Journal of Water Process Engineering 68 (2024) 106506

Contents lists available at ScienceDirect

Journal of Water Process Engineering

journal homepage: www.elsevier.com/locate/jwpe

Harnessing microalgae: Innovations for achieving UN Sustainable Development Goals and climate resilience

Ashfaq Ahmad [a,d,*], Syed Salman Ashraf [a,b,c,d,*]

[a] Department of Biological Sciences, College of Medicine and Health Sciences, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates
[b] Center for Biotechnology (BTC), Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates
[c] Center for Membranes and Advanced Water Technology (CMAT), Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates
[d] ASPIRE Research Institute for Food Security in the Drylands (ARIFSID), United Arab Emirates University, P.O. Box 15551, Al Ain, United Arab Emirates

ARTICLE INFO

Editor: Li Gao

Keywords:
Microalgae
Sustainable Development Goals
Bioremediation
Wastewater treatment, CO_2 sequestration
Greenhouse emissions

ABSTRACT

Microalgae are unicellular photosynthetic organisms that are vital in achieving UN Sustainable Development Goals (SDGs) and enhancing climate resilience. They constitute a sustainable source of essential nutrients including high-quality proteins, essential fatty acids, and micronutrients. Microalgae can treat domestic, agricultural, and industrial wastewater by consuming organic compounds and pollutants, leading to biomass production and safe water disposal, ultimately protecting aquatic ecosystems. They require minimal land and freshwater resources, rendering them viable alternatives to conventional crops for food security. Furthermore, microalgae significantly contribute to carbon capture and climate change mitigation by carbon dioxide absorption and conversion into biomass through photosynthesis. Microalgal biofuels offer a sustainable energy source with minimal carbon emissions, provide an alternative to fossil fuels, and facilitate a transition to a low-carbon economy. Their adaptability extends to waste management and environmental remediation, where they enhance water quality, prevent biofouling, and aid soil remediation and air purification. This review examines how interdisciplinary and collaborative research can unlock the potential of microalgae to address global challenges and advance a sustainable future, thereby contributing to the achievement of various UN-SDGs.

1. Introduction

In today's economic landscape, companies are under heightened scrutiny to implement sustainable practices in their production methods. It is widely acknowledged that responsible environmental management is essential for safeguarding ecosystems [1]. The pursuit of sustainable intensification in manufacturing systems has gained significant importance in recent times as it seeks to establish a sustainable future in diverse economic and social contexts. The excessive use of natural resources has led to severe depletion [2]. Without corrective measures, the quality of human life is predicted to decline significantly by 2030, as outlined in the 2023 agenda [3]. The energy crisis is a critical concern among the major threats to human existence, including food insecurity, natural disasters, and global warming. This situation urgently calls for cutting-edge technologies to provide sustainable energy solutions and to address the looming energy crisis [4]. In recent years, sustainable energy technologies have garnered considerable attention because of the global need for sustainable development [5]. A comprehensive strategy has been collaboratively formulated to guide the world towards a more sustainable and resilient future by 2030 [6]. These goals comprehensively address the social, economic, and environmental aspects of the world. However, the realization of these SDGs necessitates international collaboration. Barriers have hindered advancements, including the COVID-19 pandemic, the global financial crisis, and insufficient collaboration among countries. Furthermore, countries struggle with issues such as burgeoning populations, ineffective communication, scarcity of resources, policy gaps, political decisions, and financial constraints, underscoring the pressing need to expedite efforts to achieve these objectives [6]. Groundbreaking advancements are essential to address the interconnected challenges of sustainable growth and climate adaptability. The UN-SDGs provide a comprehensive blueprint for global progress, and innovative approaches

* Corresponding authors at: Department of Biological Sciences, College of Medicine and Health Sciences, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates.

E-mail addresses: ashfaq.ahmad@ku.ac.ae (A. Ahmad), syed.ashraf@ku.ac.ae (S.S. Ashraf).

https://doi.org/10.1016/j.jwpe.2024.106506
Received 12 September 2024; Received in revised form 26 October 2024; Accepted 5 November 2024
Available online 18 November 2024

Fig. 1. The 17 Sustainable Development Goals framework is structured as a pyramid, with each level building upon one below it. The pyramid's base consists of 17 SDGs that cover a wide range of economic, social, and environmental issues. The next level comprises 169 targets, which are specific, measurable, achievable, relevant, and time-bound goals intended to be achieved by 2030. The third level contained 230 indicators that measured progress towards the SDGs. Finally, the fourth level comprises the 600-plus specific actions that need to be taken to achieve the SDGs.

are crucial for achieving these ambitious objectives.

Microalgae, which are unicellular photosynthetic organisms, flourish in diverse environments and can endure varying parameters such as salinity, temperature, light intensity, and pH. The potential of microalgae to support the UN-SDGs and enhance climate resilience is gaining increased recognition. These versatile microorganisms offer innovative solutions across various sectors, making them invaluable in the fight against climate change and the promotion of sustainable development. Microalgae generate essential compounds, such as proteins, vitamins, polysaccharides, carbohydrates, lipids, antioxidants, and pigments. Biofuels can also be produced using indirect methods [7,8]. Employing microalgal biomass presents a considerable opportunity to foster sustainable development in multiple sectors, which is vital for advancing global sustainability. Microalgae are omnipresent in aquatic ecosystems and utilize inorganic nutrients and light. They also grow heterotrophically on organic substrates. The conversion of biomass into biofuels, such as biodiesel, bioethanol, and biogas, can be accomplished through processes such as liquefaction, pyrolysis, transesterification, fermentation, and anaerobic digestion [9–12]. In the sphere of food and pharmaceuticals, microalgae are a consistent and valuable source of essential amino acids and long-chain polyunsaturated fatty acids, exhibiting significant antimicrobial, anticancer, and antioxidant properties [13]. Fig. 1 presents the framework of the 17 Sustainable Development Goals (SDGs), structured as a pyramid.

The scarcity of water resources to meet the needs of drinking water and sanitation poses significant challenges to human well-being, economic development, environmental conservation, and ecosystem health. Furthermore, the decline in water quality due to pollutants from domestic, agricultural, and industrial sources presents severe environmental and socioeconomic issues. Therefore, it is crucial to maintain water quality while developing cost-effective and eco-friendly wastewater treatment technologies. Although current methods can address physical impurities, they are often energy-intensive and rely on microorganisms to biologically break down complex pollutants. Microalgae, with their diverse physiological traits and adaptability to various habitats, offer promising potential for advancing sustainable wastewater remediation and treatment [14–16]. Microalgae are pivotal in promoting eco-friendly and sustainable wastewater treatment methods. The presence of vital macronutrients such as carbon, nitrogen, and phosphorus in wastewater fuels the metabolism and growth of microalgae. Studies have explored the potential of microalgae for wastewater treatment, energy generation, and resource recovery, thus fostering circular economies [17–19]. In addition to enhancing biomass production and water quality, microalgae also alleviate the detrimental effects of coastal eutrophication on sectors such as fisheries, aquaculture, tourism, and public health [20,21]. Microalgae play a pivotal role in carbon sequestration, one of their primary functions. Microscopic organisms utilize photosynthesis to capture atmospheric CO_2 and convert it into biomass. This process serves a dual purpose: it helps combat climate change by reducing greenhouse gas concentrations and contributes to Goal 13: Climate Action. The resulting biomass can also be used to produce biofuels, providing an alternative renewable energy source that reduces reliance on fossil fuels [22–24]. This review aims to fill a knowledge gap concerning the augmentation of microalgal cultivation for feed, food, bioenergy production, and wastewater treatment. It delves into the principles of the circular economy and the technical and economic challenges. Furthermore, it underscores the alignment of microalgal biotechnology with the United Nations SDGs. Addressing existing obstacles in the production of microalgae could enhance environmental health and reduce production costs.

In addition to other applications, microalgae play a crucial role in wastewater treatment. These organisms thrive in wastewater environments, where they help eliminate contaminants and purify water. This multifaceted approach addresses water pollution issues and generates valuable bioproducts, supporting Goal 6: Clean Water and Sanitation. The innovative use of microalgae offers an eco-friendly method for managing water resources [23,25]. Microalgae have the ability to absorb nutrients such as nitrogen and phosphorus, improving water quality. Affordable and Clean Energy (SDG 7): Microalgae are a promising source of biofuels. Various processes can be used to produce biodiesel, bioethanol, and biogas from microalgae. Biofuels offer an eco-friendly alternative to fossil fuels and contribute to clean energy production. Zero Hunger (SDG 2): Microalgae serve as a sustainable food source. They contain essential nutrients, including proteins, vitamins, and lipids. Incorporating microalgae into the diet can help to combat malnutrition and food insecurity. Circular Economy and Ecological Health: Integrating microalgae into sustainable practices promotes circular economies. They can transform waste (e.g., wastewater) into valuable resources. Microalgae contribute to ecological health and resilience by reducing reliance on nonrenewable resources. These microorganisms are well suited to a wide range of environments, such as freshwater ponds, salty oceans, and tree bark. They exhibit significant versatility and contribute substantially to various aspects of sustainability.

