carbon dioxide (CO_2), compared to conventional diesel (Xu et al. 2022). This is because the plants used to produce biodiesel absorb CO2 as they grow, which is then released back into the atmosphere when the biodiesel is burned. This cycle results in a better carbon balance.
(4) Good lubricating properties. Biodiesel has better lubricating properties than conventional diesel, which can reduce friction and wear on the engine (Li et al. 2019). This can increase engine life and reduce maintenance costs.
(5) Higher freezing point. Biodiesel has a higher freezing point than conventional diesel, which means that it can agglomerate at higher temperatures (Rao and Chary 2018). This can be a drawback in cold climates, but this problem can be overcome by blending biodiesel with conventional diesel or using additives that lower the freezing point.
(6) Compatibility with diesel engines. Biodiesel is generally compatible with existing diesel engines, although some minor modifications may be required depending on the blend level of biodiesel and conventional diesel used (Brahma et al. 2022). Biodiesel is often used in blended form, such as B5 (5% biodiesel, 95% diesel) or B20 (20% biodiesel, 80% diesel).

17.2.2 Process and Technology for Converting Microalgae Biomass into Biodiesel

Microalgae are an attractive feedstock source for biodiesel production due to their fast growth rate, high lipid content (Kumar et al. 2022), and ability to grow under diverse conditions. The process of converting microalgal biomass to biodiesel involves several main steps, which include microalgae cultivation, biomass separation and drying, lipid extraction, and transesterification. A more detailed description of each step follows.

Microalgae Cultivation

Microalgae cultivation is an important stage in the process of converting microalgae biomass into biodiesel (Zewdie and Ali 2020). This process involves growing microalgae in open (such as ponds) or closed (such as photobioreactors) systems with optimal light, temperature, and nutrient conditions. During cultivation, microalgae produce biomass rich in lipids, which will be used for biodiesel production. In addition, as photosynthetic microorganisms, microalgae can produce proteins and carbohydrates. Lipids produced by microalgae, especially triacylglycerol (TAG), can be converted into biodiesel through a transesterification process. The cultivation process of microalgae in the biodiesel production process needs to pay attention to the following points:

(1) Microalgae strain selection. Microalgae strains that produce high lipid content and have a fast growth rate are selected to improve biodiesel production efficiency (Zhang et al. 2022). In addition, strains capable of growing in a wide range of environmental conditions were favored.
(2) Cultivation conditions. Cultivation conditions such as temperature, light, pH, and nutrients greatly affect the growth and production of lipids by microalgae. Temperature and light intensity must be optimized so that microalgae can grow well and produce lipids in optimal amounts (Christwardana et al. 2022). Nutrients such as nitrogen, phosphorus, and carbon dioxide must also be provided in sufficient quantities.
(3) Cultivation system. There are two main cultivation systems for microalgae biomass production: open systems (ponds or channels) and closed systems (photobioreactors) (Tan et al. 2020). Open systems are cheaper and easier to operate, but susceptible to contamination. Meanwhile, closed systems provide better control over environmental conditions and produce more consistent biomass, but have higher operational costs.
(4) Maintenance and quality control. During the cultivation process, monitoring and quality control are necessary to ensure optimal microalgae growth and high lipid production (Ebhodaghe et al. 2022). Parameters such as biomass concentration, lipid content, and growth rate need to be measured regularly.

Biomass Separation and Drying

Biomass separation and drying are two important steps in the process of converting microalgal biomass into biodiesel. After microalgae are cultivated, the resulting biomass must be separated from the culture medium and dried before the lipid extraction and transesterification process (Ebhodaghe et al. 2022).

(1) Biomass separation or harvesting. After cultivation, microalgae biomass must be harvested to continue the conversion process into biodiesel. The purpose of biomass separation or harvesting is to collect microalgae cells from the culture medium and separate them from water and other solid particles. Harvesting techniques include centrifugation, flotation, filtration, and coagulation-flocculation, with details as follows:

    (a) Centrifugation, is one of the commonly used technologies for harvesting microalgal biomass (Kucmanová and Gerulová 2019). This technique involves separating solid particles (in this case, microalgae cells) from a liquid medium (cultivation medium) by utilizing the centrifugal force generated by the rotation of the centrifuge, in this case, applying it to a mixture of microalgae cells and cultivation medium. The centrifugal force causes the solid particles (microalgae cells) to move to the outside of the centrifuge tube, while the lighter cultivation medium is on the inside. Thus, the microalgae cells will be separated from the cultivation medium, and the resulting biomass will collect at the bottom of the centrifuge tube. The speed and duration of centrifugation affect the efficiency of separating microalgae cells from the cultivation medium. High speeds and longer durations usually result in more efficient separation. However, the optimal speed and duration are highly dependent on the type of microalgae and cultivation conditions. Centrifugation technology can be applied in laboratory as well as industrial scale. For large-scale microalgae biomass production, a continuous centrifuge with high capacity is used to harvest the biomass more efficiently. Centrifugation offers several advantages in the microalgae harvesting process, such as high efficiency, separation speed, and high biomass concentration. This technique also produces dry biomass that is easier for further processing, such as lipid extraction or conversion to biodiesel (Patel et al. 2018). One of the main disadvantages of centrifugation technology is the high energy consumption, which can increase operational costs. In addition, large-scale use of centrifuges may require significant initial investment in equipment and infrastructure. Despite these drawbacks, centrifugation remains a popular technology for harvesting microalgal biomass due to its high efficiency and ability to produce dry biomass ready for conversion to biodiesel or other products.

(b) Flotation, is an alternative technology used to harvest microalgal biomass. This technique involves separating microalgal cells from the cultivation medium through a flotation process (Kucmanová and Gerulová 2019). Flotation is commonly used to overcome some of the limitations of other harvesting technologies (e.g., centrifugation and filtration) by utilizing the density difference between microalgal cells and the cultivation medium. In the flotation process, gas (usually air) is injected into the cultivation medium, forming bubbles that will attach to the microalgae cells. The microalgae cells attached to the bubbles will float to the surface of the liquid, allowing the separation and collection of biomass. One of the commonly used flotation techniques in microalgae harvesting is dissolved air bubble-based flotation (DAF). In the DAF process, water saturated with air at high pressure is injected into the cultivation medium, which produces fine air bubbles that will attach to microalgae cells and float them to the surface. Flotation offers several advantages over other harvesting methods, such as lower energy costs, the ability to harvest biomass with low cell concentrations, and the potential for large-scale processing. This technique is also effective in overcoming solid particle contamination that may be present in the cultivation medium. Although flotation has some advantages, the technique also has some disadvantages. The separation efficiency in flotation may be lower compared to methods such as centrifugation, especially for microalgae species that do not float easily. In addition, flotation may be less effective for producing dry biomass ready for further conversion processes, such as lipid extraction or conversion to biodiesel. Overall, flotation is an attractive technology for harvesting microalgal biomass, especially when energy costs and the ability to overcome solid particle contamination are important considerations (Branyikova et al. 2018). However, the separation efficiency and quality of the biomass produced should be taken into account before adopting this technique for large-scale applications.

(c) Filtration, is a microalga harvesting technology that involves separating microalgae cells from the cultivation medium through a filtration process. This technique utilizes filtration media or membranes with pore sizes designed to retain the microalgae cells while the liquid medium passes through the filter. Filtration utilizes the size difference between microalgae cells and cultivation medium particles (Kucmanová and Gerulová 2019). In the filtration process, the cultivation medium containing microalgae cells is pumped or flows through a filtration medium or membrane. Microalgae cells are retained by the filter because their size is larger than the pore size of the filter, while allowing the cultivation medium to pass through the filter. Various types of filters are used in the microalgae harvesting process, including, among others, fabric, sand, and microfiltration or ultrafiltration membranes. The selection of a suitable filtration medium largely depends on the microalgae cell size and process requirements. Filtration offers several advantages in microalgae harvesting processes, such as relatively lower energy costs, ease of operation, and the ability to produce biomass with lower water content. In addition, filtration can be applied at various scales, ranging from laboratory to industrial. Some disadvantages of filtration technology include the potential for filter clogging, which can reduce harvesting efficiency and require periodic cleaning or replacement of filters. In addition, filtration may not be suitable for microalgae with very small cell sizes or those that tend to form aggregates (Kucmanová and Gerulová 2019), as this may lead to faster clogging. Overall, filtration is an attractive and effective microalga harvesting technology, especially for situations where energy costs and ease of operation are important considerations. However, harvesting efficiency and filter maintenance should be taken into account before adopting this technique for large-scale applications.

(d) Coagulation-flocculation is a microalga harvesting technology that involves agglomerating microalgae cells into larger flocs (Fig. 17.2), which are then easily separated from the cultivation medium (Delgado-Plaza et al. 2019).

This process involves the addition of coagulants and flocculants, which modify the surface properties of the microalgae cells and result in clumping. The coagulation-flocculation process requires two stages. First, a coagulant (such as aluminum or iron salts) is added to the cultivation medium to agglomerate the dispersed microalgae particles. Then, flocculants (such as organic polymers or polyelectrolytes) are added to increase the size of the formed flocs, which will be more easily separated from the cultivation medium. Coagulation-flocculation efficiency depends on several factors,

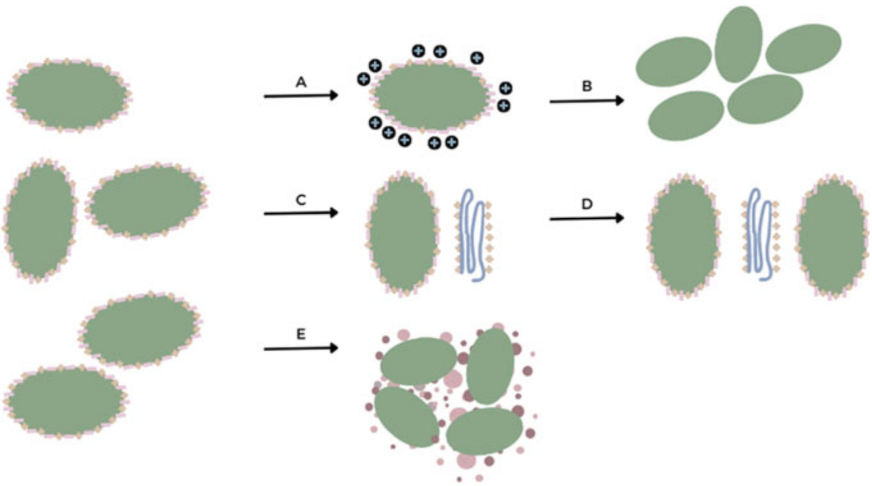

Fig. 17.2 Basic mechanism of flocculation

such as the type and concentration of coagulant and flocculant, pH, and mixing conditions. In many cases, optimization of coagulant and flocculant dosage and process conditions is required to achieve high harvesting efficiency. Coagulation-flocculation offers several advantages in microalgae harvesting processes, such as lower energy costs compared to centrifugation, the ability to treat biomass in low cell concentrations, and the potential for large-scale application (Branyikova et al. 2018). Some disadvantages of coagulation-flocculation technology include chemical consumption that may increase operational costs and have environmental impacts, as well as the possibility of lower biomass quality due to coagulant and flocculant contamination. In addition, separation of the resulting flocs may require additional steps through sedimentation, filtration, or centrifugation. Overall, coagulation-flocculation is an attractive and potentially effective microalgae harvesting technology, especially for situations where energy cost is an important consideration and biomass is in low concentration. However, chemical consumption and the quality of the biomass produced should be taken into account before adopting this technique for large-scale applications.

(2) Biomass drying. After the biomass is successfully separated from the culture medium, the process continues with drying to reduce the moisture content in the biomass. Drying is important to improve lipid extraction efficiency and reduce biomass transportation costs (Razzak et al. 2022). Some commonly used drying methods include:

(a) Convection drying, is one of the commonly used drying techniques to reduce the moisture content in a variety of materials, including harvested microalgal biomass, thereby improving product stability and facilitating use, storage and transportation. Convection drying involves the transfer of heat from a heat source (the dryer) to the microalgal biomass by convection of hot air flowing around the biomass particles. Drying can also be done under direct sunlight (Delgado-Plaza et al. 2019). While this method is simple and inexpensive, the process is slow and dependent on weather conditions. Several steps in the convection drying process using a drying device start with the preparation of the biomass. Once the microalgal biomass is harvested, usually through centrifugation, flotation, or flocculation, it needs to be prepared for the drying process. This involves surface drying or initial mechanical drying, such as the use of filter presses or centrifugation, to reduce the initial moisture content.

The prepared microalgae biomass is then arranged in thin layers or in special racks or containers that allow hot air to flow through them. Arranging the biomass in thin layers helps to improve drying efficiency by ensuring good contact between the hot air and the biomass. A heat source is used to heat the air, which will flow through the microalgae biomass. One can use different heat sources, including an electric heater, gas, or renewable energy, such as solar power. The temperature used in the convection drying process usually ranges from 40 to 80 °C, depending on the nature of the biomass and the needs of the application.

The hot air generated by the heat source is then circulated through the microalgal biomass using a fan or ventilation system (Schmid et al. 2022). This hot air flow creates heat transfer from the air to the biomass through a convection process, causing the water in the biomass to evaporate and be carried away by the air flow. The water vapor is removed from the drying system, usually using a condenser or vapor trapping system. This prevents moisture from getting back into the biomass. It will help to optimize the drying process. Once the moisture content in the microalgae biomass reaches the desired level, the dried product can be stored in sealed containers or packaged for further applications (e.g., biofuel production, animal feed, or nutritional supplements).

