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

Toward Carbon Neutrality

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Preface

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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February 2024

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Contents

Chapter 20
Algae as a Sustainable Source for Energy Storage Technologies

Astri Rinanti, Lutfia Rahmiyati, Melati Ferianita Fachrul, Sarah Aphirta, Sheilla Megagupita Putri Marendra, and Nadia Savira

Abstract This chapter provides a thorough overview of the potential of algae as a renewable energy source and energy storage technology, which includes algae biology, aquaculture technology, conversion processes, energy storage applications, and economic, social and environmental impacts. Algae is a potential raw material for sustainable renewable energy because of its ability to grow rapidly and produce high-energy biomass. As photosynthetic organisms, algae play an important role in the ecosystem and can be developed as an alternative energy source that is environmentally friendly. The discussion begins by explaining the technology and methods of algae cultivation, as well as the process of converting algae biomass into various forms of energy, such as bioethanol, biobutanol, biogas, syngas, bio-oil, biochar, and biodiesel. Energy storage technologies, such as batteries, capacitors, flywheels, and hydro pumps, can be integrated with algal biomass to create more efficient and sustainable renewable energy systems. Relevant application and case studies are also presented to provide a deeper understanding of the potential of algae in the energy sector. The economic, social, and environmental impacts of using algae as a renewable energy source need to be considered. An analysis of the life cycle, production costs, and market implications of algae-based renewable energy is presented to provide

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a thorough picture of the sustainability of this technology. In addition, the role of government regulations and policies in the development and adoption of algae-based technologies is discussed. Although algae offer great potential as a renewable energy source, there are still some challenges that need to be overcome, such as technological barriers, efficiency, and production costs. It is hoped that the latest innovations and research to address these challenges will provide visions and future projections for the algae-based renewable energy industry.

20.1 Introduction

20.1.1 The Role of Algae in the Ecosystem

Algae are a group of photosynthetic eukaryotic organisms that inhabit aquatic environments—both freshwater and marine ecosystems—as well as moist terrestrial areas. Algae can exist as single-celled or multicellular organisms, often possessing relatively simple body structures. Several types of algae have been utilized in various industrial applications, such as the production of chemicals, pharmaceuticals, cosmetics, food, and renewable energy (Abusweireh et al. 2023; Babich et al. 2022; Boukid and Castellari 2023). Generally, algae can be regarded as highly diverse organisms with numerous benefits for humans and the environment.

Several key roles of algae as photosynthetic organisms in aquatic ecosystems are listed below:

(1) Primary producers: Algae serve as primary producers in aquatic food chains (Nagappan et al. 2021). Through photosynthesis, they convert solar energy into chemical energy, which is utilized by other organisms in the ecosystem as a source of energy (Visca et al. 2017). Algae produce biomass that serves as food for primary consumers, such as zooplankton and certain species of small fish.
(2) Carbon absorption: Algae absorb carbon dioxide (CO_2) from the atmosphere and water through photosynthesis, contributing to the mitigation of greenhouse gas emissions and climate change impacts. Their photosynthetic activity also yields oxygen, which is indispensable for aquatic organisms, underscoring their vital part in maintaining the oxygen cycle within aquatic ecosystems (Iglina et al. 2022; Onyeaka et al. 2021).
(3) Nutrient cycling: Algae help regulate water quality by absorbing excess nutrients, e.g., phosphates and nitrogen. In some cases, algae can also assist in reducing pollutants like heavy metals from aquatic environments (Nguyen et al. 2022; Siwi et al. 2017).
(4) Habitat and protection: Macroalgae, such as seaweed and kelp, play a crucial role in providing habitat and shelter for various aquatic species. Macroalgae create complex, layered structures in water, offering a home to diverse creatures. For instance, kelp forests and seagrass beds provide habitat for fish, crustaceans, molluscs, and numerous invertebrate species. These ecosystems are

often referred to as "underwater forests" that provide abundant protection and food resources for many organisms.

Macroalgae provide protection for the species residing within them, particularly from predators. Animals like crabs, shrimp, and molluscs can hide among the leaves and branches of seaweed or aquatic moss, making them less visible to predators. This also applies to fish larvae and juveniles, which often seek refuge among macroalgae to grow and develop before reaching adulthood.

Many aquatic species utilize macroalgae as a medium for egg-laying and reproduction. For example, certain fish species lay their eggs on seaweed leaves, while molluscs and crustaceans attach their eggs to algal stems (Dharmono et al. 2022). Macroalgae provide a safe shelter for the eggs and larvae to grow and develop. They also serve as a food source for various aquatic organisms. Some species, such as marine herbivores, directly consume algae (Yin et al. 2019), while others feed on detritus (dead and organic particles) produced by macroalgae (Yin et al. 2019). Additionally, macroalgae provide habitat for numerous microorganisms and small invertebrates, which, in turn, serve as food for other aquatic species.

Macroalgae promote species diversity in aquatic ecosystems by providing suitable habitats for new or migratory species. For instance, fish seeking spawning grounds or refuge can find macroalgae as an ideal site, thus eventually enhancing overall ecosystem diversity and health. Moreover, macroalgae contribute to nutrient cycling within aquatic ecosystems by absorbing dissolved nutrients, such as nitrogen and phosphorus. This helps maintain water quality and supports the growth and reproduction of other aquatic species (Nguyen et al. 2022).

(5) Microecosystem foundation: microscopic algae, such as diatoms and dinoflagellates, constitute phytoplankton—the foundation of aquatic ecosystems. Phytoplankton are photosynthetic organisms that float or swim freely in the water column, serving as the cornerstone of aquatic ecosystems, with various vital roles as follows:

   (a) As primary producers, phytoplankton convert solar energy into chemical energy through photosynthesis. They produce biomass that serves as a food source for primary consumers like zooplankton, which in turn, become food for higher-level consumers like fish and marine mammals.
   (b) As oxygen providers, phytoplankton perform photosynthesis which yields oxygen as a byproduct. This oxygen becomes the main source of dissolved oxygen in water, essential for organisms like fish, amphibians, and invertebrates.
   (c) Phytoplankton play a critical role in aquatic food chains, serving as a food source for primary consumers like zooplankton. Zooplankton then sustains higher-level consumers such as small fish, which become prey for larger fish, seabirds, marine mammals, and other predators. Hence, phytoplankton support life throughout the aquatic ecosystem.

(d) Phytoplankton play a pivotal role in the water's nutrient cycle by absorbing dissolved nutrients like nitrogen and phosphorus. They utilize these nutrients for growth and reproduction, and when they die, these nutrients are released back into the environment through decomposition, sustaining nutrient availability for other organisms.

(e) Phytoplankton are crucial components of the global water system. They participate in the global carbon cycle by absorbing carbon dioxide from the atmosphere through photosynthesis and producing the oxygen essential for life on Earth. They also contribute to biomass production, supporting life in water bodies, including fisheries and the fishing industry.

(6) Erosion and Sedimentation. Seaweeds and water mosses are examples of macroalgae that grow in large and structured forms, playing a significant role in mitigating erosion and sedimentation in aquatic ecosystems by retaining soil particles and other materials that could contaminate the water. These macroalgae possess intricate structures, creating a physical network capable of capturing soil particles and other materials in the water column. As a result, macroalgae help reduce water flow velocity and slow down particle movement, effectively decreasing erosion and sedimentation in the ecosystem (Cotas et al. 2023).

Seaweeds and water mosses grow on substrates, e.g., rocks, sand, or mud at the bottom of water bodies. By attaching to such substrates, these organisms contribute to maintaining the stability and integrity of the aquatic bed, decreasing erosion caused by currents, waves, and human activities. Coastal seaweeds, particularly seagrass or kelp, can form dense coverings that protect shorelines from wave-induced erosion. The roots and rhizomes of seagrass aid in binding soil particles and sand, promoting coastal stability and mitigating erosion. Macroalgae (like seaweed and water moss) also function as natural filters, absorbing and storing nutrients, heavy metals, and other pollutants in the water column (Arumugam et al. 2018). Through absorption and accumulation of these matters, macroalgae help lower particle and pollutant concentrations in the water, hence minimizing sedimentation and pollution. They create complex ecosystems, such as seagrass meadows and kelp forests, which provide habitat for various aquatic organisms. These ecosystems enhance the stability of the aquatic bed and damp erosion by offering protection from waves and currents while retaining particles and materials in the water column.

Coastal seaweed and water moss can absorb wave energy, subsequently diminishing water flow velocity and coastal erosion (Sultana et al. 2023). For instance, coastal kelp forests serve as natural shields protecting shorelines from wave-induced erosion. Thus, macroalgae like seaweed and water moss play a vital role in mitigating erosion and sedimentation in aquatic ecosystems through particle trapping, substrate stabilization, and coastal protection.

(7) Water quality indicators: The presence and abundance of algae in water bodies can serve as indicators of water quality, reflecting the ecological and chemical conditions as well as changes occurring in the ecosystem. Various types of algae, especially phytoplankton like diatoms and dinoflagellates, are sensitive

to environmental changes and pollutants. Therefore, the presence, abundance, and species composition of algae can provide valuable insights into the overall condition of the water. Algae are used as bioindicators of water quality in the following ways:

(a) Nutrient indicator: Algae are highly sensitive to nutrient levels in water, particularly phosphates and nitrogen. Increased nutrient levels often lead to excessive algal growth or "blooms," which can result in water quality deterioration and environmental issues—such as eutrophication and hypoxia (Gökçe 2016)
(b) Pollution Indicator: Some types of algae can absorb or accumulate pollutants like heavy metals, pesticides, and organic compounds. The presence and abundance of algae resistant to specific pollutants can indicate pollution in the aquatic ecosystem (Rinanti et al. 2021).
(c) Climate change indicator: Algae are highly sensitive to temperature and light conditions, making fluctuations in their abundance or distribution indicative of climate changes or other environmental situations impacting water bodies.
(d) pH Indicator: Some algae species have specific preferences for water acidity levels. The presence of algae more tolerant to low or high pH levels can indicate changes in water acidity balance.
(e) Dissolved oxygen indicator: Algae influence the concentration of dissolved oxygen in water through photosynthesis and respiration. The existence of algae producing significant amounts of oxygen can represent a healthy water condition, while less algal abundance may indicate issues with dissolved oxygen or poor water conditions.
(f) Biological indicator: Algae species diversity and community composition in water bodies can depict the overall ecosystem health. For example, the presence of certain algae or healthy algal groups can signify good water conditions, whereas decreased diversity or changes in algal community composition may suggest disturbances or stress in the ecosystem.

By monitoring alterations in algal communities, scientists and water resource managers can detect water quality problems and take necessary actions to protect and restore ecosystem health. Hence, algae play a crucial role in maintaining the balance and sustainability of aquatic ecosystems.

20.1.2 History and Development of Renewable Energy

The development of algae-based renewable energy has a long and fascinating history. Algae have been recognized as a source of energy since ancient times, but intensive research and development on utilizing algae as a renewable energy source began in the twentieth century. The following is the historical timeline and advancement of algae-based:

(1) In ancient times, algae (particularly seaweed) were used as food and animal feed in diverse civilizations worldwide. Although algae were not explicitly utilized as an energy source during that period, their diverse applications in daily life showcased their potential and versatility. Seaweed has been consumed as food by humans since ancient times. In Asia, principally in Japan, Korea, and China, it has become an integral part of daily diets and featured in various dishes like sushi, soups, and salads. Seaweed is rich in nutrients, such as vitamins, minerals, fibre, and essential fatty acids like omega-3. Algae were also utilized as fertilizers and animal feed in agriculture: Dried seaweed was used as a nutrient-rich organic fertilizer, enhancing soil fertility and crop yields; Moreover, protein and nutrient-rich algae were used as animal feed, particularly for cattle, sheep, and poultry.

Several ancient civilizations utilized algae, notably seaweeds, for medicinal and healing purposes. As an illustration, algae were incorporated in traditional Chinese medicine to treat various ailments and digestive problems. Although the industrial use of algae was not fully developed in ancient times, some early applications were noted. For example, seaweed extracts containing polysaccharides like agar and alginate were used in food thickening and preservation. Algae were not recognized as an energy source during ancient times, as the knowledge of processes like fermentation and biomass conversion into energy was not fully comprehended. Nevertheless, the use of algae in diverse applications demonstrated their versatility and potential as valuable natural resources. Technological improvements and deeper understanding of algae and their biochemical mechanisms have enabled their utilization as a renewable energy source in modern times (Salami et al. 2021).