Approximately 80,000 microalgal species exist, half of which have been explored for commercial purposes [25]. This highlights microalgae's immense potential for future sustainable development across various sectors [7,26]. Microalgae are classified into several major groups based on their pigmentation, storage product, and cell wall composition. The main types of algae include Chlorophyta (Green Algae), which are primarily found in freshwater environments. They contain chlorophylls a and b, which give them a green color. Examples include *Chlorella* and *Dunaliella*, which are used in nutritional supplements and biofuel production [27]. Rhodophyta (Red Algae): Mostly found in marine environments, these algae contain phycoerythrin, which gives them a red color. They are used to produce agar and carrageenan, which are important for the food and pharmaceutical industries. These organisms can absorb organic pollutants from wastewater, including nitrites, nitrates, orthophosphates, and ammonia. Consequently, microalgae can be effectively utilized for wastewater remediation and biofuel production, thereby presenting an innovative approach to decrease energy production costs [25,28]. Heterokontophyta (Brown Algae): This includes diatoms and brown algae. Diatoms have silica cell walls and are major components of phytoplankton. They are used in biofuel production and as a source of omega-3 fatty acids [29]. Cyanobacteria (Blue-Green Algae): Prokaryotic microalgae are known for their ability to fix atmospheric nitrogen. *Spirulina* is widely used as a dietary supplement because of its high protein content [29,30]. Diatoms: Unicellular algae with intricate silica cell walls. They are found in freshwater and marine environments and contribute significantly to global carbon fixation [31].

Microalgae are pivotal for carbon sequestration and play a crucial role in wastewater treatment, biofuel production, and as a source of valuable bioproducts. Their diverse applications make them key assets in promoting sustainable development and climate resilience. This comprehensive review synthesizes knowledge from biotechnology, environmental science, and sustainable development to provide a holistic view of the potential of microalgae. This review article connects advancements in microalgae research to the UN Sustainable Development Goals (UN-SDGs), demonstrating their role in achieving global sustainability objectives with a focus on climate resilience, it elaborates on microalgae's capacity to address climate change through carbon capture and biofuel generation. It delves into advanced applications, including wastewater purification, bioenergy production, and bioplastic development, highlighting novel uses not extensively covered in the previous literature. This study illustrates microalgal innovations' real-world relevance and impact by incorporating case studies and practical examples. Furthermore, it presents detailed policy suggestions and implementation strategies to bridge the gap between scientific research and practical applications. This article also outlines future research paths to foster continued innovation and progress in the field.

2. Microalgae in climate change mitigation

Climate change significantly contributes to natural disasters, endangering human life and biodiversity. The relentless increase in emissions—carbon dioxide, water vapor, methane, nitrous oxide, and chlorofluorocarbons—has amplified the impact of climate change on human health [32]. These emissions pose health risks, including respiratory infections, cardiovascular diseases, and lung cancer. Poor air quality leads to short-term health issues such as eye irritation, skin conditions, and nausea. Prolonged exposure to particulate matter and free radicals in the atmosphere can cause cardiopulmonary diseases, as these particles infiltrate deep into the lung alveoli with genotoxic effects [32–34]. Urban areas, especially large cities, experience higher air pollution owing to industrial emissions and traffic congestion, resulting in fog and haze [35]. Discharging toxic chemicals, particulate matter, and biological substances harm humans and other living beings, affecting health, ecosystems, and the environment [32]. Air pollution, whether solid, liquid, or gaseous, damages the natural features and poses health risks. They also contribute to environmental and ecosystem degradation. Both short- and long-term exposure to air pollution has significant effects [32,34,36–38]. Tackling air pollution is a key factor in realizing the 17 SDGs that 193 global leaders have collectively endorsed for development from 2015 to 2030. SDG 13 focuses on reducing detrimental environmental impacts per person by prioritizing air quality and waste management. The goal is to diminish these impacts by 2030, as articulated in the SDGs: "By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management."

The urgency of addressing climate change and its repercussions is underscored by SDG 13. Collectively, SDGs offer a framework for tackling this pressing issue, highlighting the effects of global warming by 2030. The primary aim of SDG 13 is to strengthen developing nations' resilience and adaptive capacity to climate-related hazards and natural disasters. The objective of SDG 13 is to integrate climate change measures into national policies, strategies, and plans using awareness initiatives and governance structures that are both centralized and decentralized. By incorporating climate action, adaptation, impact reduction, and early warning systems into governmental legislation and programs, the goal is to promote sustainable development and effective planning in developing countries, thereby enabling them to address climate-related risks and disasters better [39].

2.1. Microalgae-based wastewater treatment

Effective wastewater management is crucial to address water scarcity and prevent uncontrolled wastewater discharge into drainage systems. The importance of wastewater management aligns with the 6th SDG, which sets ambitious objectives. Discharging untreated wastewater into the environment poses a serious threat to both the ecological balance and human health. Simultaneously, global oil production and consumption increases exacerbate environmental pollution and the energy crisis [40,41]. Therefore, it is crucial to develop eco-friendly and cost-efficient wastewater treatment methods. Although traditional methods such as A2/O, membrane bioreactor (MBR) sewage treatment, activated

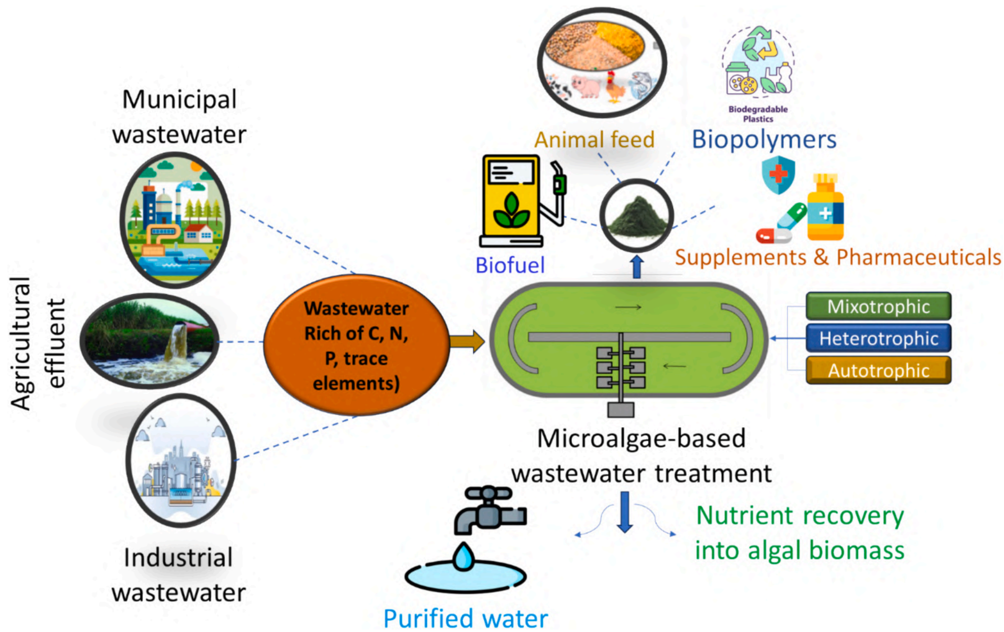

Fig. 2. Present wastewater treatment integrated with microalgae cultivation.

sludge processing, Sequencing Batch Reactors (SBR), and biofilm removal provide socioeconomic advantages, they also leave room for enhancement. These conventional techniques frequently result in high construction expenses, stringent environmental regulations, elevated energy usage, less-than-optimal denitrification and phosphorus removal rates, and restricted financial gain from biogas recycling. Therefore, innovative solutions must be explored to address these challenges and promote sustainable wastewater management. Further research and development in this area could lead to more efficient and sustainable solutions for wastewater management [42,43]. To address these challenges, wastewater treatment technologies that balance economic practicality with environmental energy advantages are necessary. This approach can mitigate environmental harm and contribute to the resolution of the energy crisis. Fig. 2 depicts the integration of different wastewater treatment processes utilizing microalgae along with their practical applications. Microalgae have been recognized as a potential solution for wastewater treatment because of their fast growth rate, variety of bioactive compounds they produce, and effective photosynthetic ability. Over the last decade, there has been noticeable progress in wastewater treatment using microalgae [44–46]. The main objective of employing microalgae in biological wastewater treatment is to eradicate pollutants, utilize CO_2, and produce microalgal biomass via growth and photosynthesis [47,48]. Certain microalgal strains, including *Scenedesmus* sp., *Chlorella* sp., *Desmodesmus* sp., and *Chlamydomonas* sp., play a vital role in wastewater treatment. Microalgae have the ability to absorb a broad spectrum of pollutants. These include heavy metals, nitrogenous compounds, and a variety of harmful chemicals. Their ability to remove these pollutants purifies water and aids environmental conservation. The elimination of detrimental substances by microalgae contributes to the well-being of ecosystems and helps preserve the equilibrium of the ecological environment. This underlines the importance of microalgae in sustainable practices and their potential for addressing environmental challenges. This is another reason why microalgae are considered valuable for the pursuit of sustainability [49,50].

Marine microalgae such as *Nannochloropsis marina*, *Chlorella marina*, *Thalassiosira* sp., and *Dunaliella saline* have been used for wastewater treatment, focusing on lipid production. *Chlorella marina* achieved a 78 % COD removal efficiency, producing 1.92 g/L of biomass and 0.7 g/L of lipids, which yielded 0.59 g/L of biodiesel through direct transesterification [51]. Similarly, another study used *Chlorella* sp. for TWW treatment for over 20 days and observed efficient removal of various heavy metals (Cr, Pb, Ni, Cd, Co, Zn, and Cu) in specific amounts. Additionally, *Chlorella* sp. produced 0.95 g/L of lipids, 250 μg/mL of carbohydrates, and 160 μg/mL of proteins, utilizing 60.50 % CO_2 [52]. These findings highlight the potential of microalgae for wastewater remediation and production of valuable by-products (Table 2). Biomass is a viable alternative to petroleum for biofuel production because it addresses energy shortages and sustainability concerns. Previous studies have explored the potential of microalgae in wastewater treatment and biomass production. Applications include integrating microalgal biofuel production systems for wastewater separation, cultivating microalgae alongside activated sludge in municipal wastewater treatment, and treating food-processing wastewater while producing additional products [22,53–57]. Owing to recent progress, numerous countries are actively exploring microalgae-based methods for wastewater treatment. To comprehensively understand this subject, it is necessary to evaluate both past advancements and current investigations [58].

Petroleum hydrocarbons, including polycyclic and halogenated compounds, primarily enter the environment through agricultural pesticide use, organic material pyrolysis, and sewage. Among the top-priority pollutants are polycyclic aromatic hydrocarbons (PAHs), known for their carcinogenic and mutagenic properties [59,60]. Microalgae, specifically *Scenedesmus obliquus* and *Nitzschia linearis*, have been found to be effective in the remediation of a variety of PAHs, including naphthalene, acenaphthene, phenanthrene, fluorene, pyrene, anthracene, fluoranthene, and benzo(*a*)pyrene. Interestingly, the growth of these microalgae and their PAHs removal capacity were enhanced by exposure to crude oil, with an increase of up to 70–75 % observed alongside an increase in biomass production [61]. Moreover, the energy efficiency of microalgae-based wastewater treatment is significantly higher than that of conventional activated sludge processes, which are known for their high energy consumption due to bacterial metabolism. For example, in Spain, the energy consumption of conventional wastewater treatment is 0.5 kWh/m^3, while microalgae-based biological techniques have managed to reduce this figure to 0.2 kWh/m^3 [62]. This suggests that microalgae-based techniques offer sustainable and energy-efficient solutions for wastewater treatment.

Wastewater from agricultural and domestic sources often contains high concentrations of nitrogen and phosphorus compounds. These inorganic nutrients are essential for microalgae growth. Nitrogen mainly appears as ammonium, nitrate, and nitrite, whereas inorganic phosphorus exists as orthophosphate. However, heavy metals and radioactive ions commonly found in wastewater can adversely affect microalgae growth [70,71]. Chloroplasts, vacuoles, and mitochondria in microalgae contribute to the bio-sequestration and bioaccumulation of heavy metals. For example, the microalgae *Scenedesmus* sp. AUBAC-002 effectively removes Cr, Cu, Pb, Zn, and Fe at rates of 82–96, 73–98, 75–98, 65–98, and 66 %, respectively [72]. *Botryococcus* sp. NJD-1 was able to remove hexavalent chromium (Cr (VI)) by forming complexes on microalgal surfaces and subsequently reducing it to 94.2 % trivalent chromium (Cr (III)) at a concentration of 5 mg/L. Microalgae can convert ammonium to ammonia under basic conditions and directly assimilate nitrates and nitrites without volatilization [73]. Enzymes, such as nitrate and nitrite reductase, are instrumental in the conversion process, which ultimately produces ammonium ions. These ions are vital for the anabolism of amino acids and the synthesis of organic nitrogen compounds, such as nucleotides, chlorophylls, polyamines, and alkaloids, all of which are essential for various cellular functions [74,75]. Ammonium, nitrate, and nitrite are actively transported into microalgal cells. When entering the cells, these substances proceed through a two-step catalytic process. During this process, enzymes, including nitrate reductase and nitrite reductase, promote the transformation of these compounds, resulting in ammonium ions as the ultimate output [76,77]. This highlights the critical role of these enzymes in microalgae nitrogen metabolism.

The immobilization of microalgae involves the use of physical and chemical means to prohibit free-living microalgal cells from moving independently in their original site. This can maintain specific biological activities and allow reusability in aqueous systems. Immobilized microalgae have a high population density, which makes wastewater treatment simple and effective. This reduces carbon emissions and improves treatment effectiveness without the need for energy-intensive recycling. Moreover, unlike suspended microalgae, immobilized microalgal cultures have a higher potential for nutrient recovery and are more economically valuable in chemical and agricultural industries [78–80]. Several microalgal immobilization techniques include biofilm formation, alginate beads, capsules, and cell entrapment in hydrogels. A study by de Jesus et al. [81] reported that immobilized *Desmodesmus subspicatus* in alginate beads at which alginate beads showed good stability in sugarcane vinasse. Immobilized *D. subspicatus* in alginate beads flourished better and removed significant amounts of potassium, carbon, and nitrogen from vinasse compared with free microalgae cultivation. A study by Alhumairi et al. [82] showed that immobilized microalgae *Chlorella* sp. was more effective than suspended *Chlorella* sp. in reducing organic compounds in contaminated areas at Dhiba Port, Kingdom of Saudi Arabia. Another study by Mujtaba et al. [83] showed that the removal of nutrients by immobilized *Chlorella* sp. was 100 % for nitrogen and 99.8 % for phosphorus over two days. Immobilized microalgae to treat wastewater are currently underdeveloped, including efficiency enhancement strategies and optimization of cultivation parameters. Current immobilized microalgal technologies primarily focus on cell attachment using affordable biological matrix materials suitable only for mild hydrodynamic environments and weak cell-substrate adhesion. Extended cultivation frequently results in leakage of connected or entrapped immobilized microalgal cells, which can harm the ecosystem. Immobilized microalgal systems have been explored for a restricted range of contaminants. Therefore, research is on optimal immobilization methods for microalgae to achieve improved system stability for long-term operation.

Antibiotic contamination has gained considerable attention because of the hazards its residues pose to the environment and human health. Although antibiotic residues are typically found in low concentrations in the environment, recent studies have revealed that they can result in detrimental ecological consequences for both target and non-target organisms. These consequences include the suppression of microbial growth and modification of the composition and activities of microbial communities [84,85]. Recent studies have consistently shown that microalgae are highly effective at removing emerging micropollutants, particularly pharmaceutically active compounds such as antibiotics, antiretroviral drugs, and steroids, from aquatic environments and wastewater [86–88]. Microalgae can enhance the photodegradation of frequently used fluoroquinolone antibiotics, including ofloxacin (OFL) when placed in an algal solution [89]. Microalgae employ various mechanisms to eliminate antibiotics, including bioadsorption, bioaccumulation, biodegradation, photodegradation, and hydrolysis, which are the primary methods used for this purpose [86].

Sulfonamides are among the most widely studied antibiotics, followed by fluoroquinolones, macrolides, and tetracyclines. Other categories of antibiotics have not been investigated extensively. Various factors, such as the type of antibiotic, initial concentrations, specific microalgal strains, and cultivation conditions, influence the effectiveness of antibiotic removal. For example, *Chlorella pyrenoidosa* can remove up to 99.3 % of sulfamethoxazole at an initial concentration of 0.1 mg/L but only 48.45 % at 2 mg/L [90,91]. Table 3 illustrates the effectiveness of different antibiotic categories for their elimination using microalgae-based systems. Specifically, the data revealed that ciprofloxacin (CIP) had a removal efficiency of 53 % through photodegradation and 93 % when paired with *Scenedesmus dimorphus* in a reactor containing Bold 3 N medium with a concentration of 25 μg/L of CIP [92]. This reduction in efficiency at higher concentrations may be due to increased toxicity, which inhibits the biodegradation pathway [93]. Different microalgae strains also show varying removal efficiencies for sulfamethoxazole under the same conditions: *C. vulgaris* (18–84 %), *Haematococus pluvialis* (94–97 %), *Scenedesmus quadricauda* (42–46 %), and *Selenastrum capricornutum* (61–86 %) [94].

Microalgae can eliminate orthophosphate by precipitating it on their outer cell surface at elevated pH levels. Microalgal cells also transport phosphates across their outer cell walls, facilitating energy transfer and nucleic acid synthesis [74]. Upon formation, orthophosphate engages with organic molecules such as phospholipids through various processes, including phosphorylation, oxidative phosphorylation, and photosynthetic phosphorylation [76]. When there is an excess of amount of phosphorus in the growth medium, microalgae have the ability to form acid-insoluble polyphosphate granules through a process known as 'luxury uptake' [75,77]. Interestingly, although treatment systems and environmental conditions influence the removal of nitrogen, the mechanisms for assimilating phosphorus-based pollutants are relatively stable and unaffected by these variables [75], suggesting robustness in the ability of microalgae to handle phosphorus-based pollutants. Despite the numerous benefits, there are challenges associated with microalgae-based wastewater treatment, including high operational costs, the need for large cultivation areas, and variability in treatment efficiency due to environmental factors. Future research and technological advancements are required to address these challenges and optimize large-scale application processes. In summary, microalgae-based wastewater treatment is a promising solution for achieving sustainable water management. By harnessing the natural abilities of microalgae, this approach can purify wastewater and contribute to bioenergy production and environmental conservation.

2.2. Microalgae for carbon sequestration

Climate-resilient development involves implementing strategies for greenhouse gas mitigation and adaptation to promote sustainable development [106]. Carbon capture and utilization technologies have attracted significant attention [107] for mitigating global warming and greenhouse gas emissions, and one of them is biological approaches, which are cost-effective and have low energy consumption. Microalgae are promising candidates for carbon capture because they can fix CO_2 levels and utilize nutrients through photosynthesis. Microalgae are

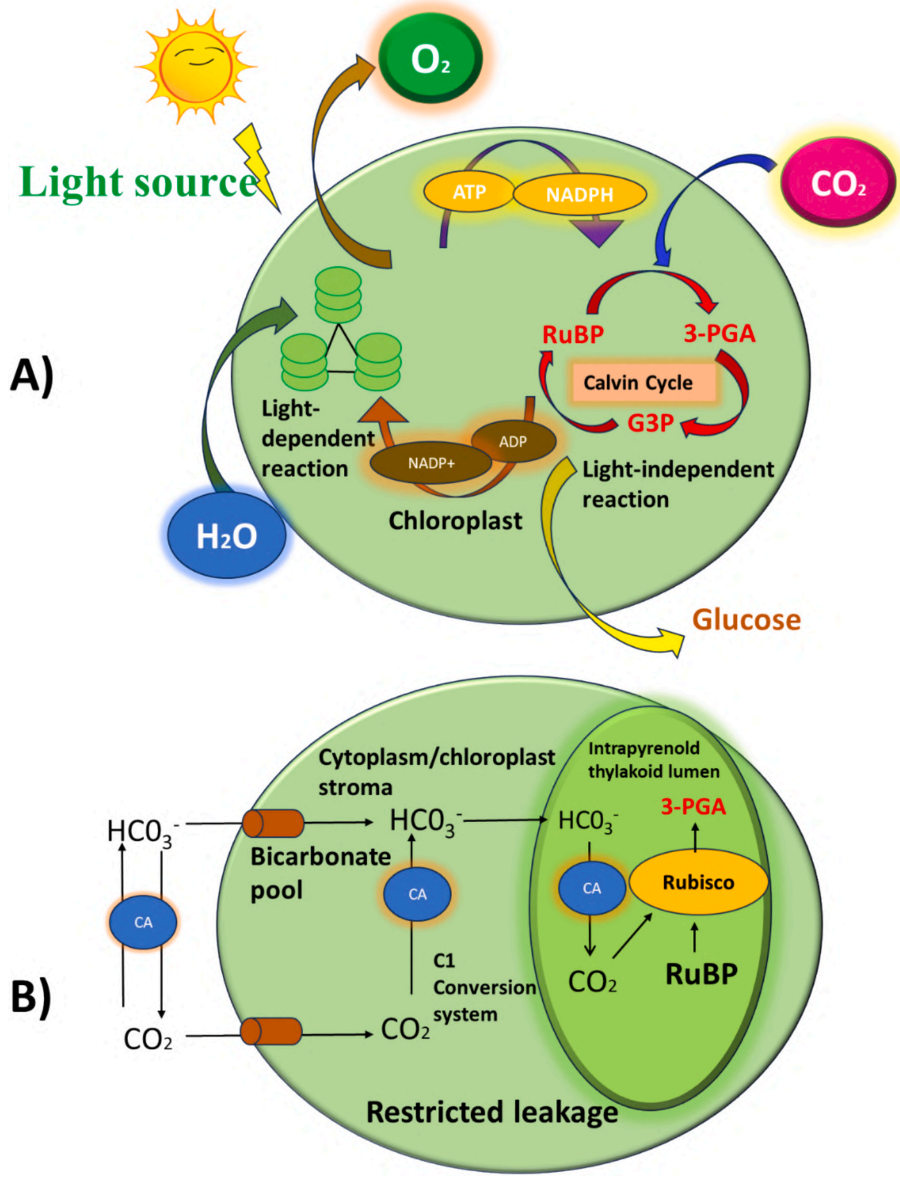

Fig. 3. Adapted: Schematic representation [A] Photosynthesis, which converts light energy into chemical energy, and [B] CO_2 concentration mechanism, a method used to capture CO_2 for photosynthesis efficiently.

significantly more efficient than terrestrial plants in capturing carbon up to 50 times more effectively because of their superior photosynthetic capabilities and high carbon capture rates [108]. In addition, microalgae do not compete for agricultural land and grow rapidly. For most algae, CO_2 fixation accounts for approximately 50 % of the biomass by weight, resulting in a CO_2-to-biomass weight ratio of approximately 2:1, with a typical value of 1.88 [109]. Microalgal cultivation has been identified as an excellent method for large-scale carbon capture. However, existing microalgal cultivation systems have not yet reached the production levels necessary for effective carbon capture and storage. Microalgae are generally cultivated in two systems: open ponds and closed photobioreactor (PBR) systems. PBRs have been shown to enhance microalgal biomass growth and carbon capture rates in these two systems [110].

Microalgae can metabolize inorganic carbon through a photoautotrophic mechanism involving multiple enzymes, including carbonic anhydrase and RuBisCo (Ribulose-1,5-bisphosphate carboxylase/oxygenase). These enzymes facilitate the conversion of CO_2 into carbohydrates and support glucose synthesis via the Calvin cycle, which is essential for CO_2 to be captured by algae. First, RuBisCo catalyzes the reaction between CO_2 and ribulose-1,5-bisphosphate to form 3-phosphoglycerate. This compound is then converted into 1,3-diphosphoglycerate by incorporating inorganic phosphate from ATP and is further reduced to 3-phosphoglyceraldehyde by the enzyme phosphoglyceraldehyde dehydrogenase. Finally, 3-phosphoglyceraldehyde is converted into ribulose-5-phosphate along with byproducts such as sugars, fatty acids, and amino acids [111,112]. Numerous microalgal strains rely on photoautotrophy, which uses light as their primary energy source. Microalgae can transform inorganic carbon into organic compounds such as carbohydrates via photosynthesis and release molecular oxygen (O_2) [113]. Photosynthesis is crucial for both plant growth and biomass production. As shown in Fig. 3a, the schematic pathway of photosynthesis can be represented by the following equation (Eq. (1)) [114].

$$6CO_2 + 12\ H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O \quad (1)$$

This equation illustrates how carbon dioxide (CO_2) and water (H_2O) are transformed into glucose ($C_6H_{12}O_6$) and oxygen, respectively, fueled by light energy.

Table 1
Biofixation rate of carbon dioxide by microalgae under the optimum growth condition.

Microalgae	Culture conditions						Ref.
	Carbon dioxide concentration % (*v*/v)	Temperature (°C)	pH	Light intensity (μmol^{-2} s^{-1})	CO_2 fixation rate (mg/L/d)	Significance	
Chlamydomonas reinhardtii	5	25	7	280	220 ± 20	Model organisms for studying photosynthesis and carbon biofixation mechanisms.	[137,138]
Gold algae	4.73	30	6	180–200	144	Adaptable species with moderate CO_2 biofixation, useful for biofuel production.	[139,140]
Haematococcus pluvialis	3	26	6.8	50–80	60 ± 2	Known for astaxanthin production and moderate CO_2 biofixation.	[141,142]
Euglena gracilis	45	27–31	7.8	100	75	High CO_2 tolerance; promising for carbon capture and wastewater treatment.	[143]
Scenedesmus obliquus	30	20	7–8	200–300	790–970	High CO_2 biofixation; suitable for large-scale biotechnological applications.	[144,145]
Dunaliella salina	5	25	7.2	100	313	Known for beta-carotene production, it is suitable for high-salinity environments.	[146,147]
Botryococcus braunii	5	26	6.5–7.5	150	500	Produces high quantities of hydrocarbons, which is important for biofuel research.	[148,149]
Chlorella vulgaris	5.35	23.4	7	163.5	101	Widely studied for biofuel and CO_2 sequestration applications.	[146]
Spirulina platensis	5	30	9.0	330	413	High protein content; potential in carbon mitigation and nutrition.	[147]

Climate change poses a substantial hurdle, necessitating amplified efforts to limit greenhouse gas emissions originating from both biogenic and anthropogenic sources, with particular emphasis on carbon dioxide and methane. Viable strategies for mitigating carbon dioxide emissions encompass underground sequestration or utilization by photosynthetic plants. The following methods can be used to decrease the concentration of harmful gases in the atmosphere while simultaneously promoting ecosystem balance. However, it is important to ensure that these strategies are implemented responsibly to avoid potentially negative environmental impacts. Further research and development in this area could lead to more efficient and sustainable solutions to combat climate change. Microalgae have been extensively studied as viable alternatives to geological storage for carbon dioxide sequestration [115–117].

Carbon capture, emission reduction, and resource utilization effectiveness in microalgae vary among species because these organisms exhibit diverse photosynthetic traits, regulatory systems, metabolic pathways, and crucial enzymes [118,119]. A study conducted by Bhola et al. [120] investigated the physiological responses of five indigenous microalgal strains to increasing carbon concentrations. Indigenous strains I-3 exhibited significant tolerance to high-carbon sources, such as 15 % CO_2. Indigenous microalgae often outperform commercial species in nutrient removal and biomass production because of their adaptability to local environments [121]. Chiellini et al. [122] investigated the resistance of six natural microalgal isolates to pollutants and their potential for wastewater remediation. The study cultivated these microalgae in cigarette end wastewater at various dilutions, revealing that their ability to remediate wastewater is contingent upon the chemical characteristics and nature of organic pollutants. The optimal CO_2 concentrations varied among the different microalgal species, with distinct tolerance levels (Table 1). Another study reported that *Spongiochloris* sp. demonstrated exceptional biomass productivity and CO_2 biofixation rates during wastewater treatment. Microalgae demonstrated exceptional potential for biomass production, achieving a maximum productivity rate of 1.5 g/L/d, as well as a CO_2 fixation rate of 2.9205 g/L/d. These results highlight the capacity of microalgae to effectively sequester CO2 and purify wastewater. Cultivated microalgae have the potential to sequester significant amounts of CO_2. According to data, 1.83 kg of CO_2 can be captured per kg of cultivated microalgae [108]. This highlights its potential for CO_2 removal. For example, *C. vulgaris* and *Anabaena* sp. can capture CO_2 at rates of 6.24 g/L/day, respectively [123]. These findings underscore the potential of microalgae in addressing environmental challenges. Indigenous microalgae

Table 2
Different types of microalgae are used in the treatment of wastewater.

Microalgae species	Growth conditions	COD %	BOD %	TSS %	Cr %	N %	P %	Ref.
Chlorella sp.	Bold basal medium (BBM), 23 °C, light intensity 110, photoperiods 12:12 h	95.46	95.17	–	95.59	–	–	[52]
Scenedesmus sp.	Medium Guillard modified, 25 °C, light intensity 80.	80.33	–	–	–	–	96.78	[63]
C. vulgaris	BBM, 25 °C, light intensity 30, photoperiods 12:12 h.	90.17	88.5	–	–	–	–	[64]
Phormidium sp.	Algae culture broth 28 °C, light intensity 150–200, photoperiods 10:14 h	71	94	–	73	–	48	[65]
Chlorella sp. and *Phormidium* sp.	Algal culture medium, 28 °C, light intensity 150–300, photoperiods 12:12 h	86.4 and 79.1	89.87 and 86.97	–	90.1 and 93.1	–	–	[66]
75R25S and 50R50S.	Medium Tris-Acetate-Phosphate, light intensity 117.3, photoperiods 12:12 h	56.70 and 56.70	25.98 and 24.77	–		58.84 and 71.74	95.54 and 97.64	[67]
C. vulgaris	Algal culture medium, 28 °C, light intensity 150–300, photoperiods 10:14 h	94.74	95.93	–	99	100	–	[66]
Scenedesmus sp.	BG11 medium, 27, light intensity 120, photoperiods 16:8 h	37.1	35	–	81.2–96.0	44.3	>95	[68]
C. vulgaris and *S. obliquus*	BG11 medium, light intensity 576–720	38.08 and 34.72	37.04 and 13.60	34.01 and 36.30	78.02 and 37.98	–	–	[69]

Light intensity unit: µmolphotons/m^2/s.

Table 3
Microalgal antibiotics removal performances and mechanisms.

Detailed species	Algal strains	Initial antibiotic concentration (mg/L)	Removal efficiency (%)	Wastewater category	Removal mechanisms	Microalgae-based systems (photobioreactors)	Ref.
Sulfacetamide	Microalgae-bacteria consortia	0.004	41–95	Groundwater	Photolysis>co-immobilization	Suspended-attached system	[95]
Sulfamethazine	*Botryococcus braunii*	0.0476	5.4–38.5	Livestock wastewater	Biodegradation	Submerged membrane photobioreactors	[96]
Sulfamethoxazole	*Nannochloris* sp.	0.01	32	F/2 medium	Algae-mediated photolysis	Flasks	[97]
Trimethoprim	*Nannochloris* sp.	0.01	3.4–17	Lake water	Biodegradation, photolysis, biosorption	Flasks	[98]
Trimethoprim	*Selenastrum capricornutum*	0.02–0.1	17.7–42.1	Synthetic wastewater	–	Flasks	[94]
Enrofloxacin	Microalgae consortia	1	26	Bold's Basal medium	Biodegradation > accumulation, adsorption	Flasks	[100]
Danofloxacin	Microalgae-bacteria consortia	$(254–322) \times 10^{-6}$	10–48	Diluted piggery wastewater	–	Open photobioreactor	[101]
Florfenicol	*Chlorella* sp.	46–159	70.7–97	BG-11 medium	Biodegradation > accumulation, adsorption	Flasks	[102]
Tetracycline	*Chlamydomonas* sp.	1–10	100	BG-11 medium	Hydrolysis>biodegradation>photolysis	Unspecified photobioreactor	[103]
Doxycycline	*Tetraselmis chuii*	3.95–121.056	49.9–97.9	F/2 Guillard medium	Photolysis>biotransformation, sorption	Beakers	[104]
Cefradine	*Chlamydomonas reinhardtii*	5	5.45–14.72	N.A.	Hydrolysis, adsorption, desorption, photodegradation	Quartz tubes	[105]

Fig. 4. Microalgae-based CO_2 sequestration in the environment.

possess properties that render them attractive candidates for extensive cultivation and potential sources of genetic material for future valuable compound production [124,125].

Microalgae can absorb and store approximately 50 % of their weight in CO_2 [126]. Similar to other plants, microalgae absorb CO_2 from the atmosphere during the day and release it at night during photosynthesis. The biofuel production process through biological CO_2 fixation is illustrated in Fig. 4. In controlled cultivation systems, microalgae can sequester a significant proportion of CO_2, with estimates ranging from 75 to 90 %. Raceway ponds, on the other hand, capture between 25 % and 50 % of CO_2 [127]. The ideal CO_2 concentration for optimal microalgal growth is between 5 % and 10 %. Higher CO_2 levels negatively affected biomass productivity. Notably, in studies involving *Scenedesmus obliquus* and *C. vulgaris*, CO_2 fixation rates were 130 and 141 mg/L, respectively [128,129]. The CO_2 conversion rates of the microalgae species *C. vulgaris* and *S. obliquus* were 14.9 % and 13.85 %, respectively. These percentages highlight the efficiency of these microalgae in converting CO_2, a greenhouse gas [130,131].

Research findings highlight microalgae's significantly higher productivity than alternative raw materials. Identifying specific microalgae species with metabolic pathways conducive to bioenergy production, such as biodiesel, is crucial for enhancing carbon sequestration and emission reduction efforts [132–134]. For instance, microalgae such as *Chlorella* sp., *Scenedesmus*, and *Chlorococcus* effectively fix CO_2. *Euthyrium* species, including *Nannochloropsis* species, belong to the Chlorophyceae family and are proficient in carbon sequestration. Identifying microalgae with superior carbon sequestration efficiency and substantial biomass production can aid the development of various carbon capture and emission reduction strategies tailored to specific needs [132,135,136]. This approach maximizes the role of microalgae in carbon capture and bioenergy generation, ultimately leading to reduced emissions and improved environmental sustainability. Future research should focus on improving cultivation techniques, developing cost-effective harvesting methods, and exploring genetic engineering to enhance microalgae carbon sequestration capabilities. Integrating microalgae-based systems with other sustainable practices can maximize their environmental and economic benefits. In summary, microalgae offer a viable and sustainable approach to carbon sequestration, with the potential to contribute significantly to climate change mitigation and the production of valuable bioproducts.

2.3. Microalgae for biofuel production

Biofuels derived from biomass have gained recognition as significant alternatives to fossil fuels owing to their environmentally friendly nature. They have the potential to enhance the global energy system, decrease dependence on fossil fuels, reduce pollutant emissions, and deliver energy in various forms, such as solids, liquids, and gases [150,151]. Escalating concerns regarding greenhouse gas emissions from fossil fuel use have intensified the search for reliable alternative energy sources. Biofuels produced by algae have recently emerged as a modern renewable energy source. Algae are promising raw materials for large-scale biofuel production, owing to their ability to harness solar energy through photosynthesis to generate chemical energy. During their growth phase, algae utilize a mix of solar energy, phosphorus, nitrogen, CO_2, and water, leading to biomass formation. This process underscores the potential of algae as a sustainable and efficient source of biofuel. This characteristic of microalgae is crucial for reducing greenhouse gas emissions. Fig. 5 illustrates a sustainable approach grounded in a circular bio-economy, focusing on bioenergy production from microalgae to reduce CO_2 emissions and minimize waste.

Moreover, microalgae contribute to the sustainability of biofuels as these microalgae provide a renewable and eco-friendly source for biofuel production. This underlines the potential for microalgae to address environmental challenges and advance renewable energy solutions [22,152]. Several cultivation factors affect lipid production in

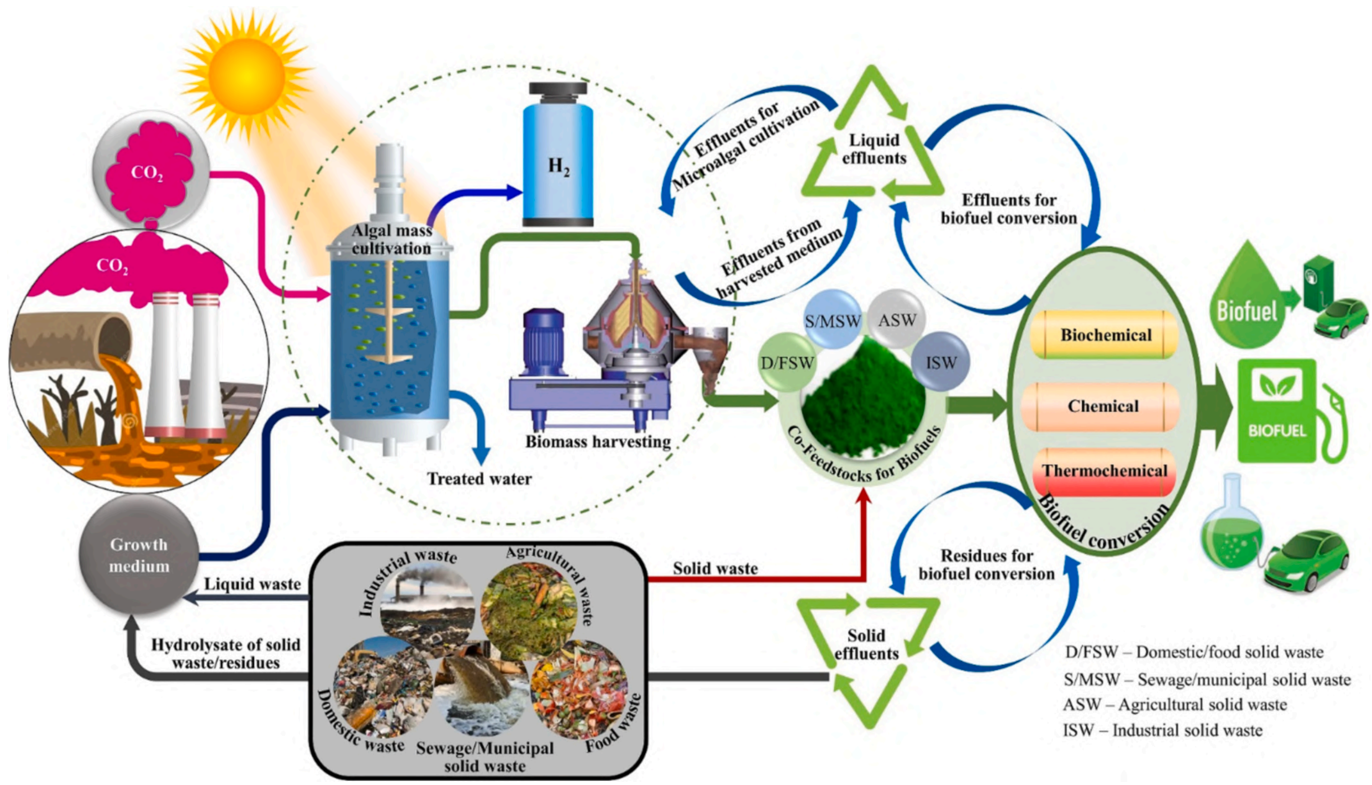

Fig. 5. Adapted: Sustainable approach based on circular bio-economy for bioenergy production from microalgae to reduce CO_2 emissions and waste [158].

microalgae, including CO_2 capture and organic carbon sources [153]. Microalgal biomass contains fatty acids that are converted into triglycerides (TGA), cholesterol, and other lipids [154]. Because of their ability to store significant lipid quantities, even in harsh environments, microalgae can be efficiently used in the transesterification process to produce biodiesel. Lipids are vital biological molecules that play a crucial role in biodiesel production as vital biological molecules [155–157].

Biodiesel derived from microalgal biomass can be converted into an environment-friendly biofuel using appropriate processing techniques. The biological composition of microalgal lipids is significantly influenced by factors such as the composition of wastewater, CO_2 concentration, temperature, and aeration rate. Notably, biodiesel produced from microalgae can be utilized in diesel engines without requiring significant modifications and can be mixed with petroleum diesel in various ratios [159]. However, it is important to note that microalgal oil contains a higher percentage of PUFAs with four or more double bonds than vegetable oil. This makes it more susceptible to oxidation, thereby limiting its storage potential as a biodiesel source. The level of unsaturated fatty acids plays a crucial role in producing microalgal biodiesel and can be controlled via catalytic hydrogenation [160]. This highlights the need for careful management of the fatty acid composition of microalgal oil to optimize its use as a biodiesel source.

Biodiesel, derived from renewable sources, such as vegetable oil and animal fat, is a viable substitute for diesel. It is environmentally friendly, non-toxic, and biodegradable, making it suitable for reducing the emissions of carbon monoxide, sulfur oxides, and unburned hydrocarbons during combustion. Microalgal biodiesel, a monoalkyl ester of fatty acids, can be produced through a process known as TGA transesterification using alcohols. This form of biodiesel has been gaining attention owing to its physicochemical properties that are similar to those of conventional fuels. This makes them a potentially sustainable alternative to traditional fossil fuels. The lipid type and fatty acid composition of microalgae, which are crucial for biodiesel production, depend on several factors. The factors that may impact the efficiency of microalgae-based biodiesel production include the specific species of microalgae used, available carbon sources, and the growth conditions under which they are cultivated. Optimizing these factors may increase the biodiesel production efficiency [161–163]. This highlights the potential of microalgae in food production, water purification, and renewable energy production. Therefore, further research on microalgae and their applications is important for a sustainable future.

Microalgal biomass can be efficiently transformed into bioethanol, making it the most widely recognized third-generation alternative fuel [164]. Bioethanol production from microalgae offers several advantages, including reduced reliance on arable land, which helps mitigate atmospheric CO_2 levels. Microalgal cells contain diverse compounds such as lipids, carbohydrates, and proteins. In the absence of oxygen, carbohydrates are initially broken down into basic sugars through chemical or enzymatic processes and are subsequently transformed into bioethanol [165]. The production of bioethanol from microalgae involves several distinct phases: initial pre-treatment, subsequent liquefaction, saccharification, anaerobic fermentation, and distillation. When refined to its most refined state, bioethanol presents a compelling alternative to gasoline because of its higher vaporization temperature and octane rating. Therefore, it is considered a potential sustainable and efficient alternative fuel source.

Additionally, the utilization of microalgae as feedstock for bioethanol generation demonstrates higher efficiency than conventional crops such as maize and sugarcane. This indicates the potential of microalgae to significantly contribute to the production of sustainable and efficient biofuels [166–170]. *Chlorella sorokiniana* has been identified as an effective hydrolysate for bioethanol production [171]. Enzyme-catalyzed hydrolysis has demonstrated high conversion rates for the marine red microalga *Porphyridium cruentum*, particularly in marine environments, where a 90 % conversion rate has been reported. In contrast, freshwater *P. cruentum* showed an 85 % conversion rate. When the simultaneous saccharification and fermentation process was performed using freshwater *P. cruentum*, the bioethanol yield was 70 %. This result surpassed the 65 % yield obtained when these processes were performed separately. These findings highlight the potential of *P. cruentum* to thrive in freshwater environments and to be a candidate for bioethanol production [172].

Biohydrogen production from microalgae has been increasingly acknowledged as a feasible approach for the generation of eco-friendly energy in recent times [173]. Microalgae and cyanobacteria are capable of performing bio-photolysis, which involves the production of hydrogen using light. In contrast, photosynthetic bacteria engage in photofermentation, a process that involves fermentation of organic molecules in the presence of light. In contrast, anaerobic bacteria participate in a process known as "dark fermentation," in which organic molecules are fermented in the absence of light [174]. Microalgae generates biohydrogen under anaerobic conditions when exposed to light and water. Bio-hydrogen is widely acclaimed for its efficiency and environmental benefits, as it produces only water as a by-product and does not emit greenhouse gases [173]. Bio-hydrogen is considered one of the most efficient fuels, with an energy density of 142 MJ/kg [175]. The microalgae-derived enzyme hydrogenase is essential for water splitting and biohydrogen production during anaerobic fermentation [176]. The efficiency of hydrogen production via dark fermentation can be improved by reducing the duration of the reaction through the gradual deactivation of hydrogenase by oxygen. Researchers have explored methods to enhance oxygen tolerance during biohydrogen production. One promising approach is dark fermentation, which is both cost-effective and eco-friendly. This method produces marketable byproducts, including acetic and lactic acids, without requiring a light source or aeration, thereby lowering the costs. For instance, the anaerobic fermentation of *Chlorella vulgaris* with *Clostridium butyricum* resulted in the production of 2.87 mmol/g of biohydrogen, highlighting the potential of dark fermentation as a sustainable and efficient method for biohydrogen production [177]. Exploring the potential of microbial systems, specifically algal and bacterial systems, to enhance biohydrogen production via dark fermentation is a promising method that could lead to scalable and cost-effective solutions. This approach holds immense promise for future application.

Microalgae provide a flexible resource for generating biogas that can be used for electricity production, fuel cells, and liquid fuel applications [178]. Given their relatively low levels of lignin and cellulose, microalgal biomass is particularly well suited for anaerobic digestion processes designed to produce biogas [179,180]. Biogas typically contains methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), hydrogen, and ammonia, with methane being the main combustible component [181–186]. Microalgae, which are rich in carbohydrates and lipids and devoid of lignin, are highly effective in biogas production through AD. Furthermore, the solid residues obtained from AD of microalgae biomass can be utilized as excellent fertilizers [187,188].

Thermal pre-treatment at lower temperatures (below 100 °C) has been implemented in continuous reactors that utilize microalgal biomass from wastewater treatment systems. This thermal pretreatment, conducted at temperatures ranging from 60 to 100 °C, resulted in a significant increase in the methane yield from 30 to 70 %. Interestingly, methane yield showed an even more substantial increase at higher temperatures (above 100 °C), specifically between 100 and 120 °C. For instance, *Nannochloropsis salina* demonstrated a 108 % increase in methane yield, whereas *Scenedesmus* sp. exhibited a threefold increase. Moreover, the application of ultrasound methods as a form of pre-treatment led to a 33 % increase in the final methane yield. These findings underscore the potential of these pretreatment methods to enhance the efficiency of biofuel production from microalgae [189,190]. The untapped potential for biogas production from microalgae is significant, and several species, including *Scenedesmus*, *Spirulina*, and *Chlorella*, are being investigated for their suitability [191]. Techniques that weaken cell walls, such as those applied to *Chlorella vulgaris*, enhance pretreatment effectiveness and increase substrate degradation during AD processes [192]. Methane production from microalgae presents a promising avenue for sustainable energy generation, the reduction of greenhouse gas emissions, and wastewater treatment. However, it is important to acknowledge the challenges that arise with this approach, including the high costs, lengthy start-up periods, cultivation complexities, and infrastructure requirements. Despite these challenges, technological advancements and ongoing scientific research hold promise in overcoming these barriers. This could pave the way for more efficient and cost-effective methane production from microalgae, contributing to a more sustainable future for energy production. This exciting field has great potential, and continued exploration, and innovation will undoubtedly lead to significant advancements. Recent studies have focused on improving the efficiency and cost-effectiveness of microalgal biofuel production. Innovations in genetic engineering, photobioreactor design, and harvesting techniques are being explored to enhance lipid yields and reduce production costs. Integrating microalgal biofuel production with other sustainable practices, such as carbon capture and wastewater treatment, can maximize environmental and economic benefits. In summary, microalgae are a promising and sustainable source for biofuel production. With continued research and technological advancements, microalgal biofuels have the potential to play a significant role in the transition to a low-carbon economy and the achievement of global sustainability goals.

3. Harnessing microalgae research to achieve the UN-SDG

The United Nations 2030 Agenda for Sustainable Development comprises a series of objectives referred to as the SDGs. Innovative approaches are necessary to restore our limited land and water resources, as we have only six years left to attain the 2030 UN Sustainable Development Goals. These goals are designed to ensure a clean and healthy environment for future generations, thereby playing a vital role in securing a sustainable future [193–195]. This section critically analyzes the role of microalgae in achieving these 17 SDGs. It specifically investigated the contributions of these microscopic entities to the accomplishment of all 17 SDGs. The following sections have been established to showcase how microalgae research can have a significant impact on achieving the SDGs.

3.1. SDG 1 and 2: no poverty and zero hunger

The main goals of this initiative are to ensure sufficient food supply and combat malnutrition. Microalgae can significantly contribute to achieving zero hunger in two ways: through the high-quality protein found in their biomass, and nutrient supplementation provided by microalgae-derived nutraceuticals [196]. Poverty and hunger are closely intertwined, and poverty is the primary driver of hunger in underdeveloped countries. Currently, 700 million individuals live in extreme poverty, surviving less than GBP£1.52 (equivalent to US$1.90) per day [197]. The COVID-19 pandemic has exacerbated this issue, pushing many people in developed countries into poverty owing to rising living costs. Given the projected global population of nearly 10 billion by 2050, it is expected that this challenge will exacerbate, especially considering the growing incidence of infectious diseases, such as coronavirus [198]. Microalgae provide an appealing solution for tackling SDGs because of their adaptability to a wide range of conditions, such as global warming and diseases [199]. Microalgae are renewable energy sources owing to their unique advantages. They do not compete with food production and do not rely on freshwater resources, significantly enhancing their sustainability. This has the potential to contribute substantially to reducing poverty and food insecurity. Although microalgae can be cultivated near marine animal cages in open seas, integrated cultivation methods are generally considered more sustainable [25]. This approach allows for efficient use of resources and can help minimize environmental impacts.

Furthermore, the culinary use of microalgae and macroalgae is deeply rooted in several cultures, particularly East Asia. In countries such as China, Japan, and Korea, these algae have been traditionally used in a variety of dishes, including salads, soups, and toppings. This adds a unique flavor and texture to dishes and enhances their nutritional value. This rich culinary heritage underscores the potential of microalgae as a sustainable food source [200–203]. Among the species of cultivated algae, brown seaweed is of significant importance. In 2012, considerable amounts of "kombu" (*Saccharina japonica*)—approximately 5.7 million tons—and "wakame" (*Undaria pinnatifida*)—around 2.1 million tons—were harvested. Furthermore, "nori" (*Porphyra*), which holds cultural significance in Japan, saw an approximate harvest of 1.8 million tons in the same year [203]. Numerous studies have highlighted the potential of algae as sustainable food sources. Algae provide essential vitamins, minerals, and proteins for human consumption while also serving as animal feed. The US Food and Drug Administration (FDA) recognizes algae safety and designates it as Generally Recognized As Safe (GRAS) based on an extensive consumption history without adverse effects or scientific evidence. Similarly, the European Food Safety Authority (EFSA) evaluates the safety of new food and feed compounds before production and marketing [198,199,203–206]. Although microalgae are often touted as a potential food source, their viability depends on several factors, including their growth rate, composition, digestibility, and nutritional content. It is worth noting that micro-algal productivity per hectare is reported to be up to 20 times higher than that of traditional oilseed crops, which could make them a more sustainable alternative. However, this needs to be balanced against other considerations, such as cost and scalability [207].

Microalgae offer various benefits, such as carbon capture and wastewater management, but they must be weighed against potential challenges in cultivation and processing. The claim that microalgal fibers are softer than land-based vegetables, thereby making them ideal for promoting intestinal regulation, also requires further investigation and validation. It is important to approach the potential of microalgae as a food source with a critical eye, taking into account all relevant factors [200,208]. Encouraging global microalgal production can unlock these advantages and contribute to a sustainable future.

3.2. SDG 3: good health and well-being

Microalgae contain several bioactive compounds that make them valuable in promoting health and well-being. These tiny organisms provide essential antioxidants, vitamins, minerals, and polyunsaturated fatty acids (PUFAs). As discussed in the previous section, incorporating microalgae into the diet can significantly contribute to overall health and vitality [209,210]. Microalgae-derived polyunsaturated fatty acids (PUFAs) are promising alternatives to fish oil. Unlike animal-based oils, microalgae-based PUFAs have minimal or no toxin accumulation and provide a high omega-3 content [211,212]. *Chlorella* species, often promoted as "health foods," serve as functional foods with potential benefits for preventing and treating various common ailments, including skin conditions and specific cancers [210]. Notably, microalgae species, such as *Phaeodactylum tricornutum*, *Cryptecodinium cohnii*, and *Isochrysis galbana*, are gaining recognition as valuable sources of PUFAs. *Isochrysis galbana* and *Phaeodactylum tricornutum* contain high levels of eicosapentaenoic acid (EPA) at 22.6 % and 29.8 %, respectively. In contrast, *Cryptecodinium cohnii* showed a significantly higher DHA concentration (51.12 %). The DHA content of microalgae was nearly six times higher than that of cod liver oil (9.2 %) and tuna fish (24.56 %). In contrast, plant-based PUFAs from terrestrial sources exhibit deficiencies in EPA and DHA levels. Thus, PUFAs derived from microalgae are a feasible option for food and feed production [207,211,213]. Fig. S1 provides an overview of the biochemical activities and technological capabilities of high-value-added compounds derived from microalgae.

Spirulina, *Caspirulan* (both sourced from *Spirulina* spp.), and *N. ellipsosporum* (originating from cyanobacteria) are well known for their powerful antiviral polysaccharides. These substances exhibit a broad range of activities against diverse conditions, including human immunodeficiency virus (HIV), cancer, and influenza [214]. Importantly, supplementation with *Spirulina* (at a dosage of 10 g/day for a duration of six months) resulted in a marked enhancement in the health of HIV patients. These benefits include increased weight, reduced arm circumference, higher CD4 count, fewer infections, and lower proteinuria (blood protein levels). Given that HIV patients often face glucose metabolism issues due to viral and antiretroviral medications, another study demonstrated that *S. platensis* supplementation (at a dose of 19 g/day) significantly enhances insulin sensitivity in HIV-positive patients [215]. Additionally, human clinical trials have highlighted the protective effects of *Dunaliella* extracts in male smokers, particularly against conditions such as diabetes and hyperlipidemia [34]. Furthermore, *Spirulina* has been associated with decreased blood pressure and improved blood sugar regulation [216].

Interestingly, the World Health Organization (WHO) proposed adding *Spirulina* spp. to the dietary regimen of National Aeronautics and Space Administration (NASA) astronauts for space travel because of their compact form and safety [210]. *Haematococcus pluvialis*, a microalga, is the most efficient producer of astaxanthin. This carotenoid has been shown to decrease the blood pressure in hypertensive rats. Moreover, long-term intake of carotenoids such as astaxanthin significantly mitigates the risk of heart attack and stroke [217,218]. Clinical trials suggest that the daily intake of *Dunaliella* spp. (in dosages ranging from 0.56 to 3 g) offers antioxidant protection and aids in the prevention of conditions such as hyperlipidemia and diabetes. Furthermore, the administration of *Arthrospira* spp. (popularly known as Spirulina) resulted in considerable reductions in low-density lipoprotein (LDL), total blood cholesterol, triacylglycerols, very-low-density lipoprotein (VLDL), lipid peroxidation, and malondialdehyde (MDA) levels in patients diagnosed with diabetes, dyslipidemia, and ischemic heart disease [219].

3.3. SDG 6: clean water and sanitation

The main goals of SDG6 are to increase efficiency and establish sustainable management of water resources for drinking and basic sanitation. To accomplish this, measures must be taken to improve wastewater treatment, reduce pollution, and promote water recovery. Additionally, commitment extends to preventing and significantly reducing marine pollution [220]. Despite this progress, the treatment of municipal wastewater continues to pose a significant challenge. The key objective was to significantly reduce organic matter to ensure the provision of safe water for human use. The removal of nitrogen and phosphorus compounds from wastewater prior to discharge is vital because high concentrations can lead to a reduction in dissolved oxygen levels, thereby posing a threat to aquatic life. Numerous countries place a high priority on enhancing water quality, particularly by reducing the levels of nitrogen and phosphorus in wastewater effluents. The European Urban Wastewater Treatment Directive outlines the maximum permissible limits for discharged wastewater, including 125 mg/L for chemical oxygen demand (COD), 1–2 mg/L for total phosphorus, and 10–15 mg/L for nitrogen, with specific thresholds determined by population size [77]. Fig. S2 shows the mechanisms by which microalgae remove contaminants [221].

The United Nations Sustainable Development Goal 6 underscores the importance of access to safe drinking water and sanitation and advocates for educational and community-based initiatives centered on cleanliness and hygiene. Microalgae-based water remediation is a sustainable solution initially employed in sewage treatment systems to counter environmental pollution, especially in rapidly expanding aquatic ecosystems [77,222,223]. Microalgae, such as *Chlorella vulgaris* and *Scenedesmus obliquus*, show promise for bioremediation of wastewater [224].

Compared to traditional techniques, such as electrochemical methods, membrane filtration, ion exchange, chemical precipitation, and flotation, microalgae present significant advantages for heavy metal removal from wastewater. Conventional methods often incur high operating costs, produce toxic sludges, and lose effectiveness at low heavy-metal concentrations (<100 mg/L) [225–227]. The treatment of municipal wastewater is both resource-intensive and expensive. In contrast, microalgae-based treatment is an eco-friendly and sustainable alternative that effectively eliminates contaminants while producing valuable biomass [228,229]. Wastewater from swine farms contains contaminants and nutrients, which pose environmental and health risks. The cultivation of microalgae enhances the phytoremediation process for swine wastewater owing to the exceptional ability of microalgae to flourish in ammonia-rich environments [230]. Swine wastewater provides essential nutrients vital for vigorous microalgal growth and biomass production. Harvested microalgal biomass has potential for various applications, including bioenergy production (such as biogas) [231,232], nutrient recovery (nitrogen and phosphorus), increased biomass and lipid productivity, biomethane production, and biobutanol production [233,234].

Microalgae perform photosynthesis and generate oxygen while simultaneously assimilating carbon dioxide. This establishes a beneficial cycle: bacteria utilize oxygen sourced from microalgae to oxidize organic carbon, and in return, microalgae absorb the carbon dioxide generated by bacterial respiration. Incorporating microalgae into wastewater treatment processes can help reduce or eliminate the need for aeration and carbon dioxide emissions, which can be achieved by retrofitting existing facilities or constructing new ones. During growth, microalgae absorb photosynthetically fixed carbon, nitrogen, and phosphorus, thereby reducing bacterial nitrogen and phosphorus removal requirements, aeration needs, and nitrous oxide emissions [235,236]. Industrial, agricultural, and domestic waste pollution has severely impacted freshwater bodies, including rivers and lakes, endangering human communities and economies. Nitrogen oxides, which are byproducts of fossil-fuel combustion, pose a considerable threat to the environment and human health. The release of these pollutants, including N_2O, NO, NO_2, N_2O_3, N_2O_4, and N_2O_5, significantly contributes to overall nitrogen pollution in the air [237,238]. Microalgae play a vital role in pollution mitigation by converting inorganic nitrogen fertilizers into organic nitrogen compounds. Furthermore, they can also produce proteins, vitamins, and polyphenols from NOx. This is evident in processes, such as the BioDeNOX method for flue gas treatment systems, which are based on microalgae. This demonstrates the potential of microalgae to contribute to environmental sustainability [236]. To successfully accomplish SDG 6, it is crucial to employ innovative approaches, such as the application of microalgae to treat polluted water. This method eliminates contaminants from water and produces valuable biomass, thereby addressing both environmental sustainability and resource restoration.

3.4. SDG 7: affordable and clean energy

The objective aims to ensure access to affordable, reliable, sustainable, and modern energy sources by 2030. To achieve this goal, research has focused on green and sustainable bioenergy production. Studies of third-generation biofuels, including biodiesel, bioethanol, biogas, bio-oil, aviation fuels, and bioelectricity, have highlighted the potential of microalgae. However, despite this potential, large-scale production of microalgae for bioenergy encounters considerable challenges that require resolution [239–241]. The European Union aims to obtain 20 % of its energy from renewable sources, with a significant contribution from biofuels [242]. Microalgae-based biofuels offer promising and sustainable alternatives, demonstrating feasibility without competing with food production [130,243]. Addressing global energy demands while reducing carbon emissions underscores the importance of utilizing microalgae for cost-effective and sustainable energy production [242]. Given the apparent unsustainability of fossil fuels such as coal and oil [60], microalgae have emerged as promising candidates for eco-friendly biofuel production, including bioethanol, biohydrogen, biodiesel, and biogas [244–246]. Fig. S3 summarizes the key techniques and processes involved in biofuel production from microalgae.

3.5. SDG 13: climate action

The urgency to combat the catastrophic consequences of climate change has not increased. Immediate action is essential to mitigate its impact. Microalgae have emerged as a critical environmental solution, both necessary and urgent. These diminutive entities have a significant impact on the biogeochemical cycles of greenhouse gases, including carbon dioxide, methane, and nitrous oxide. These gases are the major contributors to global climate change. Human activities such as industrial operations and the combustion of fossil fuels in power plants are the main sources of greenhouse gases. This has led to a rise in the temperature of over 2 °C since the pre-industrial era. This underscores the critical role of microorganisms in influencing the climate of our planet and the urgent need for sustainable practices [247]. Aligning with SDG13, it is imperative to swiftly reduce the effects of climate change and protect ecosystem integrity.

Microalgae play a vital role in the recycling of elements by interacting with diverse biotic and abiotic factors. They contribute significantly to both natural and human-engineered systems, including organic matter decomposition, wastewater treatment, agricultural enhancement, metabolite generation, and biofuel production [248]. Algal communities engage in activities such as denitrification and respiration, which can affect global variables such as CO_2 concentrations, precipitation patterns, and temperature. Modifications to these conditions have a significant impact on the structure of algal ecosystems, resulting in feedback loops that exacerbate environmental problems [249,250]. Soil microorganisms act as essential carbon sinks, ultimately influencing atmospheric carbon levels. Given the significance of soil carbon sequestration, it is imperative to gain a comprehensive understanding of the composition, ecology, and function of soil algae, as soil typically exhibits higher concentrations of organic carbon than vegetation and the atmosphere [250–252]. Indeed, a considerable hurdle persists; a large number of soil algal species are not cultivable. Overcoming this challenge requires the implementation of creative methods, including high-throughput screening. This could enable extensive investigation of a vast array of soil microorganisms and their potential capacity to reduce the impact of climate change. This highlights the need for continued research and development in this field to harness the full potential of these microorganisms in our fight against climate change [250].

Studies have investigated the production of *Chlorella* in response to the controlled addition of flue gases from coke ovens, yielding a biomass of 2.87 g/L biomass. Impressively, this process effectively eliminated 50 % of SOx and 70 % of NOx, utilizing SO_2 (87 mg/L) and NO (78 mg/L) [253]. Concurrently, several microalgal species have grown in the presence of gases emitted by thermoelectric plants, including 100 mg/L of NO and 60 mg/L of SO_2. Notably, *C. vulgaris* and *Spirulina* sp. achieved concentrations of 0.98 g/L and 1.59 g/L, respectively, while *S. obliquus* and *Aspergillus nidulans* attained concentrations of 0.68 g/L and 0.41 g/L, respectively [254]. In conclusion, using microalgae to treat gaseous effluents presents significant advantages over traditional methods, effectively reducing the toxicity of flue gas while producing valuable bioproducts and biofuels.

3.6. SDG 14: life below water

Water supply standards are crucial to human survival and sustainable development. As urbanization and industrialization continue to expand, pollutants, such as toxins, sediment, bacteria, and nutrients, are increasingly released into waterways, posing threats to public health and affecting ecological, aesthetic, recreational, biological, and economic value [255]. These impacts are in line with the objective of SDG-14, which aims to reduce marine pollution and underscores the urgent need for immediate measures to tackle eutrophication and restore ecosystems. Although various treatment options are available, they often fail owing to poor implementation, inadequate management, and constrained financial resources. Fortunately, certain microalgal species demonstrate significant potential for rapid removal or degradation of excess nutrients, thereby providing a promising biological solution for wastewater treatment. Economic technologies such as periphyton ponds, filamentous algae nutrient scrubbers, and algal turf scrubbers have been investigated for their potential in water purification. These systems leverage the natural filtering capabilities of algae and other aquatic organisms to remove pollutants. However, the effectiveness of these technologies is affected by several factors. Regular harvesting is crucial to prevent the system from being overloaded with biomass. Optimal sunlight exposure is needed for photosynthesis, and nutrient levels must be carefully managed to promote growth without causing harmful algal blooms. The water depth should be shallow to ensure that light can penetrate all the layers of the system, and the flow rate must be controlled to allow sufficient contact time for the purification process. This is a delicate balance, but when properly managed, these systems can provide an effective and sustainable method for water purification. This is another example of how microalgae and other aquatic organisms contribute to environmental sustainability [248,256]. For example, a constructed treatment system that utilizes filamentous microalgae effectively eliminates significant quantities of nitrogen and phosphorus from stormwater annually [255,257]. For example, treatment systems utilizing filamentous microalgae effectively remove substantial amounts of nitrogen and phosphorus from stormwater annually. Microalgae-based flow methods have successfully reduced nutrient runoff in aquaculture operations, particularly in shrimp, catfish, and oyster farms. Compared to constructed treatment wetlands, flowways utilizing filamentous microalgae offer superior nutrient removal rates, increased hydraulic capacities, reduced initial costs, and the potential for microalgae recovery. Aligning with SDG-7 (affordable and clean energy), SