Shailendra Kumar Arya
Madhu Khatri
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Foreword

It is with great pleasure and enthusiasm that I present this comprehensive volume on *Value Added Products from Bioalgae Based Biorefineries: Opportunities and Challenges*. This book represents a culmination of extensive research, innovative insights, and collaborative efforts dedicated to exploring the untapped potential of bioalgae in the context of biorefineries. As the editor of this compilation, I am honoured to bring together a diverse group of scholars and experts who have contributed their knowledge and expertise to shed light on the opportunities and challenges associated with this fascinating field.

The world is witnessing a paradigm shift towards sustainable and eco-friendly practices, and bioalgae have emerged as a promising candidate in the quest for renewable resources. Harnessing the power of these microscopic organisms holds the key to addressing crucial global challenges such as climate change, energy security, and resource depletion. This book delves into the multifaceted aspects of bioalgae-based biorefineries, offering readers a comprehensive understanding of the opportunities that lie within this burgeoning domain.

The journey through the pages of this book begins with a fundamental exploration of bioalgae, covering their taxonomy, physiology, and ecological significance. This serves as a crucial foundation for readers to grasp the intricacies of their potential applications in biorefineries. We then progress into the heart of the matter—the value-added products that can be derived from bioalgae through innovative biorefinery processes. From biofuels and bioenergy to high-value chemicals and pharmaceuticals, the chapters in this book provide a detailed examination of the diverse array of products that can be synthesized, paving the way for a sustainable and circular economy.

One of the distinguishing features of this compilation is its focus on the challenges and bottlenecks that researchers and practitioners may encounter in the pursuit of bioalgae-based biorefineries. Acknowledging the obstacles is crucial for devising effective strategies to overcome them. Issues such as scalability, economic viability, and technological constraints are addressed with a pragmatic approach, fostering a holistic understanding of the field.

As deeply immersed in the realms of bioalgae research, I am acutely aware of the collaborative and interdisciplinary nature of this field. The contributors to this volume bring forth a wealth of knowledge from various disciplines, including biology, engineering, chemistry, and environmental science. Their collective expertise contributes to the richness and diversity of perspectives presented in this book.

I would like to express my heartfelt gratitude to all the authors who have dedicated their time and expertise to contribute to this endeavour. Their commitment to advancing the understanding of bioalgae-based biorefineries is commendable, and I am confident that their work will inspire further research and innovation in this field.

In conclusion, *Value Added Products from Bioalgae Based Biorefineries: Opportunities and Challenges* is intended to serve as a valuable resource for researchers, students, and industry professionals seeking to explore the vast potential of bioalgae in the context of sustainable biorefineries. I hope that this compilation sparks new ideas, fosters collaboration, and contributes to the ongoing dialogue surrounding the development of a more sustainable and resilient future.

Sudarshan Sahu

Chandigarh, India

Preface

In the dynamic landscape of sustainable technologies and green innovations, the exploration of bioalgae-based biorefineries represents a significant leap towards an eco-friendlier and resource-efficient future. The book you are about to delve into, *Value Added Products from Bioalgae Based Biorefineries: Opportunities and Challenges*, is a comprehensive and timely contribution to the ever-evolving field of biotechnology.

The utilization of bioalgae, often referred to as the "green gold", has gained momentum as an invaluable resource in the pursuit of renewable energy, sustainable agriculture, and bioproduct development. This volume serves as a beacon, guiding readers through the intricate realms of bioalgae-based biorefineries, offering a nuanced understanding of the opportunities they present and the challenges they pose.

As we stand at the crossroads of environmental stewardship and technological innovation, the authors of this book navigate through the intricacies of harnessing the potential of bioalgae for the production of value-added products. The synergy between the academic rigour and industrial applicability evident in the chapters reflects a collaborative effort to bridge the gap between theory and practice.

The journey begins with an exploration of the foundational principles of bioalgae-based biorefineries, delving into the diversity of algae species, their cultivation techniques, and the underlying biochemical processes. Moving forward, the book unravels the vast array of value-added products that can be derived from algae, spanning biofuels, biofertilizers, biopolymers, and nutraceuticals, among others. Each chapter meticulously dissects the potential applications, elucidating the economic and environmental benefits that arise from the sustainable utilization of bioalgae.

Yet, as with any pioneering field, challenges are inevitable. This book does not shy away from addressing the obstacles and uncertainties that come hand-in-hand with the integration of bioalgae-based biorefineries into mainstream industries. Through insightful analyses and case studies, the authors shed light on the practical hurdles and propose innovative solutions, fostering a constructive dialogue among researchers, policymakers, and industry professionals.

In an era where the urgency to transition towards a bio-based, circular economy is paramount, *Value Added Products from Bioalgae Based Biorefineries: Opportunities and Challenges* emerges as a timely resource. It beckons scientists, engineers, entrepreneurs, and policymakers to engage in a collective effort to harness the full potential of bioalgae, ensuring a sustainable and resilient future for generations to come.

As you embark on this intellectual journey, may the pages of this book inspire new perspectives, fuel innovation, and contribute to the transformative journey towards a greener, more sustainable world.

Chandigarh, India — Shailendra Kumar Arya
Chandigarh, India — Madhu Khatri
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Shailendra Kumar Arya presently holds the position of Professor at the Department of Biotechnology Engineering within the University Institute of Engineering & Technology, Panjab University, Chandigarh, India. He attained his doctoral degree in Biotechnology from the esteemed Indian Institute of Technology, Banaras Hindu University, Varanasi, in 2010. With an affiliation dating back to 2006, Dr. Arya has been a dedicated member of Panjab University. His primary focus lies in the realm of Enzyme Engineering and Bioremediation, showcasing a profound expertise in enzymes, wastewater treatment, and sustainable development. Dr. Arya boasts an extensive publication record, contributing over 100 research articles to prestigious international journals. Furthermore, he has actively engaged in numerous international and national conferences, where he has been featured as a distinguished speaker. Leading a dynamic research group, Dr. Arya mentors both PhD and Master's students, guiding them in diverse projects encompassing Enzyme Engineering, Wastewater Treatment, Algal Studies, and Bioremediation. The collaborative efforts of his research team contribute significantly to advancing knowledge and innovation in these critical areas.

Madhu Khatri is currently working as Assistant Professor at the Department of Biotechnology, UIET, Panjab University. She received her PhD (Biomedical Engineering and Biotechnology) degree in 2012 from the University of Massachusetts, USA. During her PhD and postdoctoral training, she worked in close collaboration with Harvard School of Public Health and Northeastern University, Boston, USA. She joined Panjab University in 2014. She received the prestigious Wellcome trust/DBT IA fellowship in 2015. Dr. Khatri works in the field of Environmental Nanobiotechnology. She has expertise in the area of nanomaterial synthesis and studying their various application and environmental effects. She has published more than 60 research articles in reputed international journals and participated in various national and international conferences as a speaker. Her research group includes PhD and ME students working on interdisciplinary projects, such as in the areas of nanotoxicology, bioplastics, water purification, biosensors, and bioremediation.

Gursharan Singh is working as an Associate Professor in the Department of Medical & Laboratory Sciences, Lovely Professional University, India. He worked at UIET, Biotechnology Branch, Panjab University, Chandigarh (Sector 25-B), as an Assistant Professor (Adhoc faculty) from February 2013 to June 2017. He received his PhD from Biotechnology Department, Panjab University, Chandigarh (2009, July), and postdoctorate from South Dakota School of Mines & Technology, Rapid City, USA (January 2010 to January 2011). He also did postdoctorate from Agriculture & Agrifood, Canada, Quebec (June 2011 to June 2012). He has published more than 90 articles in scientific journals of repute. Further, his name is present in the list of 2.0% scientists of the world in the area of biotechnology for the last two consecutive years, 2022 and 2023, data released by the Stanford University, USA.

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Introduction to Algae-Based Biorefineries in the Context of Sustainable Development

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Plash Kunj, Sudarshan Sahu, and Shailendra Kumar Arya

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Abstract

Algae has proven to be the potential source of proteins, lipids and carbohydrates. Their unique chemical characteristics and the interaction with the living tissues, i.e. bioactive potential, make it an ideal choice for different industries such as nutraceuticals, food, feed and cosmetics. Also, with the latest trends evolving around the globe for the production of different compounds by green methods, algae prove to be the best fit, and to make this green synthesis sustainable the biomass can be reused making it a biorefinery approach for the production process. Algae-based biorefineries promote not only the sustainable and green methods but also the bioeconomy, i.e. it promotes the use of renewable resources from land and sea. This chapter will be focusing on different algae-based biorefineries, their working, design and need along with their advancement in recent times. Also, in this chapter different species of algae and their useful end-products will be discussed.

Keywords

Algae · Biorefinery · Sustainable development

1.1 Introduction

In 2012, the United Nations suggested 17 sustainable development goals (SDGs) that were adopted in 2015 and are to be accomplished by 2030. Sustainable development goals were the replacement to then existing Millennium development goals (MDGs) which were started in 2000 and were in existence till 2015. MDGs focused on poverty, deadly diseases, hunger, education and other development priorities but it did not focus on the economic, political and environmental issues (United Nations Development Programme n.d.). SDGs, as shown in Fig. 1.1, focuses on clean and safe environment, healthy living, social and economic aspects. The reason behind setting up these goals were increasing population, scarcity of resources, lack of policies and inadequate finances, and the aim is to provide future generation a clean, healthy and risk-free environment (Olabi et al. 2023).

Algae are aquatic organisms having diverse forms, ranging from simple single-celled to multicellular organisms. Algae are photosynthetic organisms that can grow in wide range of environment such as fresh water, terrestrial ecosystem and marine. They can tolerate variable parameters such as temperature, light intensity, pH and salinity. Algae are seen to grow in different environments such as bark of trees, sediments, soil, oceans, sea, ponds, rivers and lakes (Olabi et al. 2023). They are being used as a source of fertilisers, food and medicines from a long time but in recent times due to their high growth rates and their ability to produce large amount of lipids they are being used to produce biofuels (Vieira et al. 2022). Algae contains different organic and chemical substances also known as secondary metabolites or bioactive substances which are produced as an end-product of different metabolic processes which are then converted to biofuels such as biodiesel, bioethanol and

Fig. 1.1 Seventeen sustainability goals set by the United Nations

biomethanol that has proven to be a sustainable approach as this production do not compete with resource (Wang et al. 2023). Most commonly algae can be seen as a coupled approach for the wastewater treatment and biofuel production.

Biorefinery can be defined as a facility that integrates multiple biomass conversion processes leading to the production of bio-products. It is similar to traditional process of production in petroleum refineries but instead of producing crude oil biorefineries use biomass sources such as algae, organic waste, agriculture crops and forestry residue. The main goal of biorefinery is to convert biomass into valuable products and in return not exploiting the fossil fuels (Saral et al. 2021).

Bioeconomy can be described as an economic system that uses biological resources, principles and processes to produce a wide range of goods and services in a sustainable manner. In order to create goods that satisfy human needs, it entails harnessing the power of biological systems and processes as well as living things like plants, animals and microbes. The production of food, forestry, fisheries, agriculture and bio-based materials and energy are all included in the bioeconomy (Pacheco-Torgal 2020). Bioeconomy has some key elements such as renewable resources, sustainable practice, biotechnology and innovation, circular economy, diversification of feedstock and contribution to sustainable development.

1.2 Algae and Its Classification

Algae are broadly classified into two groups, micro- and macroalgae, as illustrated in Fig. 1.2. Microalgae are unicellular, microscopic, photosynthetic organisms that can live in fresh water, soil and saltwater; green, blue-green and golden-brown algae fall into this category. Microalgae are photosynthetic eukaryotes or prokaryotic cyanobacteria, sometimes found as nitrogen fixing organisms. They are capable of

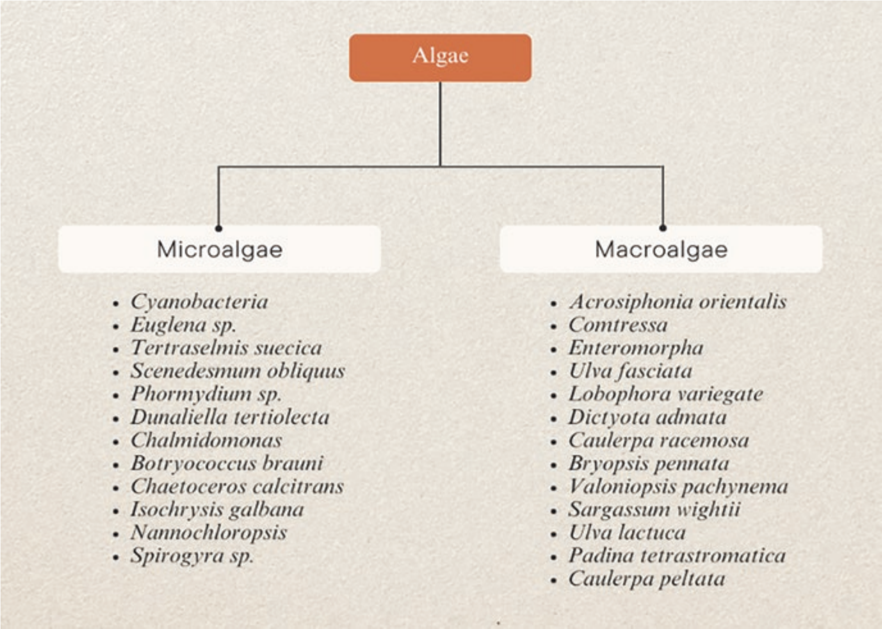

Fig. 1.2 Different types of micro- and macroalgae

carbon fixation and produce large amounts of oxygen. On the other hand, macroalgae are multicellular seaweeds that can be seen in ocean with naked eyes. These macroalgae are capable of filtering and reducing nitrates, nitrites and phosphate level. Brown, green and red algae fall under this category (Unique Benefits of Macroalgae and Microalgae in Agriculture n.d.; Jalilian et al. 2020).

Algae can be classified into eight types depending on their appearance:

1. Bacillariophyta or diatoms
2. Charophyta or stonewort
3. Chlorophyta or green algae
4. Phaeophyta or brown algae
5. Chrysophyta or golden algae
6. Cyanobacteria or blue-green algae
7. Dinophyta or dinoflagellate
8. Rhodophyta or red algae

1.2.1 Bacillariophyta or Diatoms

They are unicellular organisms belonging to the diatom algae. Diatoms appear to be like glass due to their silica wall. Diatoms are essential parts of phytoplankton, which are microscopic organisms that resemble plants and drift in aquatic environments, mostly freshwater and oceans. Some diatoms may be bottom dwellers or adhere to substrates like rocks or other aquatic vegetation, but the majority of diatoms are planktonic, or they float in the water column. Diatoms exhibit their adaptability to various ecological niches by growing on other algae or plants. Bacillariophyta have plastid that is responsible for photosynthesis; this plastid present is brownish in colour due to the presence of chlorophyll a and b along with fucoxanthin, which is a brownish pigment. These algae reproduce asexually through mitosis leading to the two daughter cells, each containing the silica content in the cell wall. In some cases, these algae show symbiotic relationship with protozoa leading to the lack of or modification in their characteristic silica cell wall (University of California Museum of Paleontology n.d.).

1.2.2 Charophyta or Stonewort

They are fresh water algae commonly seen growing in ponds, lakes and slow-flowing rivers. They grow in an anchored form to the thread like substratum rhizoids. These algae consist of shoot extending upwards from the substratum leading to the nods formation which develop into reproductive structure which resembles the structure of mosses. Charophyta are green-coloured algae due to the presence of chlorophyll a and b (Thoughtco.com n.d.).

1.2.3 Chlorophyta or Green Algae

Mostly, Chlorophyta are aquatic but these can be seen growing on tree trunks, snow surface or even in a symbiotic relationship with protozoans, fungi and hydra. Chlorophyta has a variable size range along with the variable colours, mainly green, yellow-green or blackish-green. This variable range of colours is seen due to the presence of carotenoid pigment or higher concentration of chlorophyll (Smithsonian National Museum of Natural History n.d.).

1.2.4 Phaeophyta or Brown Algae

They are entirely marine and usually found in the cold and temperate water shores. They appear to be brown, yellow-brown or beige in colour due to the presence of fucoxanthin (Smithsonian National Museum of Natural History n.d.).

1.2.5 Chrysophyta or Golden Algae

They are unicellular organisms densely found in fresh water and marine environments. They consist of chlorophyll a and c along with a pigment called fucoxanthin which is responsible for golden colour. Brown and golden algae both show similarity in terms of storing food as both store it outside the chloroplast in the form of chrysolaminarin or polysaccharide laminarin. Also, both the algae show structural similarity for the motile cells with unequal flagella (Smithsonian National Museum of Natural History n.d.).

1.2.6 Cyanobacteria or Blue-Green Algae

Although cyanobacteria, due to the absence of membrane-bound nucleus, are classified as bacteria, but due to their appearance they are classified as algae. These algae are capable of changing their appearance depending on their environmental conditions. Cyanobacteria when grown in soil, fresh and salt water with variable temperature range gives blue-green colour. Cyanobacteria can be photosynthetic, nitrogen fixing or even symbionts. They have chlorophyll a which produces free oxygen as a byproduct. Cyanobacteria does not have the organised chloroplast, instead has its own photosynthetic apparatus distributed on the periphery of cytoplasm. These algae have a light-gathering pigment, phycobilin, attached to protein granules that are attached to photosynthetic membrane which is responsible for the exhibiting variety of colours (Hachicha et al. 2022).

1.2.7 Dinophyta or Dinoflagellate

These organisms usually are pelagic unicellular eukaryotic and having two flagella algae, but they can also be benthic. They consist of chlorophyll a and c along with peridinin responsible for both green and brown pigments, respectively. Some of the species falling in this category reproduce asexually and others sexually. These algae have wide range of morphology and size along with the cell coverings called as theca which differentiates them from other algal groups. They show characteristics of both animals and plants as they can show both photosynthetic and non-photosynthetic patterns; they may have cell wall and they are capable of swimming. These algal species turn water reddish-brown leading harm to the sea-life (Smithsonian National Museum of Natural History n.d.).

1.2.8 Rhodophyta or Red Algae

They are mostly marine and multicellular and grow in attachment to the rocks or other algae, but a few species of this algae can grow in fresh water and have unicellular or colonial forms. They lack flagella and have complex structure; usually they have a pit-like connection between cell and their walls having rigid components that are made up of microfibrils and mucilaginous matrix and can be seen in bulk in nature, as shown in Fig. 1.3. They are structurally similar to cyanobacteria having chlorophyll a along with phycobilin (Smithsonian National Museum of Natural History n.d.).

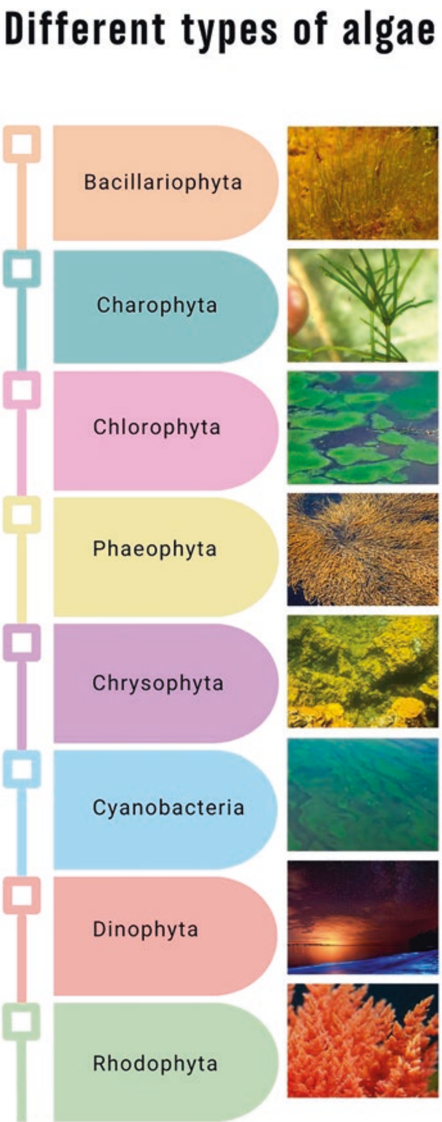

Fig. 1.3 Different types of algae grown in bulk

1.3 Biorefineries

They are defined as a framework where biomass is utilised in an appropriate manner to produce more than one product leading to no harm to the environment and a self-sustainable approach (Narayanan 2024). On a commercial scale, biorefineries in food industry, paper and pulp industry and biofuel industry can be seen. Biorefineries can be used to produce value-added products such as biofuel, bioenergy, biomaterials and biochemicals (Ng et al. 2017).

There are some characteristic features of a biorefinery:

1. There should be generation of energy in gaseous or liquid form along with the production of materials such as chemical, food and feed.
2. Biorefinery must be a combination of several processes such as thermochemical, mechanical and biological.
3. There should be the use of different raw materials from both new and residual sources (Hingsamer and Jungmeier 2019).

Depending on the feedstock used and its generation, biorefineries can be classified into different types, e.g. algae-based, wood-based, palm-based and forest-based. First-generation biorefinery uses edible oil seeds, energy crops, animal fat, food crops etc.; second-generation biorefinery uses lignocellulosic biomass; while third- and fourth-generation biorefineries are algal and other microorganism-based biorefineries (Ng et al. 2017).

The overall concept behind generating biorefinery is to optimise the economical, technical and energetic efficiency of the process for the production of valuable and marketable products (Holm-Nielsen and Ehimen 2014).

1.3.1 Algae-Based Biorefinery

Earlier, first-generation biorefineries were employed for the production of biofuel; these biorefineries used sugars, animal oils, vegetables etc. as feedstocks but due to the competitive consumption of food resources these refineries were criticised. As a replacement to first-generation biorefineries, second generation came into play which used the agricultural wastes and non-edible vegetable oils as feedstocks, but due to low availability of such wastes these biorefineries led to low yield of product (Trivedi et al. 2015).

Various steps in a biorefinery are shown in Fig. 1.4. With the increasing demand of energy globally and the need of reduction on the dependency of fossil fuels,

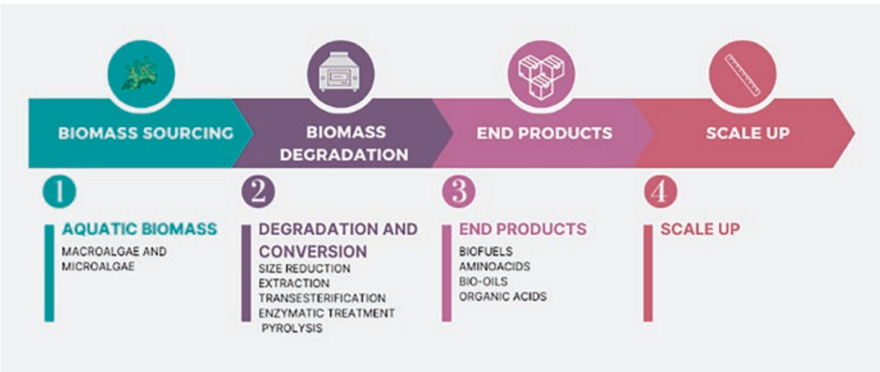

Fig. 1.4 Steps involved in the biorefineries

nowadays algae are being used as feedstocks to develop the biorefineries, which falls in third generation of biorefinery (Holm-Nielsen and Ehimen 2014). Algae helps not only in cost cutting of the production process but also in the reduction of carbon dioxide (CO_2) from the atmosphere along with higher lipid content. Algae can be grown in the wastewater leading to less consumption of fresh water, hence leading to environmentally sustainable feedstock (Trivedi et al. 2015).

1.3.2 Working and Designing of Algae-Based Biorefinery

The entire functioning of a biorefinery can be understood as a three-step process:

1. Algal biomass production and harvesting
2. Transformation processes
3. Downstream processes

As algae are classified into two types depending on their structure, the process of getting an end-product from both the types is slightly different (Andrić et al. 2017).

For microalgae the production process includes cultivation, harvesting, extraction and conversion, whereas for macroalgae the production process includes cultivation, harvesting, extract processing and purification (Seckbach et al. 2010).

To design an algae-based biorefinery, the first step is the selection of algal strain and to find the optimum conditions to grow the strain. At this point, environmental factors should also be kept in the consideration. The selection of strain is done depending on the product needed (Nelson et al. 2023). Next step is to design an appropriate cultivation system for the selected strain. During this cultivation phase, algae is allowed to grow and all the required nutrients are provided to it along with the appropriate conditions of pH, temperature and light supply. Cultivation step is then followed by harvesting. During the harvesting step, different techniques such as filtration, flocculation and centrifugation are used to separate the biomass from the culture. The obtained biomass is then dried using different methods such as sun dry, mechanical, thermal or chemical dewatering (Yaashikaa et al. 2022). The obtained biomass is then grinded well so as to extract out the intracellular compounds from the cells for the extraction of lipids which are basically converted from grinded biomass by various methods such as mechanical pressing, solvent extraction or supercritical fluid extraction. The lipid now extracted is then converted to biofuel using different methods such as transesterification or hydro processing. Algal species and their lipid contents are shown in Table 1.1. After the production of biofuel, there is still a possibility of leftover biomass; this leftover biomass is then used for the extraction of protein by various protein extraction methods such as enzymatic hydrolysis, solubilisation or mechanical separation (Katiyar et al. 2021). Biomass residue is then utilised for the production of biochar, biogas and fertiliser. To find out the environmental impact, the life-cycle assessment (LCA) of entire process is done.

Table 1.1 Various algal species with their lipid content and biomass productivity

Algal species	Lipid productivity (g/L/day)	Lipid content (% dry weight biomass)	Biomass productivity	References
Chlorella vulgaris	0.1837	32.50	0.2341–0.5322	Bošnjaković and Sinaga (2020)
Desmodesmus sp.	0.0198	48.41	–	Bošnjaković and Sinaga (2020)
Isochrysis sp.	0.0378	7.10	0.08	Xiao et al. (2013)
Elliposodium sp.	0.0473	14.00	0.17	Xiao et al. (2013)
Monodus subterraneus	0.0304	16.00	0.19	Xiao et al. (2013)
Chlamydomonas reinhardtii	0.0809	–	3.30	Bošnjaković and Sinaga (2020)
Nannochloropsis oceanica	0.0569	46.14	0.91	Xiao et al. (2013)
Dunaliella salina	0.116	23.10	0.20	Bošnjaković and Sinaga (2020)
Scenedesmus quadricauda	0.1395	38.61	0.36	Bošnjaković and Sinaga (2020)
Oocystis pusilla	0.0494	10.50	0.16	Xiao et al. (2013)

1.3.3 Life-Cycle Assessment of Algae-Based Biorefinery

This analysis is done to get the information about the net energy production and overall sustainability. Life-cycle assessment (LCA) entails assessing the environmental effects related to the biorefinery process's full life cycle, from the extraction of raw materials to the disposal of the finished product. Making educated decisions for sustainable development, streamlining procedures and locating possible environmental hotspots are all made easier with the aid of this assessment (Sander and Murthy 2010).

There are various ways to carry out the LCA of algae-based biorefineries:

1. Cradle-to-Gate LCA: The environmental effects from raw material extraction to the product manufacturing point (gate) are the main focus of this assessment. It offers information on the emissions and resource usage related to the production stage (Silva 2012). This evaluation takes into account the product's complete life cycle, which includes the stages of production, use and end-of-life. It offers a more thorough understanding of how a product affects the environment over the course of its lifetime (Finkbeiner 2014).
2. Socio-Economic LCA: It adds social and economic dimensions to the evaluation, taking into account things like the creation of jobs, health effects on people and financial ramifications (Velasco-Muñoz et al. 2019).
3. Carbon Footprint Assessment: It focuses on the greenhouse gas emissions that are directly related to the biorefinery process, giving information about the products' carbon footprint (Lenzen et al. 2018).

4. Water Footprint Assessment: It examines the amount of water used and any possible environmental effects related to it over the biorefinery's life cycle (Hoekstra and Mekonnen 2012).
5. Cumulative Energy Demand: It helps to identify the energy-intensive stages of the biorefinery life cycle by quantifying the total primary energy demand (Kuo et al. 2021).
6. Techno-Economic Assessment LCA: It examines the biorefinery process's economic viability while taking revenue generation, operating costs and capital costs into account (Davis et al. 2016).
7. Impact Category Assessment: It examines particular environmental impact categories, like toxicity, eutrophication and acidification. This offers a thorough comprehension of the various environmental effects connected to the biorefinery (Huijbregts et al. 2017).

1.3.4 Types of Algae-Based Biorefinery

They can be classified into five types depending on their valuable end-product:

1. Biorefinery for biofuel production
2. Biorefinery for carbohydrate and protein extraction
3. Biorefinery for biochemicals and biomolecules
4. Biorefinery for wastewater treatment
5. Integrated system biorefinery

1.3.5 Application of Algae-Based Biorefinery

1. Production of carbohydrates from algae
2. Production of biodiesel from algae
3. Production of polysaturated fatty acid from algae
4. Production of pigments and proteins from algae
5. Production of carotenoids from algae
6. Production of biogases such as biomethane

1.3.6 Advantages and Disadvantages of Algae-Based Biorefinery

Advantages

1. The main advantage of using algae is that it uses higher amounts of ammonium nitrate and phosphorous compounds leading to simultaneously higher growth rate and reduction of environmental pollution (Alaswad et al. 2015).
2. Algae can be grown in variable environment ranging from non-aerated lands to wastewater, hence leading to no competition for agricultural land (Chisti 2007).

3. Algae-based biorefineries support international efforts to lessen dependency on fossil fuels by advancing the development of sustainable and renewable energy sources (Mata et al. 2010).
4. Algal farming does not directly compete with food production, as some biofuel feedstocks derived from food crops do, which allays worries about food security (Wijffels and Barbosa 2010).
5. Numerous valuable compounds, such as biofuels, high-value chemicals, nutraceuticals and animal feed, can be produced by algae-based biorefineries (Ebhodaghe et al. 2022).

Disadvantages

1. At times, it can be expensive to set up and operate algae-based biorefinery (Davis et al. 2016).
2. It becomes hard to dewater and harvest algae, which overall impacts the entire process (Khoo et al. 2019).
3. The use of genetically modified algae or specific cultivation techniques may be subject to regulatory scrutiny and public perception issues, which could have an impact on the industry's social license (Radakovits et al. 2010).
4. Climate and seasonal variations can have an impact on algae cultivation, which can affect overall reliability and production rates (Singh et al. 2011).
5. Large volumes of algae biomass handling and transportation from cultivation sites to processing facilities can present logistical difficulties and extra expenses (Beal et al. 2012).

1.4 Future Aspects

1. Biofuel Production: Due to their high lipid and carbohydrate content, algae are a valuable source for the production of biofuel. Algal strains and cultivation techniques are being optimised in ongoing research to increase biofuel yields and economic viability and scalability of algae-based biofuels.
2. Pharmaceuticals and Nutraceuticals: Bioactive compounds with potential applications in the pharmaceutical and nutraceutical industries can be found in algae. The utilisation of algae-based systems for the synthesis of medicinal compounds, vaccines and therapeutic proteins is still being investigated.
3. Carbon Capture and Utilisation (CCU): By absorbing CO_2 during photosynthesis, algae can contribute to the process of carbon capture. By incorporating algae-based systems into CCU's industrial processes, the company may be able to reduce greenhouse gas emissions while simultaneously creating useful bio-based products.
4. High-Value Products: Omega-3 fatty acids, pigments, antioxidants and bioactive compounds are just a few examples of the high-value products that can be made from algae. Increasing the variety of valuable products that algae can produce can help algae-based biorefineries remain financially viable.

5. Treatment of Wastewater and Recycling of Nutrients: Algae are able to take up and retain nutrients from wastewater. When algae-based biorefineries are incorporated into wastewater treatment systems, they can remove nutrients and produce biomass for a range of uses.
6. Concepts for Integrated Biorefineries: It is anticipated that algae-based biorefineries will develop into integrated systems that optimise the use of all biomass components. This includes proteins, carbohydrates and other useful substances for a variety of applications, in addition to lipids for biofuels.
7. Scaling Up and Commercialisation: Algae-based biorefineries may be expanded for use in commercial production as technology develops and production methods become more effective. This entails streamlining downstream processing, harvesting techniques and cultivation systems.
8. Genetic Engineering and Selective Breeding: Current research endeavours to enhance algae strains via genetic engineering and selective breeding. One important area of research is customising algae strains for particular uses, like increased productivity or a higher lipid content for the production of biofuel.
9. International Cooperation and Knowledge Sharing: International cooperation among academics, businesses and governments can hasten the development of technologies for algae-based biorefineries. Cooperation and the exchange of knowledge can help solve problems and advance the long-term growth of the algae-based bioeconomy.
10. Supportive Policies and Incentives: Supportive policies and incentives can be very effective in promoting the development of the market for algae-based biorefineries. To promote the adoption of algae-based technologies, governments and businesses can fund research and development (R&D), offer financial incentives and set up regulatory frameworks.

1.5 Conclusion

In conclusion, the implementation of biorefineries based on algae is consistent with the worldwide effort to achieve the Sustainable Development Goals (SDGs) established by the United Nations. These biorefineries provide an adaptable and eco-friendly solution to a number of problems, such as resource scarcity, environmental degradation and population growth. Because of their variety and ability to adapt to various environments, algae have become a promising feedstock for biorefineries. Understanding the potential uses of algae in biorefineries is made easier by their categorisation into micro- and macroalgae. Both macroalgae, such as brown, green and red algae, and microalgae, like *Chlorella* and *Nannochloropsis*, have unique benefits in terms of biomass productivity and lipid content, which are necessary for the production of biofuel. The design of algae-based biorefineries heavily relies on the choice of appropriate algal strains and ideal growing conditions. The idea of biorefineries is a departure from previous iterations of biofuel production, which were criticised for competing with food supplies. This is especially true of those based on algae. Third-generation biorefineries that use algae as their feedstock not only lessen competition but also lower atmospheric carbon dioxide concentrations. Algae-based biorefineries produce biofuels, proteins, biochar, biogas and fertilisers through a three-step process that includes biomass production and harvesting, transformation processes and downstream processes. When assessing the overall sustainability and environmental impact of biorefineries based on algae, life-cycle assessment (LCA) becomes an essential tool. Numerous life-cycle assessments (LCAs), such as cradle-to-gate, socio-economic, carbon footprint, water footprint, cumulative energy demand, techno-economic, and impact category assessments, offer a thorough understanding of the environmental impacts related to the biorefinery process throughout its whole life cycle. Beyond producing biofuel, algae-based biorefineries are used for wastewater treatment, biochemicals, protein and carbohydrate extraction, and biomolecules. High biomass productivity, adaptability in growing conditions, smaller land and water footprint, and the generation of several valuable compounds are the benefits of algae-based biorefineries. Furthermore, the production of food is not directly hampered by the cultivation of algae, which promotes food security. Notwithstanding, it is imperative to tackle certain obstacles and drawbacks, including the requirement for optimal strain selection, cultivation systems and downstream processing. However, the continuous research and development in algae-based biorefineries highlights their potential as a financially feasible and sustainable way to meet global environmental and energy targets. Algae-based biorefineries have the potential to be a major player in creating a future that is healthier, cleaner and more sustainable as technology advances.

References

Alaswad A, Dassisti M, Prescott T, Olabi AG (2015) Technologies and developments of third generation biofuel production. Renew Sust Energ Rev 51:1446–1460. https://doi.org/10.1016/J.RSER.2015.07.058

Andrić I, Pina A, Ferrão P, Fournier J, Lacarrière B, Le Corre O (2017) The 15th international symposium on district heating and cooling assessing the feasibility of using the heat demand-outdoor temperature function for a long-term district heat demand forecast-review under responsibility of the scientific committee of the 15th international symposium on district heating and cooling. https://doi.org/10.1016/j.egypro.2018.07.028

Beal CM, Stillwell AS, King CW, Cohen SM, Berberoglu H, Bhattarai RP, Connelly RL, Webber ME, Hebner RE (2012) Energy return on investment for algal biofuel production coupled with wastewater treatment. Water Environ Res 84(9):692–710. https://doi.org/10.2175/106143012X13378023685718

Bošnjaković M, Sinaga N (2020) The perspective of large-scale production of algae biodiesel. Appl Sci 10(22):1–26. https://doi.org/10.3390/APP10228181

Chisti Y (2007) Biodiesel from microalgae. Biotechnol Adv 25(3):294–306. https://doi.org/10.1016/J.BIOTECHADV.2007.02.001

Davis R, Markham J, Kinchin C, Grundl N, Tan ECD, Humbird D (2016) Process design and economics for the production of algal biomass: algal biomass production in open pond systems and processing through dewatering for downstream conversion. https://doi.org/10.2172/1239893

Ebhodaghe SO, Imanah OE, Ndibe H (2022) Biofuels from microalgae biomass: a review of conversion processes and procedures. Arab J Chem 15(2):103591. https://doi.org/10.1016/J.ARABJC.2021.103591