(2) In the twentieth century, around the 1950s to 1960s, initial research on the utilization of algae as an energy source commenced, especially in the United States. During the 1970s, the energy crisis caused by the OPEC oil embargo prompted governments and researchers to seek alternatives for sustainable and eco-friendly energy sources. Algae emerged as an attractive option due to their rapid growth rate and ability to produce large amounts of biomass.

(3) In 1978, the United States Department of Energy (DOE) launched the Aquatic Species Program (ASP), operated by the National Renewable Energy Laboratory (NREL). The program aimed to develop biodiesel production technology from microalgae. The program lasted for nearly 20 years and yielded extensive knowledge about algae biology, cultivation technology, and the process of converting algal oil into biodiesel. Although the ASP was discontinued in 1996 due to funding constraints, research on algae as an energy source continued to advance. Several companies and universities in the United States invested resources in developing biofuel production technology from algae, including ExxonMobil, Synthetic Genomics, and Arizona State University. Algae's utilization as an energy source in the United States includes biodiesel, biogas, and bioethanol production.

(4) Since the early twenty-first century, research and development of algae-based renewable energy have rapidly progressed. Various technologies and processes

have been developed to produce various types of fuels from algae, including biodiesel, bioethanol, biogas, and biohydrogen (Salami et al. 2021). Algae are also utilized to generate high-value carbon-based products, such as pigments, omega-3 fatty acids, and protein.

(5) Technological advancements in genetics, biotechnology, and process engineering have allowed increased efficiency and cost reduction in algae-based renewable energy production. Innovations like genetic engineering and selection of highly productive algae strains have resulted in algae strains with higher productivity and lipid content, consequently amplifying fuel production efficiency.

20.1.3 Why Algae Are Important for Renewable Energy?

Algae possess immense potential as a renewable energy source for several compelling reasons as follows:

(1) Rapid growth and high productivity: Algae exhibit a remarkably fast growth rate and can generate a substantial biomass in a relatively short time. It means that algae can yield more energy per unit area compared to other renewable energy crops such as corn or sugarcane (Sawant et al. 2018).
(2) Non-competitive with agricultural land: Algae can thrive in water bodies such as lakes, ponds, or even wastewater, avoiding competition with agricultural land used for food production. This aspect is crucial for global food security and efficient land utilization (Amir et al. 2021).
(3) Carbon dioxide sequestration: Algae absorb carbon dioxide (CO_2) from the atmosphere or industrial emissions as part of the photosynthesis process. Thus, utilizing algae as a renewable energy source can aid in reducing greenhouse gas emissions and contribute to climate change mitigation efforts (Dewi et al. 2014; Iglina et al. 2022; Onyeaka et al. 2021).
(4) High lipid content: Some algae species boast high lipid content, making them ideal for biodiesel production. The biodiesel derived from algae shares similar properties with fossil diesel and can be used in conventional diesel engines without modification (Morales et al. 2021; Udayan et al. 2022)
(5) Fuel production flexibility: Algae can be processed into different types of fuels, including biodiesel, bioethanol, biogas, and biohydrogen. This flexibility allows for various energy needs to be met and promotes the diversification of renewable energy sources (Salami et al. 2021).
(6) Waste and nutrient treatment: Algae can be employed to treat excess waste and nutrients from industries and agriculture. By absorbing nutrients such as nitrogen and phosphorus, algae assist in decreasing water pollution and eutrophication while generating biomass for energy production (Nguyen et al. 2022).
(7) High-value product generation: Beyond energy, algae can yield various high-value products, including omega-3 fatty acids, pigments, and protein. This

heightens the economic value of algae and renders algae-based renewable energy production more financially feasible and sustainable.

Due to these reasons, algae are considered a prominent and promising renewable energy source. However, there are challenges to overcome for achieving efficient and economically viable algae-based energy production on a commercial scale, such as cost reduction and efficiency improvement in manufacturing and processing technologies.

20.2 Biology and Physiology of Microalgae as Energy Raw Materials

20.2.1 Cell Structure and Algal Metabolism

The cellular structure and anatomy of algae vary depending on their types and species. However, several common characteristics are shared by most algae, as depicted in (Fig. 20.1) and elaborated below:

(1) Algal cell structure: Each algal cell typically consists of various components, including the cell nucleus, cytoplasm, and cell membrane. Additional structures such as vacuoles, chloroplasts, and stigma may also be present.
(2) Cell nucleus: This central structure in the algal cell contains genetic material, such as DNA and RNA.
(3) Cytoplasm: The fluid found within the algal cell where various metabolic processes occur.
(4) Cell membrane: The outer layer that encloses the algal cell and regulates the movement of substances in and out of the cell.

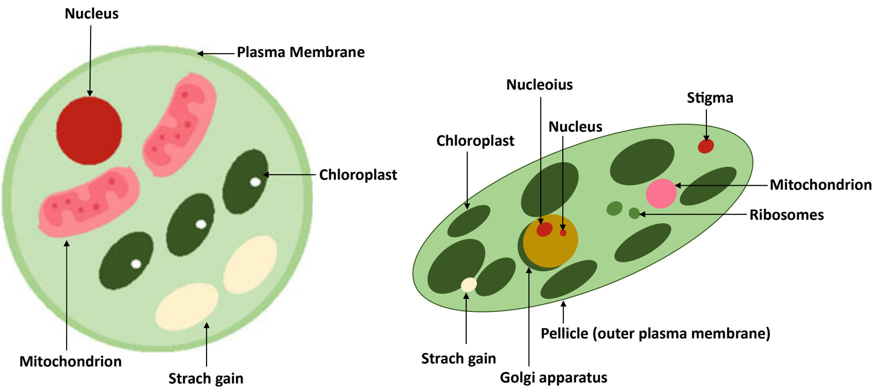

Fig. 20.1 Algal cell structure

(5) Chloroplasts: Organelles that enable algae to conduct photosynthesis. Chloroplasts contain photosynthetic pigments like chlorophyll and carotenoids.
(6) Vacuoles: Bag-shaped organelles within the algal cell responsible for storing reserve substances and maintaining osmotic pressure within the cell.
(7) Stigma: Grain-like structures within the algal cell that play a role in directing algal movement towards light.
(8) Algal cell anatomy: More complex types of algae, such as classes *Rhodophyceae*, *Chlorophyceae*, and *Phaeophyceae*, possess a more organized body structure and specialized tissues, such as leaves, stems, and roots. These body structures comprise several components, including:
(9) Thallus: The body structure consisting of algal cells without specific organs or tissues.
(10) Stipe: The stem-like part that connects the thallus to the substrate where the algae adhere.
(11) Holdfast: A specialized structure that serves as an anchor for the algae to attach to a stronger substrate.
(12) Bladder: A sac-like structure found in certain algal species that functions as a buoyancy aid to keep the algae floating at the water's surface.

The structure and anatomy of algae cells vary depending on their types and species. However, most algae cells share common features with other plant cells, such as chloroplasts, cell membranes, and nuclei. Some algae types also exhibit more intricate body structures and specialized tissues, including thallus, stipe, holdfast, and bladder.

The metabolism of algae cells encompasses a series of biochemical processes that occur within the cell. These processes aim to acquire energy and maintain vital cell functions. Algal cell metabolism consists of two stages, namely anabolism and catabolism, as explained below:

(1)(**Anabolism**The formation of complex compounds from simple molecules. Processes within this stage include photosynthesis and the synthesis of other organic compounds such as proteins and carbohydrates. Several anabolic phases occurred in algae cells are as follows:

(a) **Photosynthesis**: The conversion of light energy into chemical energy in the form of sugars. During photosynthesis, chloroplasts within the algae cells transform light energy into chemical energy and use CO_2 from the environment to create organic compounds like glucose.
(b) **Protein synthesis**: The formation of protein compounds from amino acids. During this process, algae cells require nutrients like nitrogen and sulfur.
(c) **Carbohydrate synthesis**: The formation of carbohydrate compounds from CO_2 and water. This process requires the energy generated during photosynthesis.

(2) **Catabolism**: The breakdown of complex compounds into simpler molecules, releasing energy that powers the algae cells. Processes within this stage include respiration and fermentation. Several catabolic phases occurred in algae cells are as follows:

(a) **Respiration**: The breakdown of organic compounds into CO_2 and H_2O with the aid of oxygen, producing energy in the form of ATP.
(b) **Fermentation**: The breakdown of organic compounds without the aid of oxygen, generating energy in the form of ATP (Catalanotti et al. 2013).

Accordingly, algal cell metabolism encompasses a series of biochemical processes comprising anabolism and catabolism. Anabolism is the stage of synthesizing complex compounds (e.g., proteins, carbohydrates, and glucose) from simple molecules. On the other hand, catabolism is the stage of breaking down complex compounds into simpler molecules like CO_2 and H_2O, yielding energy in the form of ATP.

20.2.2 The Process of Photosynthesis and Biomass Production

Photosynthesis is a fundamental mechanism used by algae and other green plants to generate energy and biomass (Vecchi et al. 2020). It is a process that converts solar energy into chemical energy stored in molecules of glucose and other organic compounds. It involves the conversion of carbon dioxide (CO_2) and water (H_2O) into simple sugars and oxygen, with light energy serving as the trigger. Algal biomass refers to the total dry weight of living algal organisms, composed of organic molecules such as proteins, carbohydrates, and lipids. The formation or production of algal biomass is closely related to photosynthesis (Fig. 20.2) as it provides the energy and raw materials needed for algal growth and reproduction.

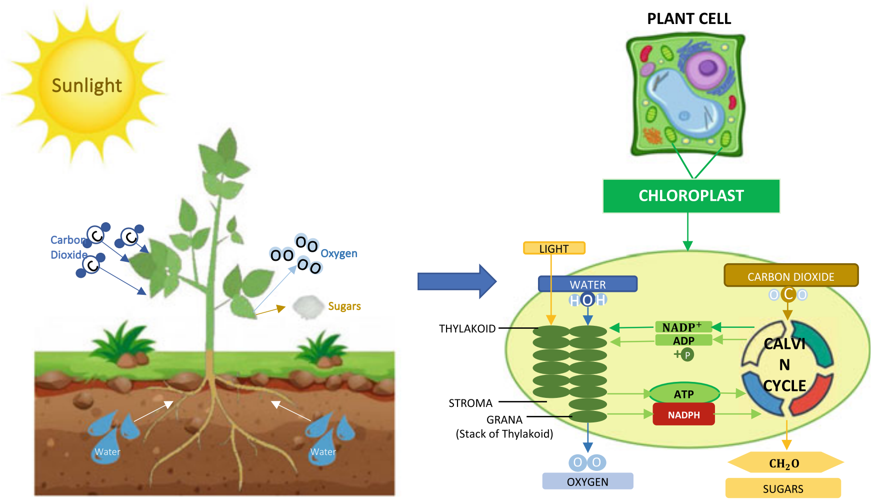

Fig. 20.2 Photosynthesis process in plants

The process of photosynthesis leading to the formation of algal biomass includes several stages as follows:

(1) **Absorption of light energy:** Algae contain photosynthetic pigments like chlorophyll that capture solar energy. These pigments convert light energy into chemical energy used in the process of photosynthesis.
(2) **Carbon fixation:** Algal carbon fixation is the process of “capturing” or absorbing CO_2 from the air and converting it into organic compounds through photosynthesis. Through the Calvin cycle, also known as the Calvin-Benson-Bassham (CBB) cycle, algae absorb CO_2 from the air to produce organic compounds such as glucose, which are used for growth and biomass production. The Calvin cycle consists of three main phases:

    (a) **Carbon fixation:** In this stage, CO_2 from the environment is bound to ribulose-1,5-bisphosphate (RuBP), the CO_2 acceptor. This reaction is catalyzed by the enzyme Rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase), the most abundant enzyme on Earth. The result of this reaction is two molecules of 3-phosphoglycerate (3-PGA), a three-carbon compound.
    (b) **Reduction:** The reduction phase involves converting 3-PGA into triose phosphates (simple sugars) through several chemical reactions. First, 3-PGA is reduced to 1,3-bisphosphoglycerate (1,3-BPG) by the enzyme phosphoglycerate kinase, using ATP. Next, 1,3-BPG is reduced to glyceraldehyde 3-phosphate (G3P) by the enzyme NADPH-glyceraldehyde-3-phosphate dehydrogenase (GAPDH), using NADPH. In this process, one molecule of G3P is exported from the cycle for glucose and other organic compound synthesis, while the other G3P molecule remains within the cycle.
    (c) **Regeneration:** The regeneration phase involves a series of reactions that convert the remaining G3P molecules back into RuBP, allowing the Calvin cycle to continue. This process incorporates several enzymes (e.g., transketolase, aldolase, and phosphoribulokinase) and consumes ATP. Once RuBP is regenerated, the Calvin cycle can repeat, enabling the fixation of more CO_2 and biomass production.

    Through carbon fixation via the Calvin cycle, microalgae convert CO_2 from the air into organic compounds necessary for growth and biomass production. This process is essential for maintaining the carbon balance in the atmosphere and holds potential for use in climate change mitigation technologies, such as carbon capture and storage (CCS) or environmentally friendly bioenergy production.

(3) **Biomolecule synthesis:** Simple sugars produced through photosynthesis serve as raw materials for synthesizing more complex biomolecules, such as polysaccharides, proteins, and lipids. Simple sugars like glucose, fructose, and galactose are monosaccharides and act as the building blocks of more complex

biomolecules like polysaccharides, proteins, and lipids. Here's how simple sugars are synthesized into more complex biomolecules:

(a) **Polysaccharides**: These are complex carbohydrates composed of long chains of connected monosaccharides. Glucose, for example, can be synthesized into polysaccharides like amylum and glycogen through a process called glycosylation. In glycosylation, enzymes catalyze the formation of glycosidic bonds between monosaccharides, resulting in longer polysaccharides. Amylum and glycogen serve as energy storage forms in plants and animals, respectively.

(b) **Proteins**: Proteins are polymers composed of amino acids as monomers. Protein synthesis involves several steps, including DNA transcription to RNA, RNA translation to polypeptides, and polypeptide folding into functional protein structures. Glucose and other simple sugars can be used as an energy source for these processes. Moreover, glucose can be converted into amino acids through gluconeogenesis and the citric acid cycle (Krebs cycle). In gluconeogenesis, glucose is converted into pyruvate, which can then enter the citric acid cycle. In the citric acid cycle, pyruvate is converted into amino acid precursors such as oxaloacetate and α-ketoglutarate. The produced amino acids can then be used for protein synthesis.

(c) **Lipids**: Lipids include molecules such as triglycerides, phospholipids, and sterols. Glucose can be used as an energy source in lipid synthesis or as a substrate to produce lipid precursors such as glycerol and fatty acids. This process involves several metabolic steps, including glycolysis, the citric acid cycle, and fatty acid synthesis. In glycolysis, glucose is broken down into pyruvate, which can then be converted into acetyl-CoA. Acetyl-CoA is a critical substrate in fatty acid synthesis, which occurs in the cytoplasm through a reaction catalyzed by the enzyme fatty acid synthase complex (FAS). Once fatty acids are formed, they can combine with glycerol to form triglycerides, the primary form of stored fat. Additionally, fatty acids can be used to synthesize phospholipids and sterols like cholesterol.

In summary, simple sugars like glucose play a crucial role in the synthesis of complex biomolecules such as polysaccharides, proteins, and lipids. These biomolecules are essential for building algal cell structures and serve as a source of energy for algal growth and reproduction.

(1) **Growth and reproduction:** Through biomolecule synthesis, algae undergo growth and reproduction, leading to an overall increase in algal biomass. Microalgae employ various methods of reproduction depending on species and environmental conditions. Reproduction in microalgae can be categorized into two main types, namely asexual and sexual reproduction, as elaborated below:

(a) **Asexual reproduction:** a process of microalgal proliferation without involving genetic material exchange. In asexual reproduction, parent cells divide into two or more identical offspring genetically. Several methods of asexual reproduction in microalgae include:

- Binary fission: The most common asexual reproduction method in microalgae. During binary fission, parent cells divide into two equally sized daughter cells. This process involves DNA replication, septum formation, and offspring cell separation.
- Some microalgae species undergo sporulation, forming asexual spores called zoospores or autospores. These spores can withstand harsh environmental conditions and remain dormant until conditions become more favorable. Once conditions improve, these spores germinate and form new algal cells.
- Fragmentation: In some filamentous algae species, filaments can break into fragments that then develop into new individuals.

(b) **Sexual Reproduction:** Sexual reproduction in microalgae comprises the exchange of genetic material between two different individuals. This process results in offspring with unique combinations of parental characteristics. Several methods of sexual reproduction in microalgae include:

- Isogamy: In isogamy, two gametes of identical size and shape (isogametes) fuse to form a zygospore. The zygospore then grows and develops into a new individual.
- Anisogamy: In anisogamy, two gametes of different sizes and shapes (anisogametes) fuse to form a zygospore. This process is similar to isogamy but involves morphologically different gametes.
- Oogamy: In oogamy, smaller, motile male gametes (sperm) fuse with larger, non-motile female gametes (oosphere) to form a zygospore. The zygospore then develops into a new individual. Sexual reproduction usually occurs under unfavorable environmental conditions or when resources are limited. This process results in genetic variation that can enhance the adaptability of microalgae to environmental changes.

In conclusion, photosynthesis plays a vital role in the formation of algal biomass by providing the energy and raw materials necessary for algal growth and reproduction. Improving photosynthetic efficiency can have a positive impact on algal biomass production, which is essential for various industrial applications such as bioenergy, animal feed, and chemical raw materials (Vecchi et al. 2020).

20.2.3 Environmental Factors Affecting Algae Growth

The growth of microalgae in their natural environment is influenced by various physical, chemical, and biological factors. Here are some key aspects that affect microalgae growth:

(1) Physical factors, including:

(a) Sunlight: Solar energy is the primary source of energy for microalgal photosynthesis. The intensity and duration of light exposure affect the rate of photosynthesis and microalgae growth (Metsoviti et al. 2020).
(b) Temperature: Environmental temperature affects the rate of metabolism and enzyme activity within microalgae cells. Each microalgae species has an optimal temperature range for its growth, and temperatures outside this range can reduce growth rate (Novosel et al. 2022).
(c) Mixing and water movement: This aspect influences nutrient uptake and light distribution. Proper mixing enhances nutrient absorption and light exposure, supporting microalgae growth (Chowdury et al. 2020).

(2) Chemical factors, including:

(a) Nutrients: Microalgae require nutrients such as nitrogen, phosphorus, and sulfur for growth and reproduction. The availability of these nutrients in the natural environment affects microalgae growth rate (Chowdury et al. 2020).
(b) Carbon dioxide (CO_2): is the primary substrate for photosynthesis and microalgae growth. The concentration of CO_2 in the natural environment affects the rate of photosynthesis and microalgae growth (Udayan et al. 2022).
(c) pH: Environmental pH balance affects enzyme activity and nutrient uptake by microalgae. Each microalgal species has an optimal pH range for its growth (Latsos et al. 2021).
(d) Salinity: Salt content in water affects microalgae growth. Some microalgal species thrive better in higher salinity, while others are more tolerant of low salinity levels (Latsos et al. 2021).

(3) Biological factors, including:

(a) Microalgae species and strains: Different microalgae species and strains have varying requirements and tolerances to physical and chemical factors, affecting their growth rate.
(b) Interactions with other microorganisms: Interactions between microalgae and other microorganisms like bacteria, protozoa, and viruses can influence microalgae growth. Some of these interactions can be mutualistic, while others can be competitive or parasitic.
(c) Predation: Microalgae serve as a food source for various organisms such as zooplankton and filter feeders. High predation rates can affect the growth of microalgal populations in their natural environment.

20.3 Technology and Methods of Algae Cultivation

The cultivation method of algae is closely linked to the potential of algae as a renewable resource for energy storage technologies. Algae, especially microalgae, offer several advantages as a raw material source for energy storage, such as biogas, biodiesel, bioethanol, and biohydrogen. The connection between algae cultivation technology and the potential of algae in energy storage can be explained as follows:

(1) (Biomass productivity: In algae cultivation, one of the main goals is to increase biomass productivity. High algal biomass will increase the amount of raw material available for energy conversion processes, such as fermentation, transesterification, or gasification (Mahmood et al. 2022).
(2) Lipid and biochemical content: Optimal algae cultivation can increase lipid, carbohydrate, and protein content in algae, directly impacting the potential of algae as a renewable resource (Visca et al. 2017). For instance, algae with high lipid concentrations are more suitable for biodiesel production, while algae with high carbohydrate content are more satisfactory for bioethanol or biogas production (Kumar et al. 2022).
(3) Environmental control and cultivation conditions: Algae cultivation allows for the control of environmental conditions, such as temperature, light intensity, pH, and nutrients. Optimizing these conditions can promote algae growth and the production of renewable energy raw materials. Algae cultivation can also reduce competition with agricultural land and freshwater resources, which are vital for sustainable renewable energy (Mahmood et al. 2022).
(4) Breeding and genetic engineering: Algae cultivation technology involves the use of breeding and genetic engineering techniques to produce algae strains that are more efficient in producing biomass or specific biochemical components. These optimized algae strains can elevate the potential of algae as a renewable resource for energy storage.

By optimizing algae cultivation method, we can improve the potential of algae as a renewable resource for energy storage technologies. This will help decrease dependence on fossil fuels and foster the development of environmentally friendly and sustainable energy technologies.

20.3.1 Algae Cultivation Techniques (Photobioreactor, Open System, Closed System)

Microalgae cultivation refers to the process of cultivating or nurturing microalgae using optimal nutrient, light sources, and environmental conditions to support their growth and reproduction. In microalgae cultivation, there are two primary systems used to support their growth and reproduction: open systems and closed systems.

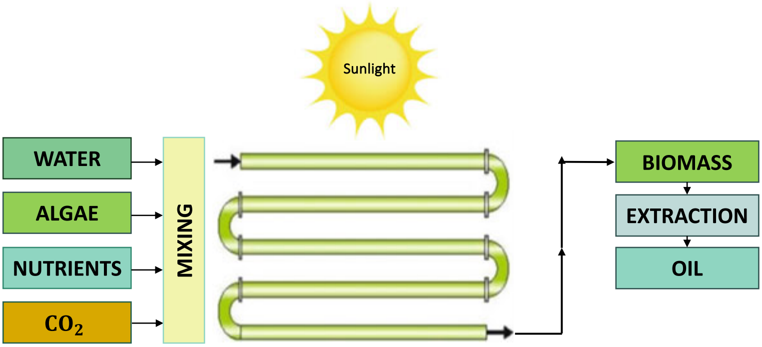

Fig. 20.3 Photobioreactor system for growing algae. Diagram shows the constituents of a tubular photobioreactor

Algae Cultivation in Closed System Photobioreactor

Cultivating microalgae in a closed system refers to a cultivation method where microalgae are grown in containers isolated from the external environment, such as photobioreactors (PBR) or tube bioreactors (Fig. 20.3) (Benner et al. 2022). Closed systems offer several advantages over open systems, such as better control over environmental conditions, protection from contamination, and higher photosynthetic efficiency. Here is how to perform microalgae cultivation in a closed system:

(1) Selecting a suitable photobioreactor or closed system: There are various types of photobioreactors, such as tubular PBRs, flat-plate PBRs, and hybrid PBRs that can be adjusted according to the cultivation needs and objectives.
(2) Preparing the inoculum: The inoculum is a collection of microalgae ready to be added to the culture medium through the inoculation process. The inoculum usually comes from existing algal cultures or isolated from natural sources. Microalgae isolated from the natural environment can be propagated on a laboratory or pilot scale to prepare sufficient inoculum under healthy and contamination-free conditions. The steps for isolating microalgae from the environment include:

    (a) Comprehensive sampling: Samples of water or substrate containing microalgae from the environment (e.g., lakes, ponds, or coastal waters) should be taken from various depths and sampling points to increase the likelihood of finding diverse microalgal species.
    (b) Initial separation: Methods like centrifugation or filtration are employed to separate microalgae from solid particles and other contaminants in the sample. The aim is to concentrate microalgae and facilitate the subsequent isolation process.
    (c) Inoculation: Microalgae are administered into suitable artificial culture media, such as Walne, f/2, or BG-11. The culture is then incubated under appropriate light and temperature conditions for microalgae growth.

(d) Colony isolation: Subsequent to the microalgae growth in the culture media, single colonies are isolated from the culture media using serial dilution or agar streaking methods to obtain pure algal colonies consisting of a single species to avoid cross-contamination.

e) Purification. After acquiring untainted microalgal colonies, further purification can be done, such as single-cell isolation or cryopreservation, to ensure the authenticity and stability of the isolated microalgal species.

(f) Identification and characterization: Identification of the isolated microalgal species can be done using morphological and/or genetic techniques, such as microscopy, pigment analysis, or DNA sequencing. Characterization of microalgal species, including growth, photosynthesis, and biochemical composition testing, is necessary to understand their important properties for further desired applications.

(g) Pre-cultivation. Microalgae are then ready to be cultivated on a laboratory scale using Erlenmeyer flasks, test tubes, or small-scale photobioreactors. The objective is to optimize growth conditions and prepare adequate inoculum for cultivation in large-scale photobioreactors.

(h) Cultivation in photobioreactor: Subsequently, microalgae are all set to be inoculated into the prepared photobioreactor, which already contains the fitting culture media (Dewi et al. 2014).

(3) Preparing the culture media: The culture media should be tailored to the needs of the microalgal species to be cultivated. Culture media are mixtures of nutrients and chemicals required for the growth and development of microorganisms, including microalgae. Culture media can be divided into two main categories, namely natural and artificial culture media, as follows:

(a) **Natural culture media**: These are media or compounds that naturally contain the nutrients and chemical components required for microalgal growth, e.g., seawater, freshwater, and nutrient-rich wastewater (Silva et al. 2014). In natural culture media, microalgae rely on existing nutrients in the environment, such as nitrogen, phosphorus, and trace elements. The advantages of natural culture media include lower costs and simpler processes since the natural nutrients are readily available in the environment. However, it often lack control and may contain contaminants or other microorganisms that can interfere with microalgal growth.

(b) **Artifical culture media**: These are mixtures of nutrients and chemicals prepared artificially to promote microalgal growth. They are typically made by adding essential nutrients like carbon sources (e.g., CO_2 or sugar), nitrogen sources (e.g., nitrate or ammonium), phosphorus sources (e.g., phosphate), as well as trace elements and vitamins required for optimal microalgal growth. Various artificial culture media have been developed for microalgal cultivation, such as Walne media, f/2 media, PHM (Provasoli Haematococcus Media), and BG-11 media. Each medium has a different composition to support the growth of different microalgal species. The advantages of artificial culture media include better control over nutrient and environmental composition, which can improve microalgal growth efficiency and lessen contamination. However, artificial culture media are often more expensive and require more careful preparation compared to natural culture media.

The choice of culture media in microalgal cultivation depends on the research or production objectives, the microalgal species used, and the environmental conditions. Natural culture media may be more suitable for large-scale applications with low costs, while artificial culture media can be used for scientific studies and applications that require tighter control over nutrients and the environment.

(4) Inoculation: In the context of cultivating microalgae in an artificial medium, inoculation refers to the process of adding microalgal inoculum to the prepared culture medium in the photobioreactor to initiate algal growth and development. Inoculation is a crucial step in microalgal cultivation to ensure that the desired microalgae are present in the culture system and can grow under the provided conditions. Before inoculation, the inoculum needs to be checked for quality, density, and the absence of unwanted contaminants, such as other microorganisms or chemicals (Bani et al. 2021).
(5) Environmental parameter control: In closed systems, environmental parameters such as temperature, pH, light intensity, and gas concentrations (CO_2 and O_2) can be well regulated. Each parameter can be adjusted to the needs of the microalgal species being cultivated to optimize growth and biomass or product production.
(6) Stirring and aeration: Closed systems are usually equipped with stirring and aeration mechanisms to keep microalgae evenly dispersed and maintain optimal oxygen and CO_2 concentrations. This also aids in nutrient absorption and more efficient light exposure.
(7) Monitoring and maintenance: These measures need to carried out periodically, including providing additional nutrients when required. The photobioreactor should be kept clean to lower the risk of potential contamination that could interfere with microalgal growth.
(8) Harvesting: Once the microalgae reach the desired density, harvesting can be performed using methods such as centrifugation, filtration, or flocculation. In closed systems, harvesting is usually easier and more efficient compared to open system.
(9) Biomass processing: After harvesting, the microalgal biomass can undergo further treatment to generate products such as biodiesel, proteins, pigments, animal feed, and more.

Algae Cultivation in Open Pond

Cultivating microalgae in open ponds is one of the most commonly used methods for large-scale microalgae production. Open ponds are typically designed as pools or channels made of soil, concrete, or plastic. The following considerations need to be taken into account when cultivating microalgae in open ponds:

(1) Pond preparation: The location of the open pond should be carefully chosen to ensure good access to water sources, nutrients, and a source of energy such as sunlight. Adequate drainage and water supply systems should be in place. Before cultivation, the pond needs to be cleaned and sterilized to minimize the risk of contamination.
(2) Inoculum preparation: Desired microalgae strains should be cultivated on a laboratory or pilot scale to prepare sufficient inoculum. The inoculum must be in a healthy condition and free from contamination.
(3) Natural cultural media preparation: Natural culture media such as wastewater containing essential nutrients (e.g., nitrogen, phosphorus, sulphur) and trace elements (e.g., iron, manganese, and zinc) need to be prepared.
(4) Inoculation: The prepared inoculum should be introduced into the open pond to mix with the natural culture media. An appropriate inoculum concentration typically ranges from 0.1 to 0.5 g/L (dry weight of microalgae per liter of water).
(5) Agitation and aeration: Regular and periodic agitation in the open pond ensures even distribution of microalgae and proper access to sunlight and nutrients. Aeration can be achieved by activating air pumps or CO_2 injection systems to sustain optimal oxygen and CO_2 concentrations.
(6) Environmental parameter control: Environmental aspects such as temperature, pH, and salinity should be monitored periodically to maintain optimal growth conditions. The ideal temperature and pH vary depending on the cultivated microalgae species.
(7) Maintenance and fertilization: Additional nutrients should be added as needed to support microalgae growth. Fertilization can be done in batches or continuously, depending on the microalgae's nutrient requirements.
(8) Harvesting: Once the microalgae reach the desired density, harvesting can be performed using methods such as centrifugation, filtration, or flocculation. Gradual harvesting is preferred to minimize disruptions to the open pond conditions and ensure sustainable microalgae growth.
(9) Biomass processing: After harvesting, the microalgal biomass can undergo further treatment to yield products such as biodiesel, proteins, pigments, or polysaccharides.

20.3.2 Optimization of Cultivation Conditions (Nutrients, Light, Temperature, pH)

Some principal parameters in microalgae cultivation include light intensity, temperature, pH, gas concentration (CO_2 and O_2), nutrients, and agitation or aeration. Optimizing these factors is paramount to achieve optimal microalgae growth and desired biomass or product generation. Here is how to optimize these parameters:

(1) Light intensity: Light intensity affects photosynthesis efficiency and microalgae growth rate. To optimize it, adjust the light source to provide sufficient and

uniform intensity. In closed systems, use LED or fluorescent lights with appropriate spectra. In open ponds, ensure sufficient sunlight exposure.

(2) Temperature: Optimal temperature for microalgae growth varies among species. Too high or too low temperatures can inhibit growth and cell metabolism. Monitor temperature regularly and adjust it within the optimal range for the cultivated species, typically ranging from 20 to 30 °C (Novosel et al. 2022).

(3) pH: pH affects nutrient availability and enzyme stability within microalgae cells. The optimal pH varies among species but generally falls within the range of 7–9. Monitor pH periodically and adjust it with suitable acid or base augmentations if necessary (Latsos et al. 2021).

(4) Gas concentration (CO_2 and O_2): CO_2 concentration influences photosynthesis rate, while O_2 concentration affects cell respiration. To optimize gas concentration, use a well-designed aeration system to maintain optimal CO_2 and O_2 levels. In closed systems, CO_2 supply can be directly controlled.

(5) Nutrients: Microalgae require nutrients such as nitrogen, phosphorus, sulfur, and trace elements like iron, manganese, and zinc. Nutrient availability determines growth rate and microalgae biomass composition. Use culture media containing the required nutrients and add supplementary nutrients during cultivation if needed.

(6) Agitation or aeration: Agitation and aeration affect nutrient uptake, light exposure, and gas concentration. To optimize agitation and aeration, use suitable pumps, impellers, or air bubble systems to create sufficient and uniform flow in the cultivation system.

Optimizing these parameters can be achieved through systematic experimentation and regular monitoring of cultivation conditions. The use of statistical approaches, such as response surface analysis or the Taguchi method, can also help identify the optimal parameter combinations for achieving satisfactory microalgae growth. Both statistical methods are useful in reducing the number of required experiments and obtaining maximum information about the effects of different parameters on the desired outcomes, such as productive microalgae growth.

(1) Response Surface Analysis (RSM) is a statistical method used to model and analyze the relationship between a response variable (output) and several independent variables (inputs). In the context of microalgae cultivation, response variables may include growth rate, biomass productivity, or secondary metabolite production, while independent variables include light intensity, temperature, pH, gas concentration, nutrients, and agitation or aeration. RSM involves the following steps:

    (a) Designing experiments, comprising different combinations of independent variables using factorial design, Box-Behnken design, or Central Composite design.

    (b) Collecting data through experiments according to the designed experimental setup and recording the results of the response variables.

(c) Building a mathematical model from the collected data by estimating regression coefficients using multiple regression analysis.
(d) Performing parameter optimization. The developed mathematical model from the previous step serves as the basis for identifying the optimal parameter combinations that will yield the desired response.

(2) **Taguchi Method** is a simpler approach to optimize a process using orthogonal experimental designs. This method focuses on reducing process variability and improving product quality by identifying the optimal parameter combinations. The steps in the Taguchi method include:

(a) Designing experiments by selecting an appropriate orthogonal experimental design based on the number of independent variables and desired levels.
(b) Collecting data through experiments according to the orthogonal experimental design and recording the results of the response variables.
(c) Analyzing the results using analysis of variance (ANOVA) to evaluate the influence of independent variables on the response variable and identify the most significant factors.
(d) Performing parameter optimization based on the analysis results and the influence of factors on the response variable. Dengan menggunakan pendekatan statistik seperti RSM atau metode Taguchi, kombinasi parameter optimal untuk pertumbuhan mikroalga yang baik dapat diidentifikasi secara efisien, sehingga memungkinkan peningkatan produktivitas dan efisiensi dalam proses kultivasi mikroalga.

By using statistical approaches such as RSM or the Taguchi method, the optimal parameter combinations for good microalgae growth can be efficiently identified, enabling increased productivity and efficiency in the microalgae cultivation process.

20.3.3 Algal Biomass Separation and Purification Techniques

The objective of algal biomass separation and purification techniques is to separate microalgae biomass from the culture medium and generate high-quality products for various applications. Microalgae have the potential to yield a wide range of high-value products, such as proteins, pigments (e.g., chlorophyll and carotenoids), omega-3 fatty acids, and bioenergy sources like biodiesel, biogas, and bioethanol (Salami et al. 2021).

The process of separating and purifying algal biomass involves the following critical steps:

(a) Biomass Concentration: In this stage, microalgae biomass is concentrated from the liquid culture by decreasing the volume of water. Some commonly used techniques for algal biomass concentration are centrifugation, flotation, filtration, and flocculation.
(b) Drying: After biomass concentration, the remaining water in the algal biomass needs to be removed to reduce transportation and storage costs. Drying also improves product stability and facilitates further processing. Commonly used drying techniques include spray drying, drum drying, freeze drying, and air drying.
(c) Extraction: The extraction process is used to separate specific components from algal biomass, such as proteins, pigments, or lipids, depending on the desired product. Commonly used extraction techniques include solvent extraction, supercritical extraction, enzymatic extraction, and mechanical extraction.
(d) Purification: After extraction, the resulting products often contain contaminants or unwanted components. Purification processes are necessary to enhance the quality and purity of the products. Commonly used purification techniques include chromatography, precipitation, crystallization, and ultrafiltration.

By employing algal biomass separation and purification techniques, high-value products obtained from microalgae can be utilized in various industrial applications, such as food, animal feed, nutraceuticals, pharmaceuticals, cosmetics, and bioenergy.

20.4 The Process of Converting Algae Biomass into Energy

20.4.1 Fermentation (Production of Bioethanol, Biobutanol, Biogas)

Production of Bioethanol

The conversion of algal biomass into bioethanol through fermentation involves several essential phases, commonly comprising pre-processing, hydrolysis, fermentation, and separation or purification of bioethanol. The steps are explained as follows (Fig. 20.4):

(1) Pre-processing: In this stage, the collected algal biomass undergoes a drying process to reduce its water content. Drying can be achieved through methods such as solar drying, oven drying, or spray drying. Subsequently, the algal biomass is crushed into smaller particles to boost enzyme accessibility during the hydrolysis stage.
(2) Hydrolysis: The purpose of hydrolysis is to break down polymers (such as cellulose, hemicellulose, and starch) in the algal biomass into simpler sugar monomers, such as glucose and fructose. Hydrolysis can be performed through enzymatic, chemical, or combined methods. Frequently used enzymes in the enzymatic hydrolysis process include cellulase, hemicellulase, and amylase.

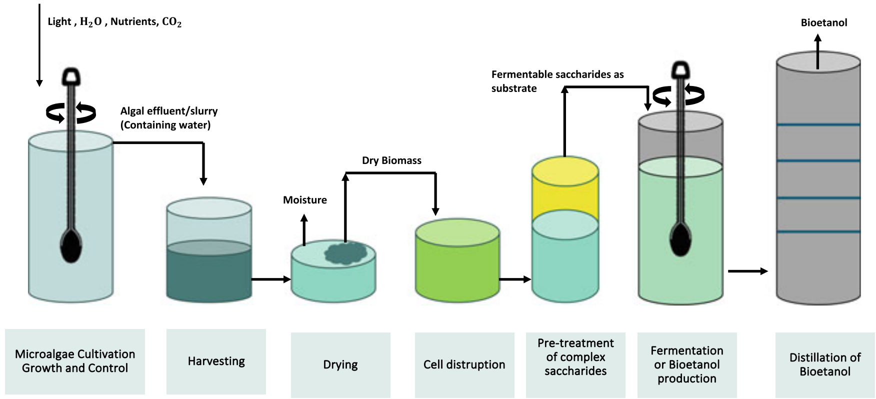

Fig. 20.4 Schematic representation of bioethanol production from microalgae feedstocks

(3) Fermentation: The simple sugars produced during the hydrolysis are then fermented by microorganisms, such as *Saccharomyces cerevisiae* (yeast), to yield ethanol and carbon dioxide. This process can be carried out aerobically or anaerobically, depending on the type of microorganism used. Fermentation typically takes several days to around one week, depending on the conditions and type of microorganism.
(4) Separation and purification: After fermentation is complete, the resulting mixture of ethanol and water needs to be separated and purified. The typical separation process is distillation, where ethanol and water are separated based on their difference in boiling points. Following the distillation, ethanol may still contain a small amount of water and other impurities. Further purification processes, such as dehydration using molecular sieves or adsorbents, may be required to produce ethanol with the desired quality for specific applications.

The bioethanol produced from algae can be used as an environmentally friendly alternative fuel, either in its pure form or as a blend with fossil fuels, such as gasoline. The use of bioethanol has the potential to mitigate greenhouse gas emissions and decrease dependence on fossil fuels.

Production of Biobutanol

The conversion of algal biomass into biobutanol through fermentation involves several primary steps that are similar to the bioethanol production process, consisting of pre-processing, hydrolysis, fermentation, and separation or purification of biobutanol, as follows:

(1) Pre-processing: In this stage, the collected algal biomass undergoes a drying process to reduce its water content. Subsequently, the algal biomass is crushed into smaller particles to enhance enzyme accessibility during the hydrolysis stage.

(2) Hydrolysis: The purpose of hydrolysis is to break down polymers (such as cellulose, hemicellulose, and starch) in the algal biomass into simpler sugar monomers, such as glucose and fructose. Hydrolysis can be performed through enzymatic, chemical, or combined methods.
(3) Fermentation: The simple sugars yielded during the hydrolysis are then fermented by specific microorganisms capable of generating biobutanol. One of the common microorganisms used for biobutanol production is *Clostridium acetobutylicum*, which undergoes the ABE (acetone, butanol, and ethanol) fermentation procedure. In this process, the microorganism consumes sugars and produces acetone, biobutanol, and ethanol as the main products.
(4) Separation and purification: After fermentation is complete, the mixture of biobutanol, acetone, ethanol, and water needs to be separated and purified. The common separation process used is distillation, where biobutanol, acetone, and ethanol are separated based on their difference in boiling points. Further purification, such as extraction with solvents or azeotropic distillation processes, may be required to produce biobutanol with the desired quality for specific applications.

Biobutanol generated from algae has several advantages over bioethanol, such as higher energy density, better compatibility with existing fossil fuel infrastructure, and lower hygroscopicity. The use of biobutanol as an alternative fuel has the potential to diminish greenhouse gas emissions and dependence on fossil fuels. However, biobutanol production through algal fermentation is still in the research and development stage, and several technical and economic challenges need to be addressed before this technology can be commercially applied.

Production of Biogas

The conversion of algal biomass into biogas through fermentation involves several important steps, including pre-processing, anaerobic fermentation, and biogas purification; each of which is described as follows (Fig. 20.5):

(1) Pre-processing: During this stage, the collected algal biomass undergoes drying (if necessary) to reduce its moisture content. Subsequently, the algal biomass is fragmented into smaller particles to enhance microorganism accessibility during anaerobic fermentation.
(2) Anaerobic fermentation: This process converts algal biomass into biogas—primarily composed of methane and carbon dioxide—by anaerobic microorganisms in an oxygen-free environment. Anaerobic fermentation involves several stages of reactions, comprising hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Han et al. 2019).
    (a) Hydrolysis: Large polymers in algal biomass, such as proteins, lipids, and polysaccharides, are broken down into smaller monomers by extracellular enzymes produced by hydrolytic microorganisms.
    (b) Acidogenesis: The monomers resulting from hydrolysis are further converted into volatile organic acids, such as acetic acid, propionic acid,

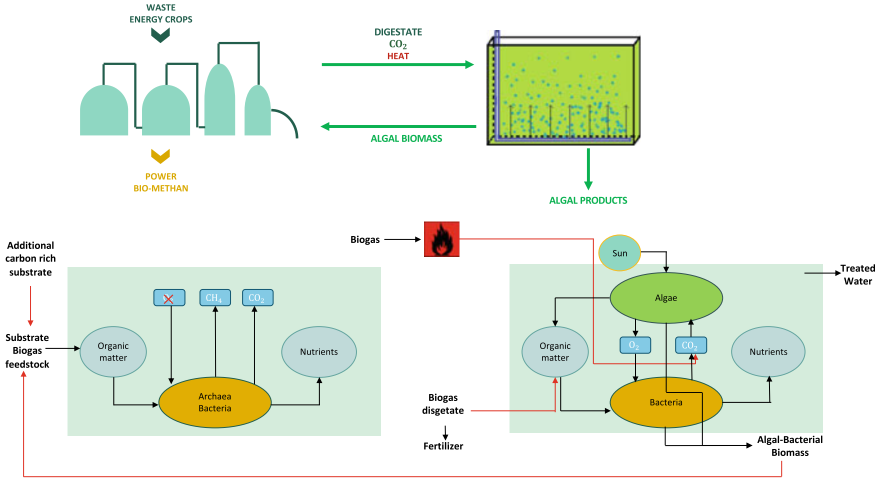

Fig. 20.5 Biogas from algae

and butyric acid, as well as gases like hydrogen and carbon dioxide by acidogenic microorganisms.

(c) Acetogenesis: In this stage, volatile organic acids and hydrogen are converted into acetic acid, hydrogen, and carbon dioxide by acetogenic microorganisms.

(d) Methanogenesis: Finally, methanogens—microorganisms that produce methane—convert acetic acid, hydrogen, and carbon dioxide into methane and carbon dioxide.

(3) Biogas purification: The biogas generated from algal anaerobic fermentation typically contains methane (CH_4), carbon dioxide (CO_2), as well as small amounts of contaminants like hydrogen sulfide (H_2S) and nitrogen (N_2). To improve biogas quality, further purification is required. Biogas purification processes involve the removal of carbon dioxide, hydrogen sulfide, and other contaminants using methods such as water scrubbing, chemical absorption, or membrane technologies.

Biogas yielded from algae can serve as an environmentally-friendly alternative fuel, either in its pure form or as a blend with natural gas. Its utilization has the potential to lessen greenhouse gas emissions and dependence on fossil fuels. Moreover, the nutrient-rich byproduct from anaerobic fermentation can be utilized as organic fertilizer.

20.4.2 Gasification (Syngas Production)

Gasification is the conversion of algal biomass into synthesis gas (syngas), rich in hydrogen (H_2) and carbon monoxide (CO). This process involves heating biomass in an environment with limited oxygen supply, preventing complete combustion (Verma and Mishra 2020). The conversion of algal biomass through gasification unfolds as follows:

(1) Pre-processing: During this stage, collected algal biomass undergoes drying to reduce its moisture content and enhance gasification efficiency. Subsequently, the algal biomass is fragmented into smaller particles to facilitate heating and conversion into syngas.
(2) Gasification: Algal biomass gasification takes place at high temperatures (between 800 and 1000 °C) within a gasification reactor. This reactor can be of various designs, such as downdraft, updraft, fluidized bed, or plasma gasification, depending on specific objectives. During gasification, the algal biomass is heated in an environment with limited oxygen supply, typically using air, pure oxygen, or steam as the gasification agent. This heating induces an endothermic chemical reaction that breaks down the biomass into syngas, comprising hydrogen, carbon monoxide, methane, and small amounts of other gases like nitrogen and carbon dioxide.
(3) Syngas purification: Syngas produced from the gasification may contain contaminants such as tar, solid particles, and acidic gases (such as H_2S and CO_2). Before syngas can be utilized as a feedstock for chemical or fuel production, a purification process is required to remove these contaminants. Syngas purification involves various technologies, such as wet scrubbing, dry scrubbing, or adsorption using media like activated carbon or zeolite.
(4) Syngas utilization: The syngas yielded from algal biomass gasification can be used as a feedstock to generate various products, such as hydrogen, methanol, or synthetic fuels through the Fischer–Tropsch process. Additionally, syngas can be utilized as fuel in gas turbines or internal combustion engines to generate electricity.

Gasification of algal biomass offers several advantages, including more efficient conversion compared to anaerobic fermentation and flexibility in generating diverse end products (Ebhodaghe et al. 2022). However, technical and economic challenges, such as the cost of algal biomass production and processing, need to be addressed before algal gasification can be implemented on a large commercial scale.

20.4.3 Lipid Extraction (Biodiesel Production)

The conversion of algal biomass into biodiesel through lipid extraction involves several essential steps (Fig. 20.6), consisting of pre-processing, lipid extraction, lipid conversion into biodiesel, and biodiesel purification, described as follows:

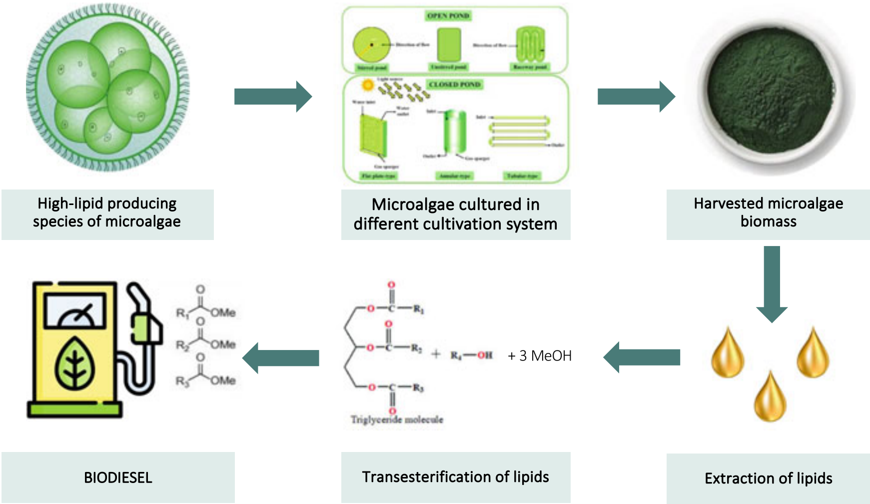

Fig. 20.6 Biodiesel production from microalgae

(1) Pre-processing: During this stage, collected algal biomass undergoes drying to reduce its moisture content. Subsequently, the algal biomass is fragmented into smaller particles to enhance lipid extraction efficiency.
(2) Lipid extraction: The goal of the extraction process is to separate lipids (fats) from the algal biomass. Lipid extraction can be carried out using organic solvents such as hexane, ethanol, or dichloromethane. Alternative methods include supercritical extraction using CO_2, ultrasound-assisted extraction, or microwave-assisted extraction (Sultana et al. 2023). After the extraction process, lipids are separated from the algal biomass, and the solvent is removed, typically through evaporation.
(3) Lipid conversion into biodiesel: The obtained lipids from the algal biomass are then converted into biodiesel through the transesterification process. In this phase, lipids are mixed with alcohol (usually methanol or ethanol) and a catalyst (usually sodium or potassium hydroxide). The reaction between lipids and alcohol produces methyl (or ethyl) esters, known as biodiesel, and glycerol as a byproduct.
(4) Biodiesel purification: After the transesterification process, the resulting mixture of biodiesel and glycerol needs to be separated and purified. Separation is usually accomplished through decantation, centrifugation, or membrane separation. Following the separation, biodiesel may still contain small amounts of contaminants like alcohol, water, and catalyst. Further purification processes, such as washing with water or drying using adsorbents, may be necessary to produce biodiesel with the desired quality for specific applications.

Biodiesel generated from algae can serve as an environmentally-friendly alternative fuel, either in its pure form or blended with fossil diesel fuel. Its utilization has the potential to reduce greenhouse gas emissions and dependence on fossil fuels.

20.5 Energy Storage and Technology Applications

20.5.1 Concept and Types of Energy Storage Technologies (Batteries, Capacitors, Flywheels, Hydro Pumps)

The concept of energy storage involves converting energy from easily generated forms into forms that can be stored and used as needed. Energy storage plays a vital role in managing the imbalance between energy demand and supply, enhancing the reliability of energy systems, and supporting the integration of intermittent renewable energy sources. Various energy storage technologies have been developed and can be classified into several categories based on how energy is stored and released. Some types of energy storage technologies include:

(1) Mechanical energy storage

   (a) Potential energy storage, for example, Pumped Hydro Energy Storage (PHES), where water is pumped to a higher reservoir during times of excess energy supply and released through turbines during periods of increased energy demand.
   (b) Kinetic energy storage, such as a flywheel, where electrical energy is used to rotate a heavy wheel at high speed, and the kinetic energy stored in the wheel can be converted back into electricity through a generator when needed (Sultana et al. 2023).

(2) Electrical energy storage

   (a) Capacitive energy storage, exemplified by capacitors, where electrical energy is stored in the electric field between two conductive plates separated by an insulator.
   (b) Inductive energy storage, like Superconducting Magnetic Energy Storage (SMES), where electrical energy is stored in the magnetic field generated by electric current flowing through superconductor coils.

(3) Electrochemical energy storage

   (a) Batteries, which store energy in the form of chemical energy through reversible redox reactions. Common types of batteries used for energy storage include lithium-ion, nickel–cadmium, and lead-acid batteries.
   (b) Fuel cells, which produce electrical energy through electrochemical reactions between a fuel, such as hydrogen, and an oxidant like oxygen.

(4) Thermal energy storage, which involves storing energy in the form of heat or cold. Examples include hot water storage tanks, where thermal energy from sources like solar thermal panels or heating systems is stored for later use.
(5) Chemical energy storage, where electrical or thermal energy is converted into chemical substances that are stored and then reconverted into energy when required.

20.5.2 Integration of Algal Biomass with Energy Storage Technologies

Integration of algal biomass with energy storage technologies can optimize the use of renewable energy sources and lower the environmental impact of energy systems (Beal et al. 2018). Several instances of this integration include:

(1) Production of biogas and chemical energy storage: Biogas is converted into a form of energy that can be chemically stored and later utilized as needed. One of the methods to achieve this objective is by converting biogas into a more easily storable fuel, such as hydrogen or synthetic methane, which can then be stored and used within a chemical energy storage system.

  (a) Conversion of biogas into hydrogen: Biogas—primarily composed of methane (CH_4) and carbon dioxide (CO_2)—can be transformed into hydrogen through a process called Steam Methane Reforming (SMR). In this process, methane reacts with steam at high temperatures in the presence of a catalyst, producing hydrogen and carbon dioxide. The generated hydrogen can be stored in either gaseous or liquid form at low temperatures and pressures. This hydrogen can then be used as a fuel within chemical energy storage systems, such as hydrogen batteries or fuel cells.
  (b) Conversion of biogas into synthetic methane (power-to-gas): One approach to integrate biogas production with chemical energy storage is through the concept of power-to-gas. In this process, hydrogen generated from water electrolysis or steam methane reforming is combined with carbon dioxide from biogas to produce synthetic methane. Synthetic methane can be stored in existing natural gas infrastructure and used as fuel for electricity generation, heating, or transportation. This approach enables large-scale and long-term energy storage.
  (c) Chemical energy storage system: Energy stored in the form of hydrogen or synthetic methane can be utilized within chemical energy storage systems, such as batteries or fuel cells, to generate electricity as needed. Chemical batteries like lithium-ion batteries or redox flow batteries can store chemical energy in the form of electric charge and release it as electricity when required. Hydrogen or synthetic methane fuel cells can directly convert chemical energy into electrical energy through electrochemical reactions, providing higher efficiency and longer operating times.

(2) Production of biodiesel and chemical energy storage: Microalgae biomass or other raw materials are converted into biodiesel, which can then be stored and used as an efficient and environmentally friendly energy source. Biodiesel is a liquid fuel that can be used as an alternative or blended with conventional diesel fuel. The integration of biodiesel production with chemical energy storage proceeds as follows:

   (a) Biodiesel production: Biodiesel is produced from microalgae oil or other feedstock through a process called transesterification. In this process, triglycerides in the oil react with alcohol (such as methanol) in the presence of a catalyst to produce methyl ester (biodiesel) and glycerol as a byproduct. The biodiesel produced has physical and chemical properties similar to diesel fuel, enabling easy storage and utilization within chemical energy storage systems (Mahmood et al. 2022)
   (b) Chemical energy storage in the form of biodiesel: Biodiesel serves as a form of chemical energy storage because the energy contained in its chemical bonds can be utilized when biodiesel is consumed as fuel. Biodiesel can be stored in conventional fuel storage tanks and used in diesel engines without significant modifications. Moreover, biodiesel offers the advantage of lower greenhouse gas emissions and better biodegradability compared to conventional diesel fuel.
   (c) Applications in energy storage systems: Stored biodiesel can be used as fuel in various applications, such as electricity generation, heating, and transportation. In the context of energy storage, biodiesel can serve as a backup energy source or be used to generate electricity when there is an increase in electricity demand or when renewable energy supply is insufficient. Additionally, biodiesel can be utilized in hybrid renewable energy storage systems, combining renewable energy sources like solar, wind, or hydro with chemical fuel-based energy storage systems to achieve higher reliability and efficiency (Dash et al. 2023).

(3) Production of syngas and chemical energy storage. The production of syngas (synthesis gas) from microalgae biomass involves converting this biomass into a synthetic gas consisting of hydrogen (H_2), carbon monoxide (CO), small amounts of methane (CH_4), and carbon dioxide (CO_2) through the gasification process. In other words, syngas, or synthesis gas, is a gas mixture rich in hydrogen (H_2) and carbon monoxide (CO) produced from the gasification of microalgae biomass or other carbon feedstocks. The integration of syngas production with chemical energy storage proceeds as follows:

   (a) Syngas production: Syngas is generated through gasification, where microalgae biomass or other carbon feedstocks are subjected to high-temperature treatment in a limited oxidation atmosphere. This process yields syngas, which can be used as fuel or as a raw material in other chemical processes, such as the production of methanol, ammonia, or Fischer–Tropsch fuels.

(b) Chemical energy storage in the form of syngas: Syngas can be stored as chemical energy because the energy contained in its chemical bonds can be utilized when syngas is consumed as fuel or as a raw material in other chemical processes. Syngas storage can be achieved in pressurized tanks at appropriate temperature and pressure or by converting syngas into more easily storable and transportable forms, such as synthetic methane, methanol, or ammonia.
(c) Applications in energy storage systems: Stored syngas can be used as fuel in various applications, such as electricity generation, heating, and transportation. In the context of energy storage, syngas can serve as a backup energy source or be used to generate electricity during periods of increased demand or when renewable energy supply is insufficient. Syngas can also be utilized in hybrid renewable energy storage systems, combining renewable energy sources like solar, wind, or hydro with chemical fuel-based energy storage systems to achieve higher reliability and efficiency.

(4) Integration with thermal energy storage: Thermal energy yielded from the conversion of microalgae biomass (e.g., direct combustion, gasification, or fermentation) can be stored in thermal energy storage media (e.g., water, molten salts, or phase change materials). The stored thermal energy can be used to produce steam and generate electricity through steam turbines or for other heating and cooling applications. The thermal energy storage media are described as follows:

(a) Water is a commonly used thermal energy storage medium. Thermal energy generated from the conversion of microalgae biomass is transferred to water, which is then stored in insulated tanks. This hot water can be used for heating applications (Pagkalos et al. 2020; Zakeri et al. 2022).
(b) Molten salts are mixtures of salts with relatively low melting points. Molten salts can absorb and store thermal energy in the form of latent heat when they melt and release this energy when they solidify. Molten salts have higher thermal energy storage capacity compared to water and can store energy at higher temperatures.
(c) Phase change materials (PCMs) are substances that store and release thermal energy during a phase change (e.g., melting and solidification). PCMs can be tailored to store thermal energy at specific temperatures, and they have a higher thermal energy storage capacity compared to water or molten salts.

(5) Integration with electrical energy storage. Electrical energy produced from the conversion of microalgae biomass (via biogas or biodiesel combustion in internal combustion engines or gas turbines) can be stored in electrical energy storage systems, such as batteries or flywheels. The stored electrical energy can be used to address fluctuations in energy supply and demand and to enhance the reliability of the energy system.

(a) Batteries are electrical energy storage devices that convert chemical energy into electrical energy. Electrical energy generated from the conversion of microalgae biomass, like biogas or biodiesel combustion, can be stored in batteries for later use. Batteries offer several advantages, such as the ability to store energy for extended periods, ease of installation, and flexibility in terms of storage capacity. Commonly used batteries in energy storage applications include lithium-ion batteries lead-acid batteries, nickel–cadmium batteries, redox flow batteries.

(b) Flywheels are electrical energy storage devices that store energy in the form of kinetic energy (Fig. 20.7). Electrical energy generated from the conversion of microalgae biomass can be stored in a rapidly rotating flywheel. When electrical energy is needed, the flywheel slows down, and the kinetic energy stored in the flywheel is converted back into electrical energy through a generator. Flywheels are efficient short-term energy storage solutions with longer lifespans compared to batteries. However, flywheel energy storage capacity is lower than that of batteries, and the installation and maintenance costs of flywheels can be higher.

Integrating algae biomass with energy storage technologies can help create a more flexible, sustainable, and environmentally friendly energy system. Combining bioenergy production with various types of energy storage (chemical energy, thermal energy, electrical energy) offers flexible and efficient solutions to manage fluctuations in renewable energy generation and meet varying energy demands. Furthermore, this

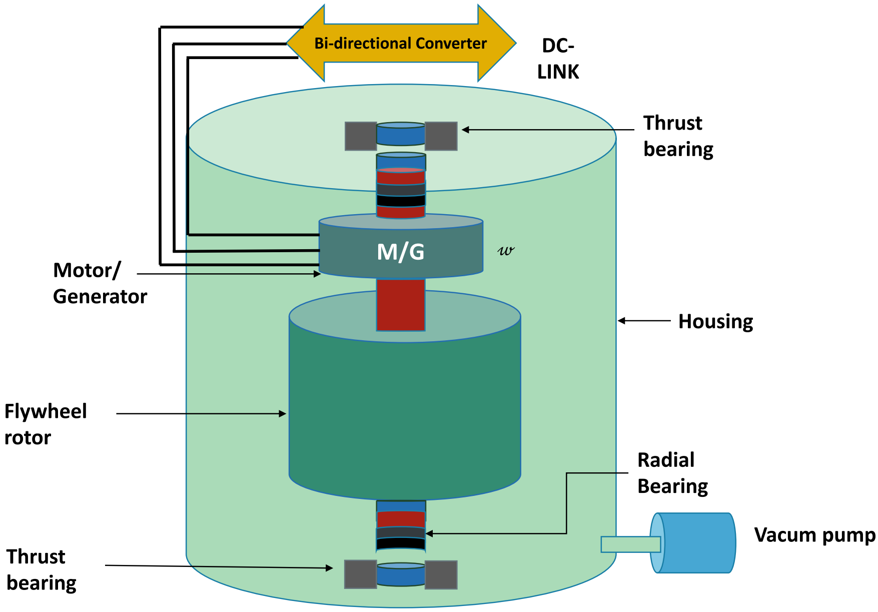

Fig. 20.7 Flywheel energy storage system

technology can contribute to mitigating greenhouse gas emissions and transitioning to a sustainable energy system. However, certain technical and economic challenges need to be addressed before this integration can be commercially applied on a large scale.

20.5.3 Application and Case Studies of Algae-Based Energy Storage Technologies

While algae-based energy storage applications are still in the research and development phase, several case studies have shown the potential of this technology in various sectors. Some applications and case studies related to algae-based energy storage technologies are as follows:

Microgrid and Isolated Energy Systems

Integrating algae biomass with energy storage technologies can be highly beneficial in microgrid scenarios or isolated energy systems, particularly in remote or island regions. A microgrid is an independent electrical network that can operate separately from the main grid, combining various renewable energy sources and energy storage systems (Santos et al. 2022). In remote or island regions, the availability of fossil fuel sources can be a challenge. Algae biomass serves as a local energy source that can be cultivated and converted into biogas, biodiesel, or bioethanol. By using local energy sources, the microgrid system can decrease dependence on imported fossil fuels and transportation costs.

Integrating algae biomass with other renewable energy sources, such as solar, wind, and hydro, in the microgrid system enhances source diversification. With a variety of energy sources, the system becomes more resilient to fluctuations in energy supply and can overcome disruptions in specific energy sources. Energy storage technologies like batteries and flywheels allow energy generated from algae biomass conversion to be stored and used as needed. This is crucial in microgrid systems, considering that energy supply and demand may vary over time. Energy storage also helps manage fluctuations in renewable energy supply, such as solar and wind.

Using algae biomass as an energy source reduces greenhouse gas emissions and enhances the sustainability of the energy system. In the microgrid system, converting algae biomass into biogas, biodiesel, or bioethanol results in lower emissions compared to burning fossil fuels (Jeswani et al. 2020; Osman et al. 2021). In some studies, algae biomass is used to yield biogas, which is then utilized to generate electricity using a gas generator. In certain cases, algae biomass can be cultivated using nutrient-rich wastewater, diminishing water pollution and recovering resources that would otherwise go to waste. This process can also aid in wastewater treatment and decrease wastewater treatment costs.

Integration with Renewable Energy Systems

In several studies, algae biomass is combined with other renewable energy technologies, such as solar and wind energy, to create hybrid energy systems. In these systems, energy from various sources like solar, wind, and algae biomass is combined to enhance the reliability and efficiency of energy supply.

In hybrid energy systems, nutrient-rich wastewater can be used for algae growth. This not only helps reduce water pollution but also cuts down on the nutrient input costs for algae growth. Renewable energy sources like solar and wind tend to be fluctuating and weather-dependent. In hybrid energy systems, algae biomass can be converted into biogas or biodiesel, serving as a backup energy source when energy from renewable sources is unavailable. This enhances the energy system's reliability and reduces dependence on fossil fuel sources. Hybrid energy systems involving algae biomass and other renewable energy sources can overall improve energy efficiency. In some cases, heat produced from algae biomass conversion can be used for water or air heating, which can further be utilized in heating or cooling systems.

Use of Algae Biogas in Public Transportation

An interesting case study is the integration of biogas generated from algae in public transportation systems. In Göttingen, Germany, a successful project yielded biogas from algae grown in photobioreactors, which was then used to power public buses. This showcases the potential of this technology to lower greenhouse gas emissions and dependency on fossil fuels in the transportation sector.

Biogas produced from algae may contain contaminants such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), and water vapor (Dash et al. 2023). Prior to being used as fuel, biogas needs to be purified to decrease the content of these contaminants. Purification processes comprise absorption, adsorption, membrane, and absorption technologies (Dash et al. 2023; Paglini et al. 2022). Once purified, the generated methane can be used as fuel in public vehicles, such as buses, trucks, or taxis. Some vehicles may require modifications to their fuel systems and engines to use biogas as an alternative fuel. In certain cases, biogas can be used in the form of compressed natural gas (CNG) or liquefied natural gas (LNG), which is easier to store and transport (Prussi et al. 2021; Shah et al. 2017).

The use of biogas in public transportation systems requires the development of suitable refueling infrastructure, including refueling stations equipped with apparatus to store, fill, and measure the biogas used in vehicles.

The use of biogas yielded from algae in public transportation offers several advantages, e.g., mitigating greenhouse gas emissions, improving energy sustainability, and potential cost savings. Algae biogas is a renewable energy source that can decrease reliance on fossil fuels and contribute to achieving greenhouse gas emission reduction targets.

Integration with the Agricultral Sector

In some case studies, algae biomass is utilized to generate energy and valuable byproducts in the context of industrial and waste treatment facilities. For instance, algae can be grown using CO_2 discharge from industrial processes, helping lower greenhouse gas emissions. The yielded algae biomass can be converted into energy and stored in energy storage systems, which can be used to meet energy needs in these facilities.

In the agricultural sector, biogas from algae can be utilized for electricity generation, heating, and cooling. For example, farmers can use algae biomass growing in ponds or photobioreactors to produce biogas through anaerobic processes. This biogas can then be stored in energy storage systems, such as batteries or flywheels and used to operate farm equipment, irrigation pumps, or heating systems for grain drying. Additionally, the residual algae biomass from biogas extraction can be incorporated as organic fertilizer for crops (Sarwer et al. 2022).

Algae can be combined with other renewable energy technologies, such as solar panels or wind turbines, to create hybrid energy systems that provide more stable and sustainable energy for agricultural operations (Morales et al. 2019). Energy storage systems enable farmers to optimize energy consumption and decrease dependence on the electrical grid. Agricultural wastewater, such as effluents from washing and processing agricultural produce, is rich in nutrients and can be used as a growth medium for algae. By integrating algae cultivation systems with agricultural wastewater management, farmers can diminish environmental pollution loads and simultaneously produce energy that can be stored and used for agricultural purposes.

Case studies and applications of algae-based energy storage technologies in the agricultural sector are still limited, but the potential it offers indicates that integrating this innovation can contribute to energy sustainability and efficiency in agricultural systems. Although algae-based energy storage technologies have shown promising potential in various applications, there are still several technical and economic challenges that need to be addressed before widespread adoption of this technology can be realized.

20.6 Economic, Social and Environmental Studies

20.6.1 Life Cycle Analysis and Environmental Impact Assessment

Life Cycle Analysis (LCA) and Environmental Impact Assessment (EIA) are two crucial tools used to evaluate the environmental impact and sustainability of algae-based energy storage technologies (Chowdury et al. 2020; Villacreses-Freire et al. 2022). LCA enables an overall assessment of the environmental impacts associated with all stages of the life cycle of a product or technology, from raw material extraction to final disposal. On the other hand, EIA is a systematic process used to identify, predict, and evaluate the environmental impacts of a proposed project or activity. Several aspects that need to be taken into account in LCA and EIA related to algae-based energy storage technologies are as follows:

(1) Resources and raw materials: The assessment should consider the resources used in algae cultivation, e.g., water, land, nutrients, and energy. LCA should comprehend the efficiency of resource utilization and the potential environmental impacts associated with their use, such as water eutrophication and energy consumption.
(2) Algae cultivation and harvesting: The environmental impact of algae cultivation and harvesting, including greenhouse gas emissions, water usage, and land utilization, should be evaluated in LCA. EIA should consider the potential consequences of algae cultivation activities on the local ecosystem and water quality.
(3) Conversion of algae biomass into energy: LCA should encompass emissions and energy consumption associated with the conversion of algae biomass into various energy products, such as biodiesel, biogas, or syngas. EIA should assess the impact of energy conversion facilities on air quality and the surrounding environment.
(4) Energy utilization and storage: The environmental impact of using and storing energy generated from algae biomass should be considered in LCA. EIA should assess the impact of energy storage infrastructure, such as tanks or battery systems, on the surrounding environment.
(5) End-of-life disposal and recycling: LCA should assess the environmental impact of disposing residues and byproducts from algae-based energy storage technologies. EIA should evaluate the potential impact of disposing these products on water, soil, and air quality.

By conducting LCA and EIA related to algae-based energy storage technologies, we can identify areas where environmental impacts can be minimized and improve the method to achieve greater sustainability. Moreover, the results of LCA and EIA can aid decision-making and policy planning concerning the development and implementation of algae-based energy storage technologies.

20.6.2 Cost of Production and Market of Renewable Energy from Algae

Renewable energy from algae is one of the environmentally friendly and promising sources that can replace fossil fuels. It has been explained that algae can be converted into various energy products such as biodiesel, bioethanol, biogas, and biohydrogen. Algae-based energy storage technology entails production costs and the microalgae-based renewable energy market.

Production Costs

The production costs of renewable energy from algae include raw material, technology, operational, and maintenance costs. Several factors influencing production costs are as follows:

(1) Raw materials: Algae can be obtained from natural water bodies or cultivated in laboratories. The cost of raw materials includes the price of algae, substrates, and nutrients required for algae growth.
(2) Technology: The cost of technology comprises equipment used for cultivation, algae cell separation, lipid extraction, energy conversion, and energy storage. More efficient and effective technologies will reduce production costs.
(3) Operational: Operational costs include labor, energy, and chemicals used in the production and energy storage.
(4) Maintenance: Maintenance costs include equipment maintenance and repair, as well as the management of waste generated from the production process.

Market of Renewable Energy from Algae

The market of algae-based renewable energy continues to grow as awareness of the negative impacts of fossil fuels on the environment and human health increases. Factors affecting this market are as follows:

(1) Government policies: Regulations, incentives, and government support for renewable energy development will influence the algae energy market.
(2) Demand: The demand for renewable energy from algae is influenced by changes in fossil fuel prices, environmental awareness, and increasing energy needs.
(3) Research and development: Studies and advancement of more efficient and effective technologies in the algae production and energy storage will boost the competitiveness of this energy in the market.
(4) Infrastructure: Adequate infrastructure for the distribution and storage of renewable energy from algae will support market growth.

20.6.3 Associated Social and Employment Implications

The implementation of algae-based energy storage technologies has several major social and employment impacts. It can create new jobs in various sectors, such as research and development, production, construction, maintenance of infrastructure, as well as the operation and maintenance of energy storage systems. This will increase employment opportunities, especially in areas with abundant algae resources.

The use of algae-based renewable energy as an alternative to fossil fuels can mitigate greenhouse gas emissions and air pollution (Onyeaka et al. 2021), leading to positive impacts on public health and quality of life. Furthermore, providing cleaner and renewable energy will improve energy resilience and decrease dependence on imported fossil fuels. As the algae-based energy industry grows, the demand for skilled workers will also increase, driving opportunities for education and training in related fields, such as biotechnology, chemical engineering, and environmental engineering. Improved access to high-quality education and training will help people take advantage of job opportunities created by this industry.

The implementation of algae-based energy storage technology will affect related industries, such as agriculture, fisheries, and the chemical industry. For instance, algae can be cultivated alongside food crops or used to process industrial and agricultural waste, which will help reduce environmental impacts and create additional economic value (Amir et al. 2021). The development and implementation of algae-based energy storage technology must consider social and environmental justice issues, such as equitable access to renewable energy, local community participation in decision-making, and protection of indigenous rights. The development of algae-based energy storage technology will require collaboration and partnerships between governments, industries, and research institutions at the international level. International cooperation can accelerate research and development, promote technology and knowledge transfer, and enhance the adoption and efficiency of this technology worldwide.

20.6.4 Government Regulations and Policies Regarding Algae-Based Renewable Energy

Government regulations and policies play a crucial role in the development and implementation of algae-based renewable energy. Several aspects commonly covered in government regulations and policies are as follows:

(1) Fiscal incentives: Governments often provide fiscal incentives such as taxes, subsidies, and tax credits to support research, development, and investment in algae-based renewable energy. These incentives aim to decrease production costs and increase the competitiveness of renewable energy in the market.
(2) Renewable energy standards: Some countries have adopted Renewable Portfolio Standards (RPS) or biofuel blending mandates that require energy companies or fuel users to incorporate a portion of energy from renewable sources, including algae. These standards aim to promote the adoption of renewable energy and lower greenhouse gas emissions.
(3) Environmental regulations: Governments also issue environmental regulations that affect the algae-based renewable energy industry, such as emission permits, air and water quality standards, and waste management requirements. These regulations aim to ensure that the production and use of algae-based energy do not have negative impacts on the environment and human health.
(4) Research and development: Governments often support research and development of algae-based renewable energy through funding, research facilities, and partnerships between research institutions, industries, and the government. The goal is to accelerate the development of more efficient, effective, and environmentally friendly technologies.
(5) Promotion and education: Governments also play a role in promoting algae-based renewable energy through public awareness campaigns, education

programs, and training. Promotion and education aim to raise public understanding of the benefits and potential of algae-based renewable energy and develop the skills necessary to support this industry.

(6) International cooperation: Governments need to collaborate with other countries, international organizations, and donor agencies to develop and promote algae-based renewable energy. International cooperation includes knowledge and technology exchange, joint funding for research and development projects, and the establishment of global policies and standards.

20.7 Challenges and Future of Algae-Based Renewable Energy

The challenges and barriers to adopting algae as a renewable energy source can be categorized into technical, economic, social, and environmental issues, as elaborated below.

20.7.1 Barriers to Technology Development and Adoption

Technical Challenges and Obstacles

Although algae-based renewable energy offers many benefits, there are several technical challenges and barriers that need to be addressed before this technology can be widely adopted, including:

(1) Production efficiency: The generation of renewable energy from algae still requires significant amounts of energy and chemicals, such as nutrients and carbon dioxide. Algae also require specific growth conditions and precise temperature control to achieve optimal production rates (Mahmood et al. 2022). Therefore, further research is needed to improve the production efficiency of renewable energy from algae.

(2) Supply Stability and Availability: The supply of renewable energy from algae is still not stable and is dependent on environmental factors such as weather and climate. This makes conventional energy sources more stable and reliable for meeting energy needs.

(3) Technological advancement: Production and conversion technologies for renewable energy from algae are still in the development phase, requiring further research and development of more efficient and effective technologies, including the cultivation systems, processing and purification technologies, and energy storage and distribution systems. In contrast, production technologies for conventional energy sources are already well-established and efficient, making conventional energy production cheaper and more efficient than renewable energy from algae.

(4) High Production Costs: The production costs of renewable energy from algae are still higher compared to fossil fuels. This makes renewable energy from algae less appealing in the market, requiring efforts to lower production costs through increased production efficiency and the use of more effective technologies.
(5) Scaling issues: The production of renewable energy from algae is still limited to small and restricted scales, necessitating efforts to elevate production scale to meet larger energy demands.
(6) Transportation and logistics issues: Transportation and logistics are significant challenges in distributing renewable energy from algae, especially if algae resources are located far from production centers. This requires the development of better infrastructure and transportation networks to ensure an effective and efficient distribution of renewable energy from algae.
(7) Waste management: The production of renewable energy from algae generates waste that needs proper disposal to avoid environmental pollution. Hence, effective waste management technologies and strategies are needed to minimize environmental impacts.
(8) Regulatory challenges: Inconsistent or unclear regulations and policies can hinder the development of algae-based renewable energy. Thus, cooperation with the government as well as clear and consistent regulations are needed to support the development of algae-based renewable energy.

Economic Challenges and Obstacles

The development of renewable energy from algae also faces economic challenges and obstacles in competing with conventional energy sources. Here are some economic issues that need to be addressed in adopting algae-based renewable energy:

(1) High production costs: The generation of renewable energy from algae still requires significant costs, including production, transportation, and distribution expenses. These high production costs make renewable energy from algae less competitive in the market compared to conventional energy sources.
(2) Limited production scale: The production of renewable energy from algae is still limited to small and restricted scales. The lack of production scale increases production costs and hinders the large-scale adoption of renewable energy from algae.
(3) Market uncertainty: The market for renewable energy from algae is not yet stable and can be affected by changes in fossil fuel prices. This market uncertainty drives investors reluctant to invest in the development of algae-based renewable energy.
(4) Inadequate infrastructure: Insufficient infrastructure, such as inadequate distribution networks and production facilities, can obstruct the development of renewable energy from algae. It can lead to increased production costs and delay the advancement of renewable energy technology from algae.

To tackle these economic challenges and obstacles, support from the government, industry, and society is essential to promote and develop renewable energy from algae.

This aid can include fiscal incentives, education and training programs, investment in research and development, as well as the establishment of more efficient and effective infrastructure and distribution networks. Additionally, efforts should be made to improve production efficiency and lessen the production costs of algae-based renewable energy through research and the development of more efficient technologies.

Environmental Challenges and Obstacles

The development of renewable energy from algae also faces environmental challenges and obstacles in competing with conventional energy sources. Some of the environmental hindrances that need to be addressed in adopting renewable energy from algae are as follows:

(1) Impact on water quality: The production of renewable energy from algae requires water and nutrients. Excessive withdrawal of water and nutrients from the environment can decrease water quality and trigger the growth of harmful wild algae, bringing negative impacts on the environment and society (Silaen et al. 2022).
(2) Impact on biodiversity: Extracting nutrients and water from the environment for algae-based renewable energy production can affect biodiversity in water bodies. The use of wild algae for renewable energy production can also impact marine biodiversity (Correa et al. 2017).
(3) Greenhouse gas emissions: The production and transportation processes of renewable energy from algae can result in greenhouse gas emissions if not managed properly (Arora et al. 2021; Sunaryo et al. 2023).
(4) Waste management: The production of renewable energy from algae generates waste that needs to be appropriately handled to avoid environmental pollution. This residue is typically nutrient-rich, so meticulous management is pivotal to prevent algal blooms that can disrupt the balance of aquatic ecosystems (Ali et al. 2020).
(5) Sustainable resource utilization: The development of renewable energy from algae must consider sustainable resource utilization, as it should not cause environmental degradation or unsustainable resource use.

To overcome these environmental challenges and obstacles, strict environmental management and monitoring are compulsory during the production of renewable energy from algae. Besides, there is a need for technological innovation of more environmentally friendly technologies, as well as the establishment of policies and regulations that promote sustainable and eco-friendly production of renewable energy from algae. Community engagement and participation are also requisite in decision-making and sustainable environmental management.

Social Challenges and Obstacles

In addition to technical challenges, the development of renewable energy from algae also faces social challenges and obstacles in competing with conventional energy source, including:

(1) Community and local resistance: Some communities and local groups may reject the development of renewable energy from algae due to environmental concerns, aesthetic reasons, or economic interests. Such opposition can slow down or even halt the development of renewable energy from algae in a particular area.
(2) Uncertainty in regulations and policies: Ambiguity in government regulations and policies regarding renewable energy from algae can be a barrier to adopting this technology, affecting investments, research and development, and decisions concerning the use of algae-based renewable energy.
(3) Lack of public understanding and awareness: Insufficient public understanding and awareness of the benefits of renewable energy from algae can hinder the adoption of this technology. Public education and campaign efforts can help accelerate its development and adoption.
(4) Imbalance in benefit distribution: The inequality in the distribution of benefits can influence public acceptance of renewable energy from algae. For instance, communities may not accept this innovation if its benefits are only experienced by a small group of individuals or companies.
(5) Social and environmental justice: The development of renewable energy from algae should consider social and environmental justice issues, such as the rights of indigenous communities, equitable access to renewable energy, and environmental protection. This can help reduce negative impacts and enhance positive benefits from the development of algae-based renewable energy.

To address these social challenges and obstacles, support from the government, industry, and society is needed to promote and develop renewable energy from algae in an inclusive and sustainable manner. This aid can include educational and training programs, community dialogues and participation, investment in social and environmental development, as well as the development of comprehensive and sustainable policies.

20.7.2 *Innovation and Current Research*

Recent advancements in renewable energy technology from algae encompass various aspects, ranging from improved energy conversion efficiency to cost reduction. Here are some principal developments and innovations that have the potential to transform the renewable energy sector using algae:

- Algae genetics and engineering: Advances in biotechnology and genetics allow researchers to optimize algae strains that are more efficient in producing biomass or desired fuels. Genetic engineering can also help lower contamination and enhance algae's tolerance to varying environmental conditions (Sreenikethanam et al. 2022).
- More efficient photobioreactors: Photobioreactors are technologies that enable algae growth in controlled environments. Innovations in photobioreactor design and materials can increase the efficiency of algae biomass production, reduce

costs, and enable larger industrial-scale operations (Fernández del Olmo et al. 2021).

- More effective biomass conversion methods: Research is ongoing to develop more effective algae biomass conversion approaches, such as hydrothermal processes, electrochemistry, and enzymatic methods (Han et al. 2019). Innovations in conversion technology can improve the quality and quantity of energy generated from algae.
- Integration of algae cultivation with other systems, such as wastewater treatment or carbon dioxide (CO_2) sequestration from factories, can enhance overall process sustainability and efficiency. This integration also helps mitigate greenhouse gas emissions and utilize previously unused resources.
- Utilization of byproducts such as proteins, pigments, and polysaccharides from algae conversion processes can create added value and help lessen the production costs of algae-based energy (Chiong et al. 2016).
- Collaboration between the public and private sectors, as well as international cooperation, can accelerate research and development of renewable energy technology from algae. These partnerships can also help address technical, economic, and environmental challenges related to this sector.

Future projections indicate that renewable energy from algae has the potential to become a significant energy source, particularly in replacing fossil fuels and diminishing greenhouse gas emissions. Furthermore, innovations in algae-based renewable energy technology can create new opportunities in the fields of energy, environment, and economy.

20.7.3 Strategies to Increase Efficiency and Reduce Production Costs

To address the technical challenges and barriers in adopting renewable energy from algae as a power source, it is necessary to develop strategies that enhance efficiency and decrease production costs. Several schemes that can be employed to achieve these goals in utilizing algae for energy storage technology are as follows:

(1) Advancement of production technology: One of the key strategies to increase production efficiency and reduce the costs of renewable energy from algae is the innovation of production technology. Utilizing more sophisticated production methods can boost productivity and efficiency, consequently lowering production costs.

(2) Development of processing technology: Another strategy to improve production efficiency and decrease production costs of algae-based renewable energy is the development of more efficient processing technology, as it can elevate the quality and quantity of production, leading to cost abatement.

(3) Optimal nutrient utilization: Increasing the appropriate use of nutrients can enhance productivity and efficiency of renewable energy from algae, resulting in cost reductions.
(4) Augmenting nutrient availability: Improved nutrient availability can elevate productivity and efficiency as well as decrease the costs of algae-based renewable energy.
(5) Efficient resource utilization: Employing more efficient resource management is another approach to boost production efficiency and lower costs of renewable energy from algae.
(6) Infrastructure and distribution network development: Establishing more efficient infrastructure and distribution networks can improve productivity and efficiency, ultimately leading to cost minimization.

To implement these strategies, support from the government, industry, and society is indispensable in promoting and developing renewable energy from algae.

20.7.4 Vision and Future Projection for the Algae-Based Renewable Energy Industry

From the discussions in the previous sections, algae possess significant potential as a future source of renewable energy and energy storage. Various technologies have been developed, ranging from cultivation processes, cultivation techniques, conversion technologies, to energy storage applications. The development of algae-based renewable energy industries can contribute to reducing dependence on fossil energy sources and mitigating negative impacts on the environment. Therefore, a grand vision for the renewable energy industry is necessary, where the sustainability and success of algae-based industries heavily rely on strong government investment, innovation, collaboration, and policy support. This vision can accelerate the growth of algae-based industries and create a multiplier effect on various other sectors, ultimately enhancing national economic growth. The use of algae as a renewable energy source presents several promising future visions and projections, including:

(1) Greenhouse gas emission mitigation: Algae can potentially lower greenhouse gas emissions by absorbing CO_2 from the atmosphere during photosynthesis.
(2) Large-scale algae-based fuels: Algae-based energy industries can develop large-scale production for algae-based fuels. The future projection for algae-based renewable energy industries includes creating systems capable of producing fuels like biodiesel or bioethanol from algae more efficiently, enabling them to compete with fossil fuels and reducing dependence on conventional fuels.
(3) Utilization as food and nutrition source: Algae can also be used as a nutritious food source, containing proteins, vitamins, minerals, and omega-3 fatty acids beneficial to human health. Developing algae production as safe and highly nutritious food is a future projection for achieving food security.

(4) Algae usage in industrial processes: Algae can be employed in various industrial processes to generate high-value products such as pigments, proteins, and antioxidants. This usage can expand the economic base of the algae energy industry and raise production efficiency.
(5) Technological innovation: Algae-based energy industries will continue to evolve. Future projections include developing more efficient photobioreactors and cultivation methods to increase algae harvesting yields. Additionally, processing and extraction technologies will be continuously improved to maximize the value of algae products.
(6) Collaboration between industry and research: To accelerate the development of algae-based energy industries, collaboration between industrial sectors and researchers is fundamental. Such partnership will have a positive impact through knowledge and technology exchange, addressing technical challenges, and expediting the adoption of algae-based solutions across various sectors. Some countries have begun recognizing the significant potential of the algae industries, such as the European Union (EU), which has conducted studies on algae production and its applications in Europe. Though still in the initiation phase, the EU also incorporates the algae sector in its economic strategy, namely the EU Blue Bioeconomy.
(7) Implementation of advanced biofuel technology: Algae-based energy industries also have the potential to adopt more advanced biofuel technologies such as bio-hydrogen, biobutanol, and methane yielded by algae. The use of these technologies can provide more sustainable and efficient alternatives to meet global energy demand.

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