(b) Vacuum drying is a drying technique used to reduce the moisture content in various materials, including harvested microalgal biomass (Bheda et al. 2019). The process involves lowering the pressure inside the vacuum drying chamber, thereby reducing the boiling point of water and allowing drying at lower temperatures compared to convection drying. Vacuum drying has several advantages, such as reducing thermal damage to the biomass and improving the quality of the final product.

Once the microalgal biomass has been harvested, usually through centrifugation, flotation, or flocculation, it needs to be prepared for the drying process. This involves surface drying or initial mechanical drying, such as the use of filter presses or centrifugation, to reduce the initial moisture content. The prepared microalgae biomass is then loaded into a vacuum drying chamber. This chamber should be designed to ensure good contact between the biomass and the heating surface, as well as allowing the flow of water vapor generated from the drying process.

The pressure inside the vacuum drying chamber is then lowered, usually using a vacuum pump. This pressure drop reduces the boiling point of water, allowing the water in the biomass to evaporate at a lower temperature. The microalgae biomass in the vacuum chamber is then heated using a heat source, such as an electric heater or steam heater. The temperature used in the vacuum drying process is usually lower compared to convection drying, ranging from 30 to 60 °C, depending on the nature of the biomass and the needs of the application.

The water vapor generated from the drying process is then removed from the vacuum drying chamber via a vacuum pump. This prevents moisture from re-entering the biomass and helps optimize the drying process. Once the moisture content in the microalgae biomass reaches the desired level, the dried product can be stored in sealed containers or packaged for further applications.

The main advantage of the vacuum drying method is that it dries at a lower temperature, which can reduce thermal damage to the biomass and maintain the quality of the final product (Yue et al. 2023). In addition, this process has better energy efficiency and is faster than convection drying, although higher operational costs.

(c) Freeze drying or lyophilization is another drying technique used to reduce the moisture content in various materials, including harvested microalgal biomass (Schmid et al. 2022), which involves freezing the biomass, followed by drying under vacuum to remove the water contained in the biomass through a sublimation process. Freeze-drying has several advantages, such as maintaining the structure and functional properties of the biomass and improving the quality of the final product.

Once the microalgal biomass has been harvested, usually through centrifugation, flotation, or flocculation, it needs to be prepared for the drying process. This involves surface drying or initial mechanical drying, such as the use of filter presses or centrifugation, to reduce the initial moisture content. The prepared microalgal biomass is then frozen, usually by exposing it to very low temperatures (Martins et al. 2022) (− 40 °C to − 80 °C) in a freezer or using rapid cooling such as liquid nitrogen. This freezing turns the water in the biomass into ice.

The frozen microalgae biomass is then placed in a freeze-drying chamber (lyophilizer), which is designed to allow sublimation of ice water from the biomass under vacuum. The pressure inside the freeze-drying chamber is then lowered, typically using a vacuum pump. This pressure drop creates conditions that allow the ice water in the biomass to evaporate directly into water vapor through the sublimation process. During the freeze drying process, gentle heating is applied to the biomass to aid the sublimation process. The heat source can be electric heaters or steam heaters placed around the freeze drying chamber. The temperature used in this process is usually very low (a few degrees above the freezing point of the biomass) to avoid damage to the biomass.

The water vapor generated from the sublimation process is then removed from the freeze-drying chamber via a vacuum pump. This prevents moisture from re-entering the biomass. Once the moisture content in the microalgae biomass reaches the desired level, the dried product can be stored in sealed containers or packaged for further applications.

Lipid Extraction

Lipids are extracted from dried microalgal biomass using organic solvents such as hexane, ethanol, or acetone (Zhou et al. 2022). This process produces microalgal oil rich in triglycerides, which are the main components required for biodiesel production. Lipid extraction from microalgal biomass is a crucial step in the process of converting microalgal biomass into biodiesel. At this stage, the lipids contained in the microalgae cells are extracted and then converted into biodiesel through the transesterification process. Some common methods used to extract lipids from microalgae biomass include:

(1) **Mechanical extraction**, is one of the approaches used to extract lipids from microalgal biomass (Zhou et al. 2022). The aim of mechanical extraction is to break the microalgal cell wall and release the lipids contained within. This process generally involves several techniques, such as high-pressure homogenization, ultrasonic extraction, and extraction using milling equipment such as an expeller press. Although these methods are simple, their efficiency is limited and may not be effective for extracting lipids from hard or difficult-to-break microalgal cells.

   (a) Mechanical extraction by high-pressure homogenization begins with pumping a suspension of microalgal biomass through a narrow slit at high pressure. This process generates high shear forces and pressure, which causes the microalgal cell walls to break and release the lipids. High-pressure homogenization is often used to treat relatively small amounts of microalgal biomass.
   (b) Ultrasonic mechanical extraction, uses high-frequency sound waves to induce cavitation in the liquid containing the microalgal biomass. The cavitation results in imploding bubbles, which in turn create sufficient pressure and shear forces to break the microalgae cell walls and release the lipids. This technique has the advantage of higher energy efficiency compared to high-pressure homogenization, but may not be suitable for larger industrial scales.
   (c) Expeller press is a mechanical extraction method that uses mechanical pressure to squeeze microalgal biomass and release lipids. The microalgal biomass is placed in a cylinder containing a serrated disk or a rotating screw. As the screw rotates, the biomass is forced through the narrow gap between the cylinder wall and the screw, thus generating enough pressure

to break the microalgae cell wall and release the lipids. Expeller presses are typically used on a larger industrial scale and have the advantage of lower cost compared to other mechanical extraction methods.

Mechanical extraction methods have the advantage of reducing the use of chemical solvents, which can reduce environmental impact and operational costs (Bitwell et al. 2023). However, the efficiency of lipid extraction using mechanical methods is often lower than that of solvent extraction methods. Therefore, in some cases, mechanical extraction methods might be combined with solvent extraction methods to improve the overall lipid extraction efficiency.

(2) **Solvent extraction** is a common technique used to extract lipids from microalgal biomass. In this method, organic solvents are used to dissolve and separate lipids from other components of the microalgal biomass. Some commonly used solvents in this extraction process include hexane, ethanol, acetone, and chloroform. Solvent extraction is generally more efficient than mechanical extraction, but the use of toxic chemicals and high energy consumption are considerations on an industrial scale (Kapadia et al. 2022).

Before extraction, the microalgal biomass must be dried to reduce the moisture content. Drying can be done using methods such as convection drying, vacuum drying, or freeze drying. The dried microalgae biomass is then mixed with a suitable organic solvent. The biomass to solvent ratio, temperature, and extraction time may vary depending on the type of microalgae and solvent used.

During the extraction process, the lipids contained in the microalgae biomass will dissolve in the organic solvent. This process is usually carried out in a closed container with constant stirring to ensure good contact between biomass and solvent. After the extraction process is complete, the mixture of biomass and solvent will form two separate phases: a solid phase containing the remaining microalgal biomass and a liquid phase containing the lipids dissolved in the solvent. The liquid phase containing lipids can be separated from the solid phase using methods such as centrifugation, decantation, or filtration. The extracted lipids are then separated from the solvent by evaporating the solvent, usually using a device such as a rotary evaporator or vacuum dryer. Once the solvent has evaporated, the remaining lipids can be collected. In some cases, the evaporated solvent can be condensed and recycled for reuse in the extraction process.

Solvent extraction methods have the advantage of higher lipid extraction efficiency compared to mechanical extraction methods (Saini et al. 2021). However, the use of organic solvents can increase operational costs and have a higher environmental impact. Therefore, research is currently being conducted to develop alternative extraction methods that are more environmentally friendly and economically efficient.

(3) Soxhlet extraction is a classic technique that has been widely used to extract lipids from various types of biomass, including microalgae biomass. This method uses a Soxhlet apparatus containing a condenser, heating walls, and an extraction chamber with a cellulose fiber-based thimble that serves as a holder for the biomass sample.

Prior to extraction, the microalgal biomass must be dried to reduce the moisture content. Drying can be done using methods such as convection drying, vacuum drying, or freeze drying. The dried microalgal biomass is then placed in a thimble, which will later be placed in the Soxhlet extraction chamber. A suitable organic solvent, such as hexane, ethanol, or chloroform, is added to a flat-walled flask placed over a heating source. This flask is connected to the Soxhlet extraction chamber containing the biomass. When the flask is heated, the solvent evaporates and rises to the top of the extraction chamber, where a condenser condenses the solvent vapor.

The condensed solvent will drip back into the extraction chamber, dissolving lipids from the microalgal biomass in the thimble (Yeong Hwang et al. 2021). This process will occur repeatedly, so that the solvent saturated with lipids will flow back into the flat-walled flask. The extraction process takes place automatically and continuously, allowing the solvent to efficiently wash the biomass and extract the maximum amount of lipids. Once the extraction process is complete, the flat-walled flask containing the lipid and solvent mixture will be removed from the Soxhlet device. The extracted lipids can be separated from the solvent by evaporating the solvent, usually using a device such as a rotary evaporator or vacuum dryer. Once the solvent has evaporated, the remaining lipids can be collected.

The Soxhlet extraction method has the advantages of high lipid extraction efficiency and a relatively simple process (Figler et al. 2019). However, this process requires a more prolonged period and uses larger amounts of organic solvents, which can increase operational costs and environmental impact. Therefore, alternative extraction methods that are more environmentally friendly and economically efficient are being developed to extract lipids from microalgal biomass.

(4) Enzymatic extraction, is a method that uses enzymes to break the microalgae cell wall and release the lipids contained within. This process is considered more environmentally friendly and selective compared to solvent or mechanical extraction methods. Prior to extraction, the microalgal biomass must be dried to reduce the moisture content. Drying can be done using methods such as convection drying, vacuum drying, or freeze drying.

The dried microalgal biomass is then mixed with the appropriate enzyme solution. Enzymes commonly used in enzymatic extraction include cellulase, hemicellulase, protease, and lipase (Raveendran et al. 2018). These enzymes work by breaking microalgal cell wall components such as cellulose, hemicellulose, and proteins, which in turn will release lipids trapped inside the cells. The biomass and enzyme mixture is incubated at a specific temperature and conditions (e.g., pH and incubation time) that are optimal for enzyme activity. During the incubation process, the enzymes will break the microalgae cell wall and release the lipids.

After incubation, the extracted lipids must be separated from the biomass and enzyme mixture. This separation can be done by centrifugation, filtration, or decantation methods. In some cases, additional solvent extraction may be required to efficiently separate the lipids from the mixture. The extracted lipids then need to be purified to remove residual enzymes and other contaminants. This purification process may involve steps such as precipitation, filtration, or chromatography.

The enzymatic extraction method has several advantages over other extraction methods (Handayani et al. 2018). First, this process is more environmentally friendly as it reduces the use of organic solvents and energy. Second, enzymatic extraction tends to be more selective, resulting in lipids with higher purity. However, this method can have a higher cost due to the use of enzymes and may require a longer time to achieve optimal extraction efficiency. Therefore, research is underway to develop more efficient and economical enzymatic extraction methods.

(5) Supercritical extraction, is an advanced method that uses supercritical fluid as a solvent to extract lipids from microalgal biomass. Supercritical fluids are substances that are above their critical pressure and temperature, which gives them unique properties between gases and liquids. The most commonly used supercritical fluid in the extraction of lipids from microalgal biomass is supercritical carbon dioxide ($SCCO_2$).

Prior to extraction, the microalgal biomass must be dried to reduce the moisture content. Drying can be done using methods such as convection drying, vacuum drying, or freeze drying. The dried microalgal biomass is fed into a high-pressure extraction reactor. A supercritical fluid, such as carbon dioxide, is then injected into the reactor under appropriate pressure and temperature. The pressure and temperature conditions will determine the solvent properties of the supercritical fluid and the lipid extraction efficiency.

During the extraction process, the supercritical fluid will dissolve the lipids present in the microalgal biomass (Zhou et al. 2022). Due to its unique properties, the supercritical fluid can penetrate the microalgae cell wall and dissolve the lipids with high efficiency. The extraction process usually lasts for several hours to a day, depending on the operating conditions and the type of microalgae biomass. After the extraction process is complete, the supercritical fluid containing lipids is expanded to a lower pressure and temperature. This expansion will result in the fluid changing from supercritical phase to gas phase, which results in the lipids separating from the fluid and precipitating as solids or liquids. The separated lipids can then be collected from the extraction reactor. After lipid separation, the supercritical fluid that has turned into the gas phase can be condensed and recycled back to the extraction system, thus reducing the cost and environmental impact associated with solvent use.

Supercritical extraction methods have several advantages compared to conventional extraction methods, such as high extraction efficiency, better product purity, and the use of more environmentally friendly solvents. However, this method has higher operational costs due to the high-pressure equipment required and greater energy consumption.

Transesterification

Transesterification is a key step in the process of converting microalgal biomass into biodiesel (Akubude et al. 2019). After lipids are extracted from microalgae biomass, the triacylglycerol (TAG) compounds contained in the lipids need to be converted into methyl esters (biodiesel) through a transesterification chemical reaction.

Transesterification is the reaction between triacylglycerol (TAG) and an alcohol (usually methanol or ethanol) with the help of a catalyst (acid, base, or enzyme). This reaction produces methyl esters (biodiesel) and glycerol as a by-product. The general reaction can be formulated as follows:

$$\text{TAG} + 3\ \text{Methanol} \rightarrow 3\ \text{Methyl Esters(Biodiesel)} + \text{Glycerol}$$

Catalysts are needed to increase the reaction speed and produce biodiesel with good quality. Catalysts used in the transesterification reaction include:

(a) Base catalysts. Base catalysts such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) are commonly used in the transesterification process because the reaction proceeds faster than with acid catalysts. However, base catalysts are not effective if the lipids contain high amounts of free fatty acids (FFA), as soap will form and reduce the quality of the biodiesel.
(b) Acid catalysts. Acid catalysts such as sulfuric acid ($H_2\ SO_4$) or hydrochloric acid (HCl) are used if the lipids contain high FFA. Acid catalysts can overcome soap formation, but the transesterification reaction proceeds more slowly than using base catalysts.
(c) Enzymatic catalyst. Lipase is an enzyme that can be used as a catalyst in transesterification reactions. The advantages of using enzymes as catalysts are that they are environmentally friendly and tolerant of high FFA content. However, the cost of enzymes and slower reaction speed are considerations in industrial scale applications.

After the transesterification reaction is complete, the resulting product is a mixture of methyl esters (biodiesel), glycerol, and catalyst (Anisah et al. 2019). The separation of the methyl ester (biodiesel), glycerol, and catalyst mixture involves physical processes that separate the components based on differences in physical properties, such as density and solubility. Sedimentation, decantation, and centrifugation are commonly used separation methods. All three methods have similarities in that they utilize density differences between components and do not require specialized equipment, except centrifugation requires centrifuge equipment. The differences between the three are:

(a) Sedimentation, is a process of separating a mixture based on the difference in density between solid particles and a liquid where the solid particles sink to the bottom of the container as a precipitate or sediment. In the context of the separation of methyl esters, glycerol and catalysts, the speed of sedimentation depends on the difference in density and particle size. A relatively slow process as it relies on the earth's gravitational force. Less efficient for the separation of components with very similar densities or particles with very small sizes.

(b) Decantation, is a method that allows lighter or clear liquids to be separated from heavier sediment or solid particles by pouring the liquid into another container. This method is often used after sedimentation to further separate the mixture. A process that relies on the user's skill to pour the liquid without disturbing the sediment. It may be less efficient if the sediment is easily disturbed or solid particles easily re-dissolve in the liquid.

(c) Centrifugation is a separation method that uses centrifugal force to separate solid particles from a liquid. A device called a centrifuge is used to speed up the separation process. The separation of a mixture of methyl esters, glycerol, and catalyst can be done more quickly and efficiently using the centrifugation method. Centrifugation requires specialized equipment, the centrifuge. The process is faster because it uses centrifugal force to separate the components.

Various factors need to be considered when choosing a separation method (sedimentation, decantation, or centrifugation) to separate a mixture of methyl esters (biodiesel), glycerol, and catalyst (Ampairojanawong et al. 2023). Some factors to consider include:

(a) Component density. The density difference between the components affects the efficiency of the separation method. If the density difference is large enough, methods such as sedimentation and decantation may be quite effective. However, if the density difference is small, centrifugation may be preferable as it can separate components with very similar densities.

(b) Particle size. Particle size also affects the efficiency of the separation method. If the solid particles are large, sedimentation may be quite effective. However, if the particles are very small or in colloidal form, centrifugation is more suitable as it can separate particles of very small size.

(c) Process time. If the speed of the separation process is a priority, centrifugation may be the best choice as it can separate components quickly compared to sedimentation and decantation. Sedimentation and decantation take longer as they depend on the earth's gravitational force.

(d) Cost and equipment. Sedimentation and decantation do not require specialized equipment and tend to be less expensive. However, centrifugation requires a centrifuge, which can be a higher initial investment. Consider budget and equipment availability when choosing the most suitable separation method.

(e) Separation quality. If the main objective is to obtain a highly efficient separation and high product quality, centrifugation may be preferred as it can produce a better separation. Sedimentation and decantation may be less efficient in some cases, especially if the precipitate is easily disturbed or the solid particles easily re-dissolve in the liquid.

Overall, the specific requirements of the separation process and the above factors are important to consider first when selecting the most suitable method for separating a mixture of methyl esters (biodiesel), glycerol, and catalyst (Ampairojanawong et al. 2023).

Purification of Biodiesel

The biodiesel purification process is an important step in the process of converting microalgae biomass into biodiesel. After the transesterification reaction and product separation, the resulting biodiesel may still contain traces of glycerol, catalyst, water, and other impurities. Purification is necessary to improve the quality of biodiesel and meet the standard specifications set by regulatory agencies. Several common methods are used in the biodiesel purification process:

(1) Water washing. This method involves washing the biodiesel with water to remove residual catalyst, glycerol, and other impurities. The biodiesel is mixed with water, and after some time, the water and biodiesel will separate due to the difference in density. Water containing impurities will settle at the bottom, while clean biodiesel will be on top. Water washing may need to be repeated several times to achieve the desired level of purity.
(2) Acid washing. This method involves washing the biodiesel with a dilute acid solution, such as citric acid or phosphoric acid, to neutralize the residual base catalyst and remove impurities. After washing, the acid solution will separate from the biodiesel, and the impurities will be carried away by the acid solution.
(3) Adsorption. This method uses adsorbents, such as silica gel, magnesium silicate, or activated carbon, to bind and remove impurities from biodiesel. The biodiesel is mixed with the adsorbent, and after some time, the adsorbent containing the impurities will separate from the biodiesel through filtration or centrifugation.
(4) Distillation. This method involves heating the biodiesel under vacuum pressure to vaporize and separate lighter components, such as water and volatile impurities. Vacuum distillation allows the separation of components at lower temperatures, reducing the risk of thermal damage to the biodiesel.
(5) Fractional crystallization. This method uses the principle of different melting points of components in the biodiesel mixture to separate and remove impurities. The biodiesel is cooled to a certain melting point (Samsuri et al. 2017), where unwanted components will crystallize and can be separated through filtration or centrifugation.
(6) Once the refining process is complete, the resulting biodiesel must meet set quality standards, such as viscosity, flash point, moisture content, and free fatty acid (FFA) content. Effective biodiesel purification will lead to improved performance, stability, and lower emissions when used as an alternative fuel.

Biodiesel Quality Standard

Quality standards for microalgae-based biodiesel, similar to biodiesel from other sources, are determined by various quality parameters important for performance, efficiency, and emissions. Some key parameters in biodiesel quality standards include viscosity, flash point, moisture content, and free fatty acid (FFA) content. The following describes each of these parameters:

(1) Biodiesel viscosity, refers to the viscosity of a liquid, which affects the flow of fuel through storage systems, pipes, and fuel injectors (Hoang 2021). Biodiesel

with the right viscosity will flow smoothly through the system and provide efficient combustion. Too high viscosity can cause problems in the fuel system and incomplete combustion. International standards such as ASTM D6751 (USA) and EN 14,214 (Europe) set biodiesel viscosity limits between 1.9 and 6.0 mm^2/s at 40 °C.

(2) The flash point of biodiesel, is the temperature at which fuel vapors can ignite when exposed to a fire source. This parameter is important for the safe storage and transportation of biodiesel. A higher flash point indicates a lower risk of fire. ASTM D6751 and EN 14,214 set the minimum flash point of biodiesel at 93 °C (200 °F) to prevent accidental fires.

(3) Moisture content in biodiesel affects fuel performance, oxidation stability, and fuel system corrosion. High moisture content can lead to the growth of microorganisms in the fuel storage system and increase the risk of corrosion of metal components. Therefore, moisture content should be kept at a low level. ASTM D6751 sets the maximum moisture content at 500 ppm, while EN 14,214 sets a stricter limit at 200 ppm.

(4) The free fatty acid (FFA) content of biodiesel indicates the amount of unesterified fatty acids that can potentially cause corrosion in the fuel system. Biodiesel with a high FFA content may require further treatment, such as esterification, to reduce the FFA content. ASTM D6751 sets the maximum FFA limit at 0.05% (500 ppm) by weight, while EN 14,214 sets a stricter limit at 0.02% (200 ppm) by weight.

The technology and process of converting microalgal biomass into biodiesel is still in the research and development stage. Some of the challenges that must be overcome include high production costs, low lipid extraction efficiency (Saini et al., 2021), and large-scale technologies that have yet to be fully developed. However, with further research and innovation, microalgae could become a sustainable and environmentally friendly feedstock source for biodiesel production.

17.2.3 The Potential of Microalgae as a Renewable Energy Source

Microalgae have great potential as a renewable energy feedstock for the following detailed reasons:

(1) Fast growth rate. Microalgae can reproduce quickly; some species can double their biomass within hours to days. This high growth rate enables the production of large amounts of biomass in a short period of time.

(2) High lipid content. Many microalgal species have a high lipid content, which can reach 20–50% of the dry weight of the biomass (Udayan et al. 2022). These lipids can be converted into biodiesel or renewable jet fuel through processes such as transesterification or hydro-processing. Obviously, efficiency can be increased accordingly.

(3) Light and land conversion efficiency. Microalgae have more efficient photosynthetic abilities than terrestrial plants; thus, they can convert solar energy into biomass more efficiently. In addition, microalgae can be grown in open or closed systems, allowing for more efficient land use compared to land crops such as soybean or oil palm.
(4) Use of renewable resources. Microalgae can grow by utilizing renewable resources such as wastewater, CO_2 from industrial emissions, and nutrients that land plants cannot normally utilize. This can reduce pressure on natural resources and help reduce environmental pollution.
(5) Does not compete with food production. Microalgae can be grown on land that is unsuitable for conventional agriculture, such as wastelands, deserts, or rocky areas. As such, microalgae do not compete with food production and can help reduce pressure on existing agricultural land.
(6) Ability to grow in diverse conditions. Microalgae can grow in various environmental conditions, from freshwater to saltwater (Figler et al. 2019) and in a wide temperature range. This makes microalgae more tolerant to climate change and allows them to be grown in various geographical regions.
(7) Use in other energy applications. Besides biodiesel, microalgae also have the potential to be used in the production of bioethanol, biogas, and renewable jet fuel. This diversity can help diversify renewable energy sources and reduce dependence on fossil fuels.

Although microalgae offer great potential as a renewable energy feedstock, there are still several challenges that need to be overcome before this technology can be commercially applied. Some of these challenges include high production costs, large-scale technologies that have yet to be fully developed, and low lipid extraction efficiency.

17.3 Wastewater Management in Biodiesel Production

17.3.1 Sources and Characteristics of Wastewater from Biodiesel Production

Biodiesel production involves several processes that generate wastewater and requires special treatment (Fig. 17.3). The main source of wastewater comes from the biodiesel production process, which includes the following processes:

(1) Oil extraction. The process of extracting oil from feedstocks such as grains, animal fats, and microalgae involves the use of organic solvents such as hexane, ethanol, or acetone. The wastewater generated from these processes generally has a high organic solvent content and may contain feedstock residues.

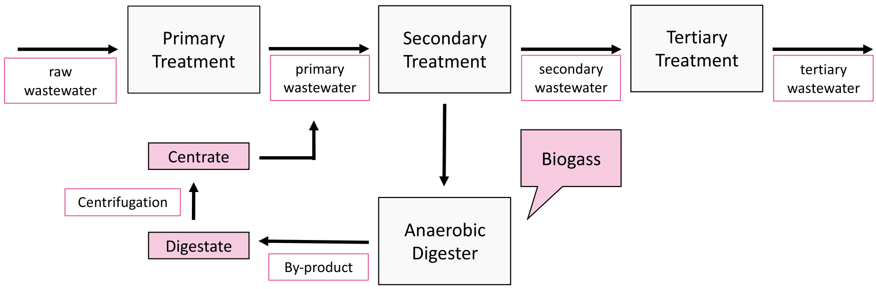

Fig. 17.3 Special treatment of liquid waste

(2) Transesterification. The transesterification process involves the reaction of oil (triglycerides) with alcohol (usually methanol) in the presence of a catalyst (alkali metal or acid). This process produces biodiesel (methyl ester) and glycerol as by-products. The resulting wastewater may contain residual methanol, catalyst, and glycerol, as well as free fatty acids and solids.
(3) Purification of biodiesel. After the transesterification process, biodiesel needs to be separated from glycerol and then purified to remove catalyst, water, and solvent residues. This purification process often involves the use of large amounts of water, so the resulting wastewater may contain residual glycerol, catalyst, and solids (Miyuranga et al. 2022).
(4) Biodiesel washing. Biodiesel washing is an additional step used to remove any remaining contaminants from the final product. This process involves washing the biodiesel with water or water-containing additives. The wastewater produced from this washing is rich in contaminants removed from the biodiesel, such as catalyst residue, glycerol, and solids.

Wastewater from biodiesel production generally has certain characteristics that can indicate the manufacturing process and the materials used. The following are some general characteristics of the wastewater produced (Postaue et al. 2022):

(1) Oil and fat content. Residual oils and fats from raw materials, such as vegetable oils or animal fats, can be found in wastewater. These contents need to be removed before the wastewater can be discharged or treated further.
(2) Glycerol content. Glycerol is a by-product of the transesterification process. This glycerol needs to be separated from the biodiesel and can be found in wastewater.
(3) pH. Wastewater from biodiesel production is usually alkaline due to the use of alkaline catalysts such as sodium hydroxide (NaOH) or potassium hydroxide (KOH). Therefore, the pH of the wastewater will tend to be high and needs to be neutralized before discharge or treatment.
(4) Metal content. Metals such as sodium, potassium, and calcium, which are components of catalysts, can be found in wastewater. The concentration of these metals needs to be reduced to meet discharge or treatment requirements.

(5) Methanol content. During the transesterification process, methanol is used as a reagent. Unreacted methanol that is not separated from the final product can be found in wastewater.
(6) Suspended solids content. The biodiesel production process can generate suspended solids, such as oil or grease particles, which can be found in wastewater.
(7) Organic matter content. Wastewater from biodiesel production may contain unwanted organic substances, such as free fatty acids (FFA) and other organic compounds.

Given these characteristics, wastewater from biodiesel production requires special treatment before it can be discharged or reused. Processes such as coagulation, flocculation, flotation, filtration, and biodegradation can be used to treat wastewater to meet applicable environmental standards (Amenorfenyo et al. 2019); Rinanti et al. 2017).

17.3.2 Conventional Wastewater Treatment Methods and Technologies

Conventional wastewater treatment in the context of biodiesel production involves a range of methods and technologies designed to reduce pollutants and contaminants generated during the production process. Wastewater from biodiesel production can contain chemicals, oils and fats, and suspended solids that need to be removed before being discharged into the environment. The following are some conventional wastewater treatment methods and technologies commonly used in biodiesel production:

(1) Pre-treatment, is the initial stage in wastewater treatment that aims to reduce the content of coarse solids, oil, and grease before the wastewater is treated further in the wastewater treatment system. Pre-treatment helps protect wastewater treatment equipment from damage and clogging that may be caused by coarse particles and non-degradable materials. Some common pre-treatment methods used in microalgae feedstock biodiesel production are:

    (a) Skimming system, used to remove oil, grease, and solids floating on the surface of wastewater. Skimming can be done mechanically using a surface skimmer or by gravity in a skimming tank, where the wastewater is allowed to settle, and the floating oil and grease layer will naturally separate from the wastewater. The separated oil and grease layer can then be removed and further treated.
    (b) Grinding, is a mechanical process used to reduce the particle size of coarse solids in wastewater, thus preventing clogging of wastewater treatment equipment. Grinding can be done using a specially designed grinder to

crush coarse into smaller particles. This process also facilitates more efficient separation and treatment of solids at subsequent stages of wastewater treatment.

(c) Screening, aims to separate coarse solids and particles suspended in wastewater. Screening can be done using various filter types, such as mechanical, sand, or sieve filters. The filter will capture coarse solids and suspended particles, while the filtered water will proceed to the next stage of treatment.

In the context of microalgae-based biodiesel production, wastewater pre-treatment is essential to ensure the efficiency and sustainability of the wastewater treatment process (Krishnamoorthy et al. 2022). Pre-treatment helps reduce the load of coarse solids, oil, and grease on wastewater treatment equipment, and reduces the risk of damage and clogging that may affect the overall performance of the wastewater treatment system.

(2) Primary treatment, in the conventional wastewater treatment commonly used in microalgae-based biodiesel production, aims to remove most of the suspended solids and dissolved organic material. This process involves the physical separation of solids and organic matter from wastewater through sedimentation or coagulation-flocculation. Some of the methods used in primary treatment are:

(a) Sedimentation, is the process of separating suspended solids from wastewater by gravity. In this stage, wastewater is passed through a sedimentation tank (also known as primary clarifier) where the velocity of the water flow is controlled to allow suspended solids to settle to the bottom of the tank. The settled solids, also known as sludge, can then be removed from the bottom of the tank using sludge collection equipment. Water that has passed the sedimentation stage will contain a lower amount of suspended solids and is ready to proceed to the secondary treatment stage.

(b) Coagulation-Flocculation, is a chemical process used to separate suspended and dissolved particles in wastewater that are difficult to remove through sedimentation involves the addition of coagulant chemicals, such as aluminum sulfate or organic polymers, which will react with suspended particles and form larger solid clumps called flocs. Flocculation is the process of combining those flocs into larger aggregates that are easier to settle or filter.

(c) After the coagulation-flocculation process, the wastewater is then passed through a sedimentation tank or filtration unit to separate the flocs from the treated water. As a result, the water that has gone through the primary treatment stage will have lower suspended solids and organic material content and is ready to proceed to the secondary treatment stage.

In the context of microalgae-based biodiesel production, primary treatment of wastewater helps reduce the suspended solids and organic matter load before further treatment. This increases the efficiency of wastewater treatment and helps produce cleaner water that can be reused in the biodiesel production process or discharged into the environment with minimal environmental impact.

(3) In conventional wastewater treatment commonly used in microalgae feedstock biodiesel production, secondary treatment aims to remove most of the remaining organic matter, including suspended and dissolved solids, after the primary treatment stage (Amenorfenyo et al. 2019). This process involves the utilization of microorganisms to decompose organic matter and convert it into gas, water, and microorganism cells. Some of the methods used in secondary treatment are:

(a) Activated Sludge Process. The sludge activation process involves the use of aerobic microorganisms that grow in a mixture of sludge and wastewater. In this process, wastewater that has gone through primary treatment is mixed with activated sludge rich in aerobic microorganisms, and then flowed into an aeration tank. In the aeration tank, air or oxygen is pumped into the mixture to maintain sufficient oxygen levels for microorganisms to decompose the organic matter. After this process, the mixture is flowed into a secondary sedimentation tank, where the activated sludge is separated from the treated water. A portion of the activated sludge will be returned to the aeration tank to maintain the microorganism population, while the rest will be further treated or disposed of.

(b) Suspended Growth Systems. Suspended sludge treatment systems involve the use of microorganisms that grow in the form of aggregates or flocs suspended in wastewater. Examples of suspended sludge treatment systems include intermittent batch treatment reactors (SBRs) and installed total oxidation systems (TFOTs). These processes are similar to sludge activation but use different operating systems and tank configurations.

(c) Attached Sludge Treatment Systems (Attached Growth Systems). Attached sludge treatment systems involve the use of microorganisms growing on solid surfaces, such as filter media, stone, or plastic, in wastewater treatment systems. Examples of attached sludge treatment systems include trickling filters and attached biofilm reactors. In this process, wastewater that has gone through primary treatment is passed through filter media inhabited by aerobic microorganisms. Organic matter in the wastewater is decomposed by the microorganisms, which is then precipitated or filtered from the treated water.

After secondary treatment, the wastewater will have a much lower organic matter content and is ready to proceed to the tertiary treatment stage (if required) to remove certain nutrients or pollutants before discharge or reuse.

(4) Tertiary treatment is an advanced stage that aims to remove certain pollutants or nutrients that are not removed efficiently in the primary and secondary treatment stages (Geremia et al. 2021). Tertiary treatment includes various physical, chemical, and biological methods that help produce water of very high quality and safe for discharge into the environment or reuse. Some of the methods used in tertiary treatment include:

(a) Filtration, is a physical process used to remove fine suspended particles remaining in wastewater after the secondary treatment stage. Filtration can be done using various types of filter media, such as sand, ceramic, or activated carbon. Filtration can also help remove pathogens, heavy metals, and certain organic chemicals from wastewater.
(b) Adsorption, is the process of binding specific pollutant or nutrient molecules to the surface of a solid material, such as activated carbon or zeolite. Adsorption is used to remove pollutants such as heavy metals, dissolved organic compounds, and nutrients such as phosphate and ammonia from wastewater.
(c) Denitrification, is a biological process used to remove nitrogen from wastewater in the form of nitrate. The process involves the use of denitrifying microorganisms that decompose nitrate into nitrogen gas, which is then released into the atmosphere. Denitrification is usually carried out in anaerobic or anoxic treatment systems.
(d) Phosphorus removal is usually achieved through a chemical process that involves the addition of coagulants such as aluminum sulfate, ferric chloride, or organic polymers. These coagulants react with phosphates in wastewater to form solid compounds that can be precipitated or filtered.

In the context of microalgae-based biodiesel production (Fig. 17.4), tertiary treatment of wastewater helps produce water that is very clean and safe for reuse in the biodiesel production process or be discharged into the environment with minimal environmental impact. Tertiary treatment also ensures that the wastewater meets water quality standards set by environmental regulations and local or national water management authorities.

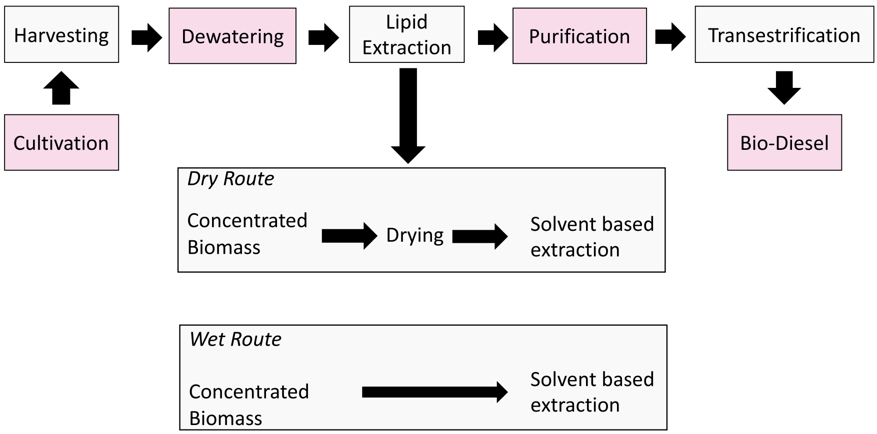

Fig. 17.4 Conversion of microalgae to biodiesel

(5) Disinfection, is the final stage in wastewater treatment that aims to remove or reduce pathogens such as bacteria, viruses, and protozoa. The disinfection process includes the use of chemicals such as chlorine, ozone, or hydrogen peroxide, or physical methods such as ultraviolet light or heating (Ghernaout and Elboughdiri 2020)

(a) Chlorination is the process of using chlorine or chlorine compounds, such as sodium hypochlorite or chlorine gas, to kill or inhibit the growth of pathogens, such as bacteria, viruses, and protozoa. Chlorine is very effective in destroying the cell walls of microorganisms and stopping the enzyme activity of microorganisms. However, there are some disadvantages in using chlorine in wastewater treatment, namely:

- After chlorination, residual chlorine still present in the treated water can become an environmental problem. Residual chlorine can be toxic to aquatic life and affect aquatic ecosystems.
- Chlorine can react with organic matter present in wastewater to form toxic trihalomethane (THM) compounds and potentially harmful halogen organic compounds. These THMs and halogen organic compounds can have negative effects on water quality and the environment as well as human health.
- The use of chlorine in wastewater treatment incorporates chemicals in the system, which may be undesirable in some applications or environments.

  To overcome some shortcomings in the use of chlorine, several disinfection alternatives, such as ozonation, ultraviolet disinfection, and heating, can be used. However, chlorination remains a common and economical disinfection method in wastewater treatment, including in microalgae feedstock biodiesel production. In these applications, it is important to monitor and control residual chlorine levels in the treated water and take measures to reduce the formation of harmful compounds such as THMs.

(b) Ozonization, is a disinfection process that uses ozone (O3), a highly reactive form of oxygen, to kill pathogens such as bacteria, viruses, and protozoa. Ozone is very effective in destroying the cell walls of microorganisms and stopping the enzyme activity of pathogenic microorganisms (Xue et al. 2023). Some of the advantages of using ozone in wastewater treatment are:

- It leaves no chemical residue in the treated water and naturally breaks down into oxygen (O_2). This means that no additional contaminants are generated during the disinfection process, which is a major advantage compared to chlorine-based disinfection methods.
- Ozone is highly effective in destroying various types of pathogens, including bacteria, viruses, protozoa, and spores. In addition, ozone

is also effective in oxidizing water-soluble organic compounds, such as pesticides and phenols, and removing unwanted odors and tastes.
- The disinfection process takes place relatively quickly. The contact time required to achieve an effective level of disinfection is usually shorter than other disinfection methods such as chlorination or ultraviolet disinfection.

However, there are some disadvantages in the use of ozone in wastewater treatment, namely:

- Ozonization requires specialized equipment and higher operating costs compared to chlorine-based disinfection methods. This includes the cost of generating ozone and maintaining the necessary equipment.
- While ozone leaves no chemical residue in treated water, it still involves the use of chemicals in the disinfection process, which may be undesirable in some applications or environments.

Although ozonation has some drawbacks, its use in wastewater treatment, including in microalgae feedstock biodiesel production, can provide high disinfection rates with lower environmental impact compared to chlorine-based disinfection methods.

(c) Hydrogen peroxide (H_2O_2) is a chemical that can be used in conventional wastewater treatment commonly used in microalgae feedstock biodiesel production. Hydrogen peroxide has strong oxidative properties and can be used as a disinfecting agent to remove or reduce the number of pathogens in wastewater that has passed through primary, secondary, and tertiary treatment stages. The use of hydrogen peroxide helps produce water that is safe to be reused in the biodiesel production process or discharged into the environment with minimal environmental impact. Some advantages of using hydrogen peroxide in wastewater treatment:

- Once reacted, hydrogen peroxide leaves no harmful chemical residue as it breaks down into water and oxygen, both of which are environmentally safe and do not contaminate the treated water.
- Hydrogen peroxide shows high effectiveness in destroying various types of pathogens, including bacteria, viruses, and protozoa. In addition, hydrogen peroxide is also effective in oxidizing water-soluble organic compounds, such as pesticides and phenols, and removing unwanted odors and tastes.
- Hydrogen peroxide is highly biodegradable, so it breaks down into water and oxygen and poses no long-term environmental risks.

However, there are some disadvantages to the use of hydrogen peroxide in wastewater treatment, namely:

- Hydrogen peroxide is a strong oxidizer and can cause corrosion of wastewater treatment equipment. Therefore, it is necessary to use corrosion-resistant equipment and compatible materials to reduce the risk of damage to the wastewater treatment system.

- Hydrogen peroxide tends to be unstable and decompose easily, especially when exposed to sunlight or high humidity. Therefore, proper storage and protection from sunlight and moisture are necessary to maintain the stability of hydrogen peroxide during the wastewater treatment process.
- Although the cost of hydrogen peroxide itself may be lower compared to ozone, for example, operating costs associated with equipment maintenance can be higher, so it is necessary to consider the cost of storage, and the use of hydrogen peroxide in large-scale applications.

Although the use of hydrogen peroxide in wastewater treatment has some disadvantages, it is an effective and environmentally friendly alternative for wastewater disinfection, including in microalgae feedstock biodiesel production (Rafa et al. 2021). In these applications, it is important to consider factors such as operating costs, hydrogen peroxide stability, and protection of equipment against corrosion.

(d) The use of ultraviolet (UV) light is an effective physical method for conventional wastewater disinfection in microalgae-based biodiesel production. UV light can inactivate pathogens, including bacteria, viruses, and protozoa, without leaving chemical residues or producing harmful byproducts. The process involves lighting wastewater that has passed through primary, secondary, and tertiary treatment stages with UV light, which damages the DNA and RNA of microorganisms and stops their reproduction. Some of the advantages of using UV light in wastewater treatment are:

- The UV light method does not involve chemicals and leaves no chemical residue in the treated water. This means that no additional contaminants are generated during the disinfection process, which is a major advantage compared to chlorine-based or ozonation disinfection methods.
- UV light is highly effective in inactivating various types of pathogens, including chlorine-resistant bacteria. In addition, UV light can also reduce the amount of water-soluble organic compounds, such as pesticides and phenols, and remove unwanted odors and tastes.
- Disinfection with UV light is a relatively fast process. The contact time required to achieve effective disinfection levels is usually shorter than other disinfection methods such as chlorination or ozonation.

However, there are some disadvantages in using UV light in wastewater treatment, namely:

- The effectiveness of UV light is highly dependent on the transparency of the wastewater. If the water has a high suspended solids content, the UV light may not be able to penetrate deeply enough to effectively inactivate pathogens.

- While the cost of UV light equipment may be lower than chemical-based disinfection methods, the maintenance and energy costs of running a UV light system are important considerations, especially in large-scale applications.
- UV lamps have a limited lifespan and require periodic replacement. This can increase the operation and maintenance costs of UV light disinfection systems.

Although the use of UV light in wastewater treatment has some disadvantages, it is an effective and environmentally friendly alternative for wastewater disinfection, including in microalgae feedstock biodiesel production. In these applications, it is important to consider factors such as water transparency, operating costs, and maintenance of the UV light system. In the context of biodiesel production, wastewater treatment processes need to be optimized to ensure compliance with environmental regulations and to reduce the negative impact of wastewater discharge on ecosystems and water sources.

17.3.3 Advantages and Challenges of Using Microalgae in Wastewater Treatment

Microalgae are producers or photosynthetic microorganisms that can be used to treat wastewater while producing lipid-rich biomass, which can then be converted into biodiesel (Udayan et al. 2022). Several advantages of using microalgae in wastewater treatment are associated with biodiesel production technology:

(1) Wastewater treatment and biodiesel production in one process. Wastewater treatment and biodiesel production in a single process using microalgae offers several advantages that make it an attractive and sustainable solution. Here are some of the advantages of using microalgae in wastewater treatment:

  (a) Wastewater treatment and biomass production. Microalgae can clean wastewater by removing excess nutrients (such as nitrogen and phosphorus) and organic contaminants through their metabolic processes. During this process, microalgae grow and produce lipid-rich biomass, which can be used as a feedstock to produce biodiesel.
  (b) Reduction of greenhouse gas emissions. Microalgae absorb CO_2 from the environment during photosynthesis, thereby reducing greenhouse gas emissions. In addition, biodiesel produced from microalgae produces lower emissions compared to fossil fuels, thus contributing to climate change mitigation.
  (c) Nutrient recycling. In an integrated system, nutrients present in wastewater can be used as a nutrient source for microalgae, thereby reducing the need for additional nutrient inputs and aiding in sustainable nutrient management.

(d) More efficient land use. Microalgae can grow on land that is unproductive or unsuitable for conventional agriculture, such as swampy or contaminated areas. This enables more efficient land use and reduces competition between land for food and renewable energy production.
(e) Product diversification potential. In addition to biodiesel, microalgae can also produce a variety of high-value products, such as proteins, pigments, and omega-3 fatty acids. This opens opportunities for product diversification and additional revenue, which can improve the competitiveness and sustainability of the microalgae-based biodiesel industry.
(f) Lower water consumption. Microalgae can grow in wastewater, brackish water, or saltwater, thus reducing pressure on increasingly scarce freshwater sources.
(g) Increased sustainability. By integrating wastewater treatment and biodiesel production using microalgae, the industry can create a more sustainable system, reducing environmental impact and making efficient use of existing resources.

(2) Energy efficiency. Utilization of microalgae can improve energy efficiency in wastewater treatment because (Plöhn et al. 2021; Permatasari and Rinanti 2018):

(a) Microalgae can use solar energy for growth and biomass production through photosynthesis. This process has the potential to produce more energy per unit area than conventional bioenergy crops, such as oil palm or soybean.
(b) Efficient photosynthesis. Microalgae have efficient photosynthetic capabilities, which allow them to absorb solar energy and convert it into chemical energy in the form of biomass. During this process, microalgae absorb nutrients and contaminants from wastewater, resulting in cleaner water and biomass that can be used to produce renewable energy such as biodiesel.
(c) Biodiesel produced from microalgae is a renewable energy source that is more environmentally friendly than fossil fuels. By replacing fossil fuels with biodiesel, greenhouse gas emissions and fossil energy consumption can be reduced, thereby improving overall energy efficiency.
(d) An integrated system that combines wastewater treatment and biodiesel production using microalgae can create a more efficient energy cycle. For example, methane gas generated during the anaerobic process of wastewater treatment can be collected and used as an energy source for biodiesel production or other energy needs.
(e) Microalgae can grow in a variety of environmental conditions, including wastewater, brackish water, or saltwater. By using less water resources and utilizing the nutrients present in wastewater, microalgae can reduce the energy consumption required for growth and maintenance.
(f) The use of microalgae in wastewater treatment can reduce energy requirements in conventional treatment processes, such as aeration or intensive chemical processes. This can reduce operating costs and energy required to treat wastewater.

(3) Carbon dioxide sequestration. Carbon dioxide (CO_2) sequestration by microalgae is one of the main advantages of using microalgae in wastewater treatment (Molazadeh et al. 2019), especially in the context of climate change mitigation and reduction of greenhouse gas emissions. Here are some important points related to CO_2 absorption by microalgae in wastewater treatment:

   (a) Photosynthesis and CO_2 sequestration. Microalgae, like plants, utilize photosynthesis to produce energy and biomass. During the photosynthesis process, microalgae absorb CO_2 from the environment and convert it into chemical energy and biomass. This helps reduce the concentration of CO_2 in the atmosphere and contributes to the reduction of greenhouse gas emissions.
   (b) Climate change mitigation. Reduction of CO_2 emissions through sequestration by microalgae can help in climate change mitigation. Biodiesel produced from microalgae, as a substitute for fossil fuels, also produces lower emissions, thus contributing to efforts to reduce the impact of climate change.
   (c) Increased productivity. The absorption of CO_2 by microalgae can increase the productivity and growth of microalgae, which in turn increases the efficiency of wastewater treatment and biomass production. The biomass produced can be used to produce biodiesel and other high-value products.
   (d) Utilization of industrial emissions. Microalgae can be grown in integrated systems that use CO_2 emissions from industries, such as power plants or cement factories, to enhance microalgae growth and CO_2 sequestration efficiency. This can reduce the environmental impact of industrial emissions and create a more sustainable system.
   (e) Technology development potential. 2Research and development of microalgae technology for CO_2 sequestration could lead to a more efficient and economical system to reduce greenhouse gas emissions and create a more sustainable energy system.

The utilization of microalgae in wastewater treatment related to biodiesel production technology faces serious challenges related to cost, scalability, and microalgae species selection (Zewdie and Ali 2020).

(1) Cost. One of the main challenges in using microalgae for wastewater treatment and biodiesel production is the high cost of cultivation, harvesting, and lipid extraction. This can include costs for construction and maintenance of photobioreactor systems or open culture ponds, as well as lipid separation and conversion technologies.
(2) Scalability. Developing efficient and economical processes for large-scale cultivation of microalgae remains a challenge. Factors such as optimal environmental conditions, resistance to contamination, and high productivity need to be addressed to achieve commercial scale production.

(3) Microalgae species selection. Selecting the right species from thousands of microalgae species for wastewater treatment and biodiesel production is challenging. The ideal species should be resistant to wastewater conditions, have a fast growth rate, and produce high lipid content for efficient biodiesel conversion.

These constraints must be overcome to utilize the full potential of microalgae in wastewater treatment and biodiesel production technologies. Continued research and development will help optimize processes and reduce associated costs, thus making the use of microalgae in these technologies more economically and environmentally viable.

17.4 Integration of Microalgae in a Circular Economy System

17.4.1 Absorption of Nutrients by Microalgae from Wastewater

Microalgae are photosynthetic organisms that can absorb nutrients from wastewater, such as nitrogen and phosphorus, as well as carbon dioxide from the atmosphere or other emission sources (Al-Jabri et al. 2021). The integration of microalgae in circular economy systems can help reduce the environmental impact of wastewater and energy production and create value-added products. Here are some aspects of nutrient uptake by microalgae from wastewater related to the integration of microalgae in circular economic systems:

(1) Microalgae can be used in wastewater treatment systems to remove nutrients such as nitrogen (N) and phosphorus (P) that can cause eutrophication if released into the environment. The process involves the uptake of nutrients by microalgae, which are then used for growth and biomass production. In the context of a circular economy, this reduces the need for synthetic chemicals or more intensive wastewater treatment processes.
(2) The biomass generated from nutrient uptake by microalgae can be used for various purposes, such as the production of biodiesel, animal feed, fertilizer, or high-value chemicals. In a circular economy system, this biomass can be used to replace fossil raw materials or non-renewable natural resources.
(3) During photosynthesis, microalgae absorb carbon dioxide (CO_2) from the atmosphere or other emission sources, such as industrial exhaust gases. This CO_2 sequestration can help reduce greenhouse gas emissions and contribute to climate change mitigation. In a circular economy system, it creates added value by reducing the environmental impact of CO_2 emissions.

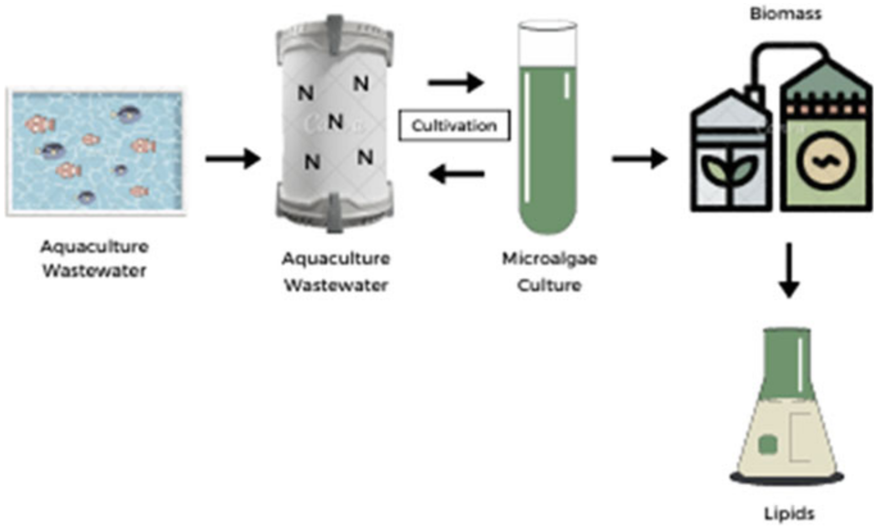

Fig. 17.5 Wastewater treatment process with microalgae

(4) After wastewater treatment and biomass production, the nutrients contained in the microalgal biomass can be recovered and used as fertilizer or other value-added products (Geremia et al. 2021). In a circular economy system, this increases the efficiency of resource use and reduces the need for synthetic fertilizers or minerals extracted from the environment.
(5) The use of microalgae in wastewater treatment and biomass production, as well as nutrient recovery, can help create a circular economy system through more efficient, sustainable, and environmentally friendly production and consumption processes. The process is illustrated in (Fig. 17.5).

17.4.2 Microalgal Biomass Growth and Lipid Extraction for Biodiesel Production

Microalgae offer potential as an alternative source for biodiesel production through biomass growth and lipid extraction. In the context of a circular economic system, the integration of microalgae in biodiesel production can improve resource use efficiency and reduce the environmental impact of energy production.

(1) Microalgae biomass growth. Microalgae grow quickly and can produce large amounts of biomass in a short period of time. They require nutrients, such as nitrogen and phosphorus, and CO_2 for growth. In a circular economy system, microalgae can be grown on wastewater or CO_2 emission sources (e.g., industrial exhaust gas), helping to reduce pollutants and reduce greenhouse gas emissions.

(2) Lipid production. Some species of microalgae produce large amounts of lipids that can be converted into biodiesel through the transesterification process. These lipids are usually stored in the cells in the form of triacylglycerol (TAG). In a circular economy, lipid production by microalgae can replace conventional feedstock sources for biodiesel, such as palm oil or soybean, which are often associated with land use change and greenhouse gas emissions.
(3) Lipid extraction. After the growth of microalgal biomass, lipids must be extracted from the cells for the biodiesel production process. Commonly used lipid extraction methods include solvent extraction, mechanical extraction, or micro-wave or ultrasonic-based technologies. In a circular economy system, the selection of efficient and environmentally friendly extraction methods will be important to reduce the energy consumption and environmental impact of the biodiesel production process.
(4) Conversion of Lipids into Biodiesel. The extracted lipids are then converted into biodiesel through a transesterification process, which involves a chemical reaction between lipids and alcohol (usually methanol) in the presence of a catalyst. The resulting biodiesel can be used as an alternative fuel that is more environmentally friendly than fossil fuels.

During the biodiesel production process, by-products such as glycerol and cellular biomass remaining after lipid extraction can be further processed to produce value-added products, such as fertilizer, animal feed, or industrial chemicals. In a circular economy system, such by-products or Value-Added Products can improve resource use efficiency and reduce waste disposal (Saadaoui et al. 2021; Rinanti and Purwadi 2018).

17.4.3 Utilization of Remaining Microalgae Biomass for Value-Added Products (Animal Feed, Fertilizer, Biogas)

Utilization of remaining microalgae biomass for value-added products such as animal feed, fertilizer, and biogas is an important concept in the integration of microalgae in the circular economy system. Microalgae are microscopic organisms that can grow rapidly and thus can be raw material to produce biofuels, nutrients and food (Fig. 17.6), animal feed, and chemicals.

However, after the extraction of the main products such as oil or protein, there is still a large amount of microalgal biomass remaining. Utilizing this leftover biomass for value-added products can help integrate microalgae in the circular economy system, as follows:

(1) Animal Feed. The remaining microalgal biomass contains protein, fatty acids and other nutrients that are beneficial for animal feed. The protein contained in microalgal biomass can be a sustainable alternative source for animal feed,

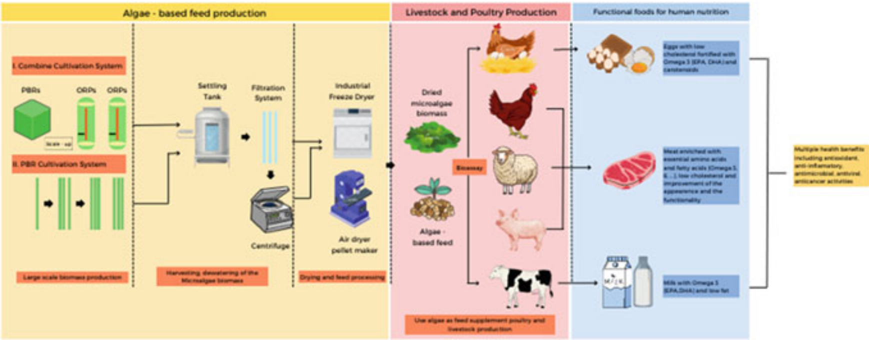

Fig. 17.6 Various use of microalgae

replacing conventional protein sources such as soybean and fish. In addition, the use of microalgal biomass in animal feed can improve the quality and health of livestock and reduce greenhouse gas emissions from the livestock industry (Saadaoui et al. 2021).

(2) Fertilizer. The remaining microalgae biomass can also be used as an organic fertilizer that is rich in nutrients. Microalgae contains nitrogen, phosphorus, and potassium, which are key nutrients required by plants. Using microalgae biomass as fertilizer can improve soil fertility, support healthy plant growth, and reduce dependence on chemical fertilizers that are not environmentally friendly.

(3) Biogas. The remaining microalgal biomass can be utilized to produce biogas through anaerobic processes, such as anaerobic digestion or gasification. The resulting biogas, which mainly consists of methane and carbon dioxide, can be used as a renewable energy source to generate electricity and heat. Biogas production from microalgal biomass can help reduce greenhouse gas emissions and replace fossil fuels in the energy system.

Integration of microalgae in circular economy systems through utilization of residual biomass for value-added products helps to create a more efficient and sustainable production cycle (Sarma et al. 2021) as in (Fig. 17.7). By reducing waste, maximizing resource utilization, and producing value-added products, microalgae can make important contributions to environmental sustainability and the global economy.

17.4.4 *Treatment and Recycling of Water After Treatment with Microalgae*

Water treatment and recycling after wastewater has been treated by microalgae is important and needs to be implemented in the context of microalgae integration in circular economy systems for the following reasons:

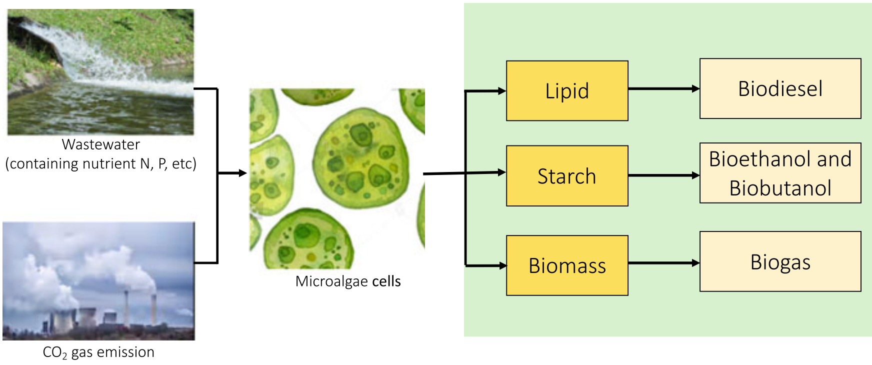

Fig. 17.7 Biogas production using microalgae

(1) Conserving water resources. Water is a limited natural resource that is essential for life. Utilizing microalgae to treat wastewater and then recycling the treated water can save water resources and reduce the consumption of clean water. This will improve water use efficiency and reduce pressure on limited water resources.
(2) Reducing environmental pollution. Microalgae can be utilized to treat wastewater by removing excess nutrients such as nitrogen and phosphorus, as well as heavy metals and other contaminants. This process helps reduce environmental pollution due to the release of untreated or inadequately treated wastewater into the environment. Recycled water after treatment with microalgae will reduce negative impacts on aquatic ecosystems and water quality.
(3) Supporting microalgae growth. Wastewater that has been treated by utilizing microalgae is rich in nutrients and thus becomes recycled water that can be used to support further microalgae growth. As such, the recycled water can help to maintain the availability of nutrients necessary for the sustainable growth of microalgae, while reducing the need for external nutrient inputs.
(4) Minimizing water treatment costs. Water that has been treated with microalgae or recycled water can reduce wastewater disposal costs and the costs associated with using new water sources.
(5) Creating a sustainable cycle. The integration of microalgae in circular economic systems involves closing the loop in the production and consumption process. Water treatment and recycling after wastewater treatment with microalgae is an important part of creating a sustainable process and reducing negative impacts on the environment.

Recycling treated wastewater has great potential in reducing clean water consumption, reducing the environmental impact of wastewater discharge, and utilizing previously unused resources. Some potential utilizations of treated wastewater recycling (Bauer and Wagner 2022) are:

(1) Agricultural irrigation. Treated wastewater can be used for crop irrigation, especially for non-food crops or crops that are not directly consumed by humans. This use of recycled water can reduce pressure on clean water sources and help address the water shortages that many regions are facing.
(2) Landscape and garden irrigation. Treated wastewater can also be used for watering gardens, public parks, and other green spaces. This can save clean water that would otherwise be used for these purposes.
(3) Industry. Treated wastewater can be used in industrial processes that do not require high water quality, such as in cooling systems, equipment cleaning, or certain manufacturing processes.
(4) Groundwater recharge. Treated wastewater can be used to recharge groundwater through infiltration or direct injection into aquifers. This can help maintain groundwater balance and reduce the risk of land subsidence or aquifer depletion.
(5) Use in construction. Treated wastewater can be used as a concrete admixture or to control dust at construction sites and reduce the need for clean water (Mojapelo et al. 2021).
(6) Toilet flushing: Treated wastewater can be used to flush toilets, saving drinking water and reducing the use of clean water.
(7) In some cases, recycled water can also be used as drinking water, especially when the quality of the treated water meets safety standards and has undergone a rigorous advanced treatment and disinfection process.

The recycling potential of treated wastewater is highly dependent on the quality of the treated water and the local policies and regulations in place. To maximize the utilization of treated wastewater, there needs to be a collaboration between government, industry, and communities in developing wastewater treatment technologies, regulating the use of recycled water, and raising public awareness about the importance of sustainable use of water resources. Microalgae-based treatment and recycling of treated water is an implementation of the circular economy system to achieve more efficient and sustainable water management, reduce environmental pollution, and optimize the utilization of natural resources.

17.5 Design and Operation of Microalgae-Based Systems

The design and operation of microalgae-based systems need to be considered in wastewater treatment, especially concerning the circular economy system of biodiesel production, for the following reasons (Srimongkol et al. 2022):

(1) Resource efficiency. Proper design and operation of microalgae-based systems ensure the efficient use of resources, such as water, nutrients, and energy. In a circular economy system, the goal is to reduce resource consumption and wastage through recycling and reuse of materials.

(2) Operation and investment costs. Good design and operation of microalgae-based systems reduce operating and investment costs in wastewater treatment and biodiesel production. In a circular economy system, minimizing costs throughout the product's life cycle is crucial to remain competitive in the market.
(3) Product quality. Effective design and operation of microalgae-based systems yield high-quality products, such as lipid-rich microalgae biomass for biodiesel production. The circular economy system emphasizes the importance of creating high-quality, durable products and services that can enhance value and competitiveness in the market.
(4) Environmental impact reduction. The eco-friendly design and operation of microalgae-based systems reduce the environmental impacts of wastewater treatment and biodiesel production, such as greenhouse gas emissions and eutrophication. Circular economy systems aim to reduce environmental impacts and promote sustainability.
(5) Process synergy. Integrated design and operation of microalgae-based systems enable synergy between wastewater treatment and biodiesel production processes, such as nutrient and energy recovery from wastewater to support microalgae growth. Circular economy systems encourage collaboration and integration between various processes and sectors to create added value and reduce resource wastage.

Further discussions on the design and operation of the microalgae-based systems in wastewater treatment related to the circular economy concept in biodiesel production will be as follows.

17.5.1 Closed (Photobioreactor) and Open (Pond) Systems for Microalgae Cultivation

Microalgae cultivation systems can be classified into two main categories: open systems (ponds) and closed systems (photobioreactors). Both systems have their advantages and disadvantages, which will influence the decision regarding the most suitable system for a specific application (Wimmerova et al. 2023). Open Systems (i.e., ponds) for microalgae cultivation involve the use of ponds that are open to the atmosphere. These ponds can be natural or artificial and generally have a shallower depth. Commonly used open systems in microalgae cultivation include:

(1) Raceway Pool. This oval-shaped pond has a rotating water flow that follows the pond's shape. The raceway pond is equipped with stirrers to ensure circulation and even nutrient distribution while keeping the microalgae exposed to sunlight.
(2) Multipurpose Ponds. These ponds are often used for dual purposes, such as microalgae cultivation and wastewater treatment. They are usually larger and deeper than raceway ponds.

The advantages of an open system include:

(1) Lower initial costs for construction and equipment.
(2) Easier scalability.
(3) Relatively simple maintenance.

The disadvantages of an open system include:

(1) Contamination from foreign organisms (e.g., bacteria, fungi, protozoa, or other algae) may disrupt microalgae growth.
(2) Variability in environmental conditions (e.g., temperature, humidity, wind speed) can affect microalgae growth and quality.
(3) Higher water usage and potential water loss through evaporation.
(4) Lower light capture efficiency.

Closed systems for microalgae cultivation utilize photobioreactors (PBRs), which are controlled and isolated systems from the surrounding environment. PBRs are typically made of transparent materials such as glass or plastic and are designed to optimize microalgae growth conditions. Some common types of photobioreactors used in microalgae cultivation include:

(1) Tube Photobioreactor (Tubular PBR). This type of photobioreactor consists of a series of interconnected transparent tubes where microalgae are cultured. The tubes can be arranged horizontally, vertically, or spirally. Although this system provides excellent lighting and efficient environmental control, it comes with higher investment and maintenance costs than open systems.
(2) Flat Plate Photobioreactor (Flate Plate PBR). Flat plate photobioreactors have transparent plates on which microalgae are cultured. These plates can be placed horizontally or vertically and are generally easier to assemble and maintain than tubular PBR. However, they may be less efficient in terms of light capture and cooling compared to tubular PBR.
(3) Column Photobioreactor (Column PBR). This photobioreactor involves a transparent column filled with microalgae cultures. The column can be a bubble column, where air or gas is passed through the microalgae culture to create circulation and even lighting, or an airlift column, which uses the density difference between the bubble-rich and the bubble-poor zones to create circulation. Column photobioreactors have a simple design and relatively lower investment costs than tube or flat plate photobioreactors, but the light capture efficiency may be lower.
(4) Panel Photobioreactor (Panel PBR). These photobioreactors consist of transparent open or enclosed panels where microalgae are cultured. They can be placed vertically, horizontally, or at an angle and are generally easier to assemble and maintain than tube photobioreactors. The light capture efficiency in panel PBRs is better than flat plate PBRs but may be less efficient than tubular PBRs.

The advantages of a closed system (photobioreactor) for microalgae cultivation (Al-Dailami et al. 2022):

(1) Better environmental control. Photobioreactors allow better control over environmental conditions, such as temperature, pH, nutrient concentration, and light intensity. This enables the setting of optimal conditions for the specific growth of microalgae, ultimately enhancing productivity and product quality.
(2) Lower risk of contamination. The risk of contamination from foreign organisms (e.g., bacteria, fungi, protozoa, or other algae) in closed systems is much lower compared to open systems. This is very important, especially when cultured microalgae are used for applications with high hygiene standards, such as food products, cosmetics, or pharmaceuticals.
(3) Higher light capture efficiency. Photobioreactors are designed to maximize light capture by microalgae. This usually results in higher light capture efficiency than open systems, ultimately improving microalgae productivity.
(4) More Efficient Water Use. Closed systems usually utilize water more efficiently than open systems. This is because closed systems reduce water loss through evaporation and maintain more stable water conditions, thus reducing the need for frequent water replacement.

Disadvantages of the closed system (photobioreactor) for microalgae cultivation are (Al-Dailami et al. 2022):

(1) Higher investment and operational costs. Photobioreactors usually have higher initial investment costs than open systems due to the more advanced equipment and technology. In addition, the operational and maintenance costs for closed systems also tend to be higher, mainly because of greater energy consumption to control environmental conditions and keep the system running efficiently.
(2) Difficulties in Scalability. Closed systems, such as photobioreactors, may be more challenging to scale than open systems. This is because increasing the size and complexity of closed systems often results in higher costs and greater technical challenges.
(3) More complicated maintenance. Photobioreactors generally require more complex maintenance than open systems related to equipment cleaning, sanitization, monitoring, and setup.

17.5.2 Operational Parameters and Factors Affecting the Efficiency of Wastewater Treatment

In the context of a circular economy for biodiesel production using microalgae, wastewater treatment plays a crucial role in supporting microalgae growth and reducing environmental impacts. Several operational parameters and factors influence the efficiency of wastewater treatment, which must be carefully considered to achieve optimal results.

(1) Nutrient concentration. Wastewater contains rich nutrients such as nitrogen and phosphorus, which are essential for microalgae growth. Maintaining proper

nutrient concentration in wastewater affects the growth rate of microalgae, leading to improved nutrient absorption efficiency and contaminant reduction.

(2) Temperature. Temperature is an important factor affecting the growth rate and metabolism of microalgae. Each microalgae species has an optimal temperature range for efficient growth. Therefore, regulating wastewater temperature within the appropriate range enhances the efficiency of wastewater treatment.

(3) pH. The pH level influences nutrient availability and the biochemical activity of microalgae. Most microalgae thrive in neutral to slightly alkaline pH (Yu et al. 2022). Controlling wastewater pH within the optimal range for the microalgae species enhances wastewater treatment efficiency.

(4) Aeration and agitation. Adequate mixing and oxygen supply are essential for microalgae growth and wastewater treatment. Proper aeration and agitation ensure even nutrient distribution, CO_2 absorption, oxygenation, and preventing microalgae settling. Optimizing these parameters leads to high wastewater treatment efficiency.

(5) Light intensity. Microalgae require light for photosynthesis, a fundamental process for growth and metabolism. Providing sufficient light intensity and appropriate lighting duration significantly impacts the growth rate of microalgae and wastewater treatment efficiency.

(6) Microalgae Species Selection. Some microalgae species are more effective in treating wastewater than others. Selecting suitable microalgae species that thrive under wastewater conditions and produce high lipids for biodiesel production will increase the overall system efficiency (Srimongkol et al. 2022). The lipid content in microalgae is strongly influenced by growth conditions such as nutrient deficiency, light intensity, and environmental stress. Under specific stress conditions, such as nutrient deficiencies (especially nitrogen) or increased light intensity, the lipid content in microalgae can significantly increase. Some examples of microalgae with high lipids can be seen in (Table 17.1) (Srimongkol et al. 2022).

In a circular economy, the efficiency of wastewater treatment using microalgae is essential to reduce environmental impact, optimize resource utilization, and establish a sustainable process. It is imperative to optimize operational parameters and consider factors affecting wastewater treatment efficiency to effectively support the circular economy concept (Yue et al. 2023).

17.5.3 Strategy for Optimization of Biodiesel Production and By-Products

Strategies for optimizing the production of biodiesel and by-products by utilizing microalgae in a circular economy are as follows:

(1) Selecting microalgae species with high lipid content as potential raw materials for biodiesel production. Additionally, select microalgae capable of thriving in

Table 17.1 Types of microalgae with lipid content

Microalgae	Lipid content (%) per g dry weight (%)
Chlorella vulgaris	4–58
Chlorella protothecoides	15–55
Scenedesmus obliquus	11–45
Nannochloropsis gaditana	20–50
Neochloris oleoabundans	20–54
Botryococcus braunii	25–75
Dunaliella tertiolecta	15–30
Isochrysis galbana	15–35
Phaeodactylum tricornutum	20–40
Haematococcus pluvialis	25–50
Tetraselmis suecica	10–25
Spirulina platensis	4–16

diverse environmental conditions. Some species may also yield valuable by-products, such as pigments, proteins, and polysaccharides.

(2) Optimizing growth conditions such as temperature, pH, light intensity, and nutrient concentration promotes proper microalgal growth and lipid accumulation (Udayan et al. 2022). Certain stress conditions (e.g., nutrient or light deficiency) can stimulate higher lipid production and desired by-products.

(3) Utilizing nutrient and CO_2-rich wastewater from industrial emissions as a source of nutrients and carbon for microalgae growth. This practice reduces input costs, minimizes environmental impacts, and aligns with the circular economy concept.

(4) Developing energy-efficient technologies to separate microalgal cells from media and extract lipids. Methods such as centrifugation, flotation, and flocculation can be used for cell separation, while solvent extraction, supercritical extraction, and electrocoagulation can be used for lipid extraction.

(5) Optimizing the biodiesel conversion processes, such as transesterification, using efficient and environmentally friendly catalysts to enhance the overall sustainability of the process.

(6) Identify and develop high-value applications for by-products generated during biodiesel production, such as proteins, pigments, and polysaccharides. These valuable by-products can be used in various industries, including food, feed, pharmaceutical, cosmetic, and agricultural, supporting the circular economy concept.

(7) Ensure that the biodiesel and by-product production processes using microalgae can be economically upscaled and integrated with existing industrial processes. This scalability allows for broader implementation of the technology on a larger scale.

By optimizing these strategies, biodiesel and by-product production using microalgae can become integral to the circular economy. This approach fosters efficient resource utilization, reduces environmental impacts, and generates economic value.

17.6 Case Studies and Best Practices

17.6.1 Examples of Circular Economy Applications in Biodiesel Production Using Microalgae

Some examples of circular economy applications in biodiesel production using microalgae that have been carried out in European countries (Casanova et al. 2023), in several projects are shown in (Table 17.2).

Some examples of circular economy applications in biodiesel production using microalgae have been conducted in Asian countries (Casanova et al. 2023):

(1) Sinopec-Algae Biofuel Project (2011–2016) in China. Sinopec, a Chinese energy company, in collaboration with Tsinghua University and the Environmental Research Institute is developing biodiesel production technology from microalgae. The project incorporates wastewater for microalgae cultivation and integrates various processes to produce biodiesel and value-added products such as pigments and polysaccharides.
(2) Bharat-OUCRU Project (2014–2019) in India. Bharat Renewable Energy Limited and Oil and Natural Gas Corporation Limited (OUCRU) collaborate on producing biodiesel from microalgae. The project utilizes industrial and agricultural waste as nutrients for microalgae cultivation and CO_2 from industrial emissions as a carbon source. In this project, the solid waste generated is also utilized as organic fertilizer or animal feed.
(3) Korea Institute of Energy Research (KIER) Algae Biofuel Project in South Korea. KIER has been researching biodiesel production from microalgae, employing wastewater for microalgae cultivation and CO_2 from industrial emissions as a carbon source. The project also integrates biodiesel production with creating value-added products such as proteins, pigments, and omega-3 fatty acids.
(4) Project of Algaetech International Sdn. Bhd. In Malaysia. Algaetech International, a Malaysian company focused on microalgae technology, developed a biodiesel production project from microalgae. In addition, the company is also developing other value-added products, such as pigments, proteins, and nutraceuticals from microalgae. The waste generated in this project is also used as organic fertilizer or animal feed, promoting the circular economy concept.
(5) Taipower-Green Energy Development Corporation (GEDC) project in Taiwan. Taipower collaborates with GEDC to produce biodiesel from microalgae. The

Table 17.2 Examples of circular economy application projects in biodiesel production in Europe

Project title	Duration	Funding	Partners	Focus
BIOFAT	2011–2016	European Union	10 partners from 6 European countries (Italy, Portugal, France, Germany, Slovakia, and Belgium)	• Biodiesel and value-added products from microalgae • Utilization of industrial and agricultural wastewater as a source of nutrients for microalgae cultivation and CO_2 from industrial emissions as a carbon source
SPLASH	2012–2016	European Union	20 partners from 9 European countries (Netherlands, France, Germany, Belgium, Spain, England, Denmark, Austria, and Italy)	• Polymers and high-value chemicals from microalgae and biomass • Combine biodiesel production processes and value-added products to create a more efficient and sustainable circular economy
PUFAChain	2013–2017	European Union	11 partners from 8 European countries (Norway, Germany, France, Belgium, Spain, Italy, Austria, and Greece)	• Polyunsaturated fatty acids (PUFA) from microalgae and biomass • Utilization of waste and renewable resources to produce high-value products and promote a circular economy
ALG-AD	2018–2021	Interreg Program Europe North-West	Partners from England, Belgium, and France	• High-value products (animal protein and pigments) from microalgae and anaerobic digestate waste • Reducing greenhouse gas emissions, saving resources, and creating value-added products from waste from the products they produce

project utilizes wastewater and CO_2 from power plant emissions as inputs for microalgae cultivation. Besides biodiesel, the project also yields other value-added products such as proteins, pigments, and omega-3 fatty acids.

Some examples of circular economy applications in biodiesel production using microalgae have been conducted in American countries (Casanova et al. 2023):

(1) Sapphire Energy project. Sapphire Energy, a US biotechnology company, focused on developing renewable fuels from microalgae. The project employs

wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation. It also produces other value-added products such as proteins, pigments, and omega-3 fatty acids. The waste generated is used as organic fertilizer or animal feed, supporting the circular economy concept.

(2) Solazyme Project. Solazyme, another US biotechnology company, develops technologies to produce biodiesel and high-value chemical products from microalgae. The project utilizes industrial waste and renewable resources to create renewable fuels and value-added products such as proteins, pigments, and nutraceuticals.
(3) Algenol Biofuels project. Algenol Biofuels, a US company, focused on producing renewable fuels from microalgae and developing technologies to produce ethanol, biodiesel, and high-value chemical products. The project incorporates wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation and integrates multiple processes to produce fuels and other value-added products.
(4) Pond Technologies project. Pond Technologies, a Canadian company, develops technologies to produce renewable fuels and high-value products from microalgae. The project collaborates with industry to produce biodiesel and other products from microalgae, utilizing wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation and integrating various processes to produce fuels and other value-added products.

Although research on microalgae and biodiesel production in Africa may be less advanced than in some other regions (Casanova et al. 2023), here are several efforts have been made in African countries to implement circular economy principles in biodiesel production using microalgae:

(1) The SANBI (South African National Biodiversity Institute) project in South Africa. This project involves research and development of biodiesel production from microalgae grown in local waters. It utilizes wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation. Besides biodiesel, the project yields other value-added products like proteins, pigments, and omega-3 fatty acids. The generated waste is also used as organic fertilizer or animal feed, supporting the circular economy concept.
(2) AlgaePARC-Morocco project. AlgaePARC-Morocco is a collaborative project between Wageningen University & Research in the Netherlands and Université Mohammed VI Polytechnique in Morocco. This project focuses on research and technology development to produce biodiesel and other value-added products from local microalgae. It involves using wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation, and integrating various processes to produce fuels and other value-added products.
(3) The University of Ilorin Project. This research initiative by the University of Ilorin, Nigeria, focuses on biodiesel production from local microalgae. It utilizes wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation, integrating various processes to produce fuel and other value-added products such as proteins, pigments, and omega-3 fatty acids.

(4) Jomo Kenyatta University of Agriculture and Technology (JKUAT) project. JKUAT in Kenya has been conducting research on biodiesel production from microalgae. The project involves utilizing wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation and integrating various processes to produce fuel and other value-added products such as proteins, pigments, and omega-3 fatty acids.

17.6.2 Lessons Learned from Case Studies and Best Practices

Based on the lessons learned from the case studies and best practices mentioned above, here are some key points regarding wastewater utilization using microalgae to implement the circular economy for biodiesel production (Geremia et al. 2021):

(1) Utilizing wastewater and CO_2 from industrial emissions as inputs for microalgae cultivation can reduce the environmental impact of water pollution and greenhouse gas emissions while utilizing existing resources, thus reducing pressure on natural resources.
(2) Selecting the appropriate microalgae species is crucial to improve wastewater treatment efficiency and biodiesel production. Fast-growing species with high lipid content are preferred in this context.
(3) Optimizing cultivation conditions such as temperature, light intensity, and nutrient concentration is essential to enhance microalgae productivity and wastewater treatment efficiency.
(4) Efficient and effective cultivation technologies, such as closed photobioreactors or open pond systems, can reduce operational costs and increase biodiesel production efficiency.
(5) Producing value-added products other than biodiesel, such as proteins, pigments, and omega-3 fatty acids, can enhance the overall economic value of the system.
(6) Integrated waste management within biodiesel production systems, such as using solid waste as organic fertilizer or animal feed, can reduce environmental impacts and create additional economic value.
(7) Collaboration between industry, academia, and government in developing and implementing technologies for biodiesel production using microalgae is essential to achieve a sustainable circular economy.

Applying the principle of circular economy in biodiesel production using microalgae is expected to create a more efficient, sustainable, and environmentally friendly system, ultimately providing economic, social, and environmental benefits.

17.6.3 Potential for Scale-Up and Commercialization of Microalgae-Based Systems

The potential for scaling up and commercializing microalgae-based systems in the context of a circular economy for biodiesel production is enormous. Here are some aspects to consider in achieving commercial scale (Bošnjaković and Sinaga 2020):

(1) Further research is needed to optimize microalgae cultivation technologies and methods and improve the conversion efficiency of microalgae biomass into biodiesel. Research on new microalgae species with higher potential for biodiesel production is also important.
(2) Developing innovative technologies, such as more efficient and environmentally friendly photobioreactors and open pond systems, will increase microalgae productivity and reduce operational costs.
(3) Reducing the production cost of microalgae is essential to achieve price competitiveness with fossil fuels. Cost reduction can be achieved through process optimization, improved energy efficiency, and utilization of renewable resources and waste.
(4) Strategic partnerships, including collaboration between industry, government, and research institutions, are expected to facilitate technology transfer, capacity building, and the necessary investments for scaling up and commercializing microalgae-based systems.
(5) Policy support and incentives from the government, such as favorable taxes, subsidies, and regulations promoting renewable fuel use, will influence the adoption and growth of microalgae-based systems in biodiesel production.
(6) Increasing public awareness and understanding of the economic, environmental, and social benefits of microalgae-based systems will help drive demand and adoption of this technology.
(7) Developing markets for value-added products generated from microalgae-based systems, such as proteins, pigments, and nutraceuticals, will enhance the economic competitiveness of this system.

By considering these aspects, microalgae-based systems have significant potential to be integrated into the circular economy and achieve commercial scale in biodiesel production. However, achieving this will require continuous research and development efforts and support from various stakeholders to address existing challenges and create an enabling environment for the growth of this sector.

17.7 Policy, Regulation, and Support

17.7.1 Policies and Regulations that Support the Development of Circular Economy in Biodiesel Production

Policies and regulations that support the development of circular economy in biodiesel production by wastewater management using microalgae are essential to encourage the adoption and growth of this technology (Zewdie and Ali 2020). Policies and regulations that can support the development of microalgae-based systems in the context of circular economy are as follows:

(1) The government can set strict CO_2 emission and wastewater quality standards, encouraging industries to seek environmentally friendly wastewater treatment technologies, such as microalgae-based systems.
(2) The government can provide tax incentives and subsidies to companies investing in microalgae-based technologies or using biodiesel produced from microalgae can stimulate the growth of this industry.
(3) The government can establish targets and mandates for using renewable fuels, such as biodiesel, in the transportation and industrial sectors. This will increase the demand for microalgae-based biodiesel and drive investment in this sector.
(4) The government can support research and development in microalgae technology by providing funding, facilities, and partnerships between research institutions and industries.
(5) The government can develop waste management policies that support the utilization of wastewater as a nutrient source for microalgae cultivation. This may include providing incentives for companies implementing this technology.
(6) The government could develop quality and certification standards for microalgae-based biodiesel, ensuring the product meets certain quality requirements and supporting its adoption in the market.
(7) The government can support education and public awareness programs about the economic, environmental, and social benefits of microalgae-based technologies and circular economy.

By implementing policies and regulations that support the development of circular economy in biodiesel production by wastewater management using microalgae, the government can create an enabling environment for the growth of this industry. A combination of incentives, mandates, and research and development support will drive innovation and investment in microalgae-based technologies, ultimately contributing to the goals of a circular and sustainable economy.

17.7.2 Government Incentives and Support for Research and Development of Green Technologies

Here are some examples of government incentives and support for research and development of green technologies in the context of the circular economy in biodiesel production by managing wastewater using microalgae (Culaba et al. 2020):

(1) The government can provide funding and grants for research and development in microalgae-based technologies, including microalgae cultivation, biomass conversion into biodiesel, and wastewater treatment technologies.
(2) The government can provide tax incentives or rebates for companies investing in microalgae-based technologies or adopting circular economy practices in biodiesel production.
(3) The government can partner with the private sector to develop and commercialize microalgae-based technologies, such as photobioreactors and open pond systems.
(4) The government can support training and capacity-building programs to improve knowledge and skills in microalgae-based technologies and wastewater management.
(5) The government can provide infrastructure support, such as research facilities and laboratories, to facilitate the development of microalgae-based technologies.
(6) The government can establish targets and mandates for using renewable fuels, such as biodiesel, to drive investment and research in microalgae-based technologies.
(7) The government can support international collaboration in the research and development of microalgae-based technologies through knowledge exchange, joint research, and exchange programs.
(8) The government can recognize and reward companies and researchers contributing to developing microalgae-based technologies and circular economy in biodiesel production.

By providing appropriate incentives and support, the government can encourage innovation and investment in microalgae-based technologies, enabling the development of a sustainable circular economy in biodiesel production by wastewater management using microalgae.

17.7.3 The Role of Industry and Society in Adopting the Circular Economy Concept

The role of industry and society in adopting the circular economy concept is crucial in the context of biodiesel production using microalgae and wastewater management. Here are some strategies that industry and society can follow:

(1) Collaboration between industry and research institutions to develop and optimize microalgae-based technologies and identify the best microalgae species for biodiesel production and wastewater treatment.
(2) Increase public awareness and understanding of the economic, environmental, and social benefits of microalgae-based technologies and circular economy concepts. This may include information campaigns, seminars, and training programs.
(3) Industries should invest in innovation and development of microalgae-based technology to improve efficiency and reduce biodiesel production costs.
(4) Industries should adopt sustainable business practices by reducing resource consumption, efficient waste management, and utilizing renewable energy.
(5) Industry can adopt corporate policies that support the use of microalgae-based technologies and the circular economy, such as prioritizing sourcing raw materials and energy from sustainable sources.
(6) Society can support the market for microalgae-based biodiesel products and value-added by-products, such as animal feed and fertilizer, by choosing these products and encouraging companies to adopt microalgae-based technologies.
(7) Communities can participate in local initiatives that support the development of microalgae-based technologies and the circular economy, such as collaborative projects involving universities, government, and industries.
(8) Communities and industries can collectively urge the government to adopt policies that support the development of microalgae-based technologies and the circular economy in biodiesel production.

By following these strategies, industry and society can play a significant role in adopting the circular economy concept in biodiesel production by wastewater management using microalgae. Collaboration among various stakeholders will drive innovation and investment in this technology and help create an enabling environment for the sector's growth.

17.8 Research, Innovation, and Education

17.8.1 Recent Research in Circular Economy and Wastewater Management Using Microalgae

Recent research in circular economy and wastewater management using microalgae (Vaz et al. 2023):

(1) Advanced selection and genetic engineering of microalgae for improved nutrient uptake efficiency and lipid production.
(2) Discovery and development of more efficient and energy-saving photobioreactor or pond systems.
(3) Research on new and efficient methods for lipid extraction and conversion into biodiesel.

17.8.2 Technology and Process Innovations Supporting Circular Economy in Biodiesel Production

Technological and process innovations supporting circular economy in biodiesel production (Wynn and Jones 2022; Rinanti and Purwadi 2019):

(1) Real-time monitoring and control technology to optimize microalgae cultivation and wastewater treatment. Here are some reasons why this technology is important and how it supports the circular economy:

  (a) Efficient wastewater treatment. Real-time monitoring and control enable rapid adjustments to environmental conditions that may affect the performance of microalgae-based wastewater treatment systems. By optimizing operational conditions, this technology helps improve wastewater treatment efficiency and reduces environmental impacts from pollutants.
  (b) Efficient resource utilization. Real-time monitoring and control technology enable adjustment of operational parameters, such as temperature, light, and nutrient concentration, to enhance microalgae productivity and ensure efficient resource utilization. This contributes to circular economy principles of reducing resource consumption and minimizing waste.
  (c) Increased biodiesel yield. Real-time monitoring and control technology aid in optimizing microalgae cultivation conditions to maximize lipid production, thereby increasing biodiesel yield. This supports the creation of efficient and environmentally friendly renewable energy, in line with the circular economy goals.
  (d) Reduce production costs. By monitoring and controlling the process in real time, companies can reduce the operational and maintenance costs of microalgae cultivation and wastewater treatment systems. This cost reduction will enhance the economic competitiveness of microalgae-based biodiesel and encourage wider-scale adoption of this technology.
  (e) System integration. Real-time monitoring and control technologies enable better integration between biodiesel production, wastewater treatment, and utilization of value-added by-products (such as animal feed and fertilizer). This integration supports the circular economy concept by creating a complementary system and maximizing the value of each component.
  (f) Adaptability and flexibility. The ability to monitor and control processes in real-time enables operators to respond quickly to external changes or potential issues that may arise. This ensures the system remains flexible and adaptive, a crucial quality supporting a dynamic and sustainable circular economy.

(2) Integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies in microalgae-based biodiesel production systems. The integration of the Internet of Things (IoT) and Artificial Intelligence (AI) technologies in microalgae-based biodiesel production systems is an important technological

and process innovation supporting the circular economy in biodiesel production (Dębowski et al. 2023). Here are some reasons why these technologies are important and how they support the circular economy:

(a) Real-time monitoring and control. IoT enables real-time data collection from various sensors and devices placed throughout the microalgae cultivation and wastewater treatment system. AI can analyze this data and make timely decisions regarding adjustments to operational parameters, such as temperature, light, and nutrient concentration. This enhances system efficiency and reduces resource consumption.
(b) Prediction and planning. AI can analyze historical data and identify patterns that may affect system performance. By predicting changes in environmental conditions or production needs, AI can assist operators in planning and anticipating changes in system operations, which supports the circular economy by increasing efficiency and reducing waste.
(c) Process optimization. AI can be used to optimize processes in microalgae-based biodiesel production systems, such as cultivation, lipid extraction, and conversion of lipids to biodiesel. By optimizing these processes, AI helps increase biodiesel yields and reduce production costs, which supports the circular economy.
(d) Energy management. IoT and AI can be used to manage energy consumption in microalgae-based biodiesel production systems, such as optimizing lighting and energy use in photobioreactor systems. Efficient energy management reduces resource consumption and greenhouse gas emissions, aligning with circular economy principles.
(e) Utilization of by-product. IoT and AI can be used to monitor and optimize the utilization of by-products generated from microalgae-based biodiesel production systems, such as animal feed and fertilizer. By optimizing the utilization of these by-products, these technologies support the circular economy by creating added value from waste and reducing environmental impact.
(f) Scalability and flexibility. The integration of IoT and AI allows microalgae-based biodiesel production systems to be more easily scaled and adapted to changing needs. The ability to adapt to market-changing conditions and demands is key to creating a sustainable and dynamic system within the context of a circular economy.

(3) Development of recycling and nutrient recovery technologies from microalgae biomass residues. The development of recycling and nutrient recovery technologies from microalgae biomass residues is an important technological and process innovation to support the circular economy in biodiesel production for the following reasons:

(a) Waste reduction. Recycling and nutrient recovery from microalgae biomass residues reduce the waste generated during biodiesel production. Waste reduction is one of the key principles of the circular economy, aiming to minimize the environmental impact of industrial processes.

(b) Resource efficiency. The nutrient recovery process allows previously considered waste resources (such as phosphorus and nitrogen) to be reused in the microalgae production processes. This enhances resource utilization efficiency and reduces raw material consumption, aligning with circular economy goals.

(c) Production costs reduction. Companies can reduce raw material and waste disposal costs by implementing nutrient recycling and recovery technologies. These cost reductions can improve the economic competitiveness of microalgae-based biodiesel and encourage wider adoption of this technology.

(d) Support for sustainable agriculture. Nutrients recovered from microalgae biomass residues can be used as fertilizer in agriculture. Using these fertilizers can help reduce the environmental impact of conventional agriculture and support the transition to more sustainable agricultural systems.

(e) Support for related industries. Nutrient recycling and recovery technologies can create value-added by-products (such as fertilizer and animal feed) that can be used in related industries. This creates additional business opportunities and strengthens relationships between complementary industries, an essential aspect of the circular economy.

(f) Research and innovation. The development of nutrient recycling and recovery technologies promotes research and innovation in biotechnology and environmental technologies. These innovations can help address the environmental and economic challenges faced by the biodiesel industry and support the transition to a more circular and sustainable economic system.

Overall, the development of recycling and nutrient recovery technologies from microalgae biomass residues can contribute to creating a more efficient, environmentally friendly, and economically viable biodiesel production system, supporting the principles of the circular economy (de Carvalho et al. 2022).

Education and training programs in circular economy and wastewater management using microalgae:

(1) Curriculum and educational programs emphasizing circular economy concepts, biodiesel production, and wastewater management.
(2) Training and certification for professionals working in the biodiesel industry and wastewater management.
(3) Development of educational materials to increase public awareness of circular economy and the benefits of microalgae utilization.

Collaboration between academia, industry, and government:

(1) Collaborative research initiatives involving universities, research centers, and industries focusing on circular economy and wastewater management using microalgae.

(2) Government support for research and development of innovations in circular economy and biodiesel production.
(3) Public–private partnerships for the development and implementation of green technologies.

Case studies and examples of educational applications:

(1) Successful and innovative education program that teaches circular economy concepts and wastewater management using microalgae.
(2) Implementation of educational technologies, such as virtual and augmented reality to enrich the learning experience on circular economy and biodiesel production.
(3) The influence of education and public awareness on the adoption of environmentally friendly technologies.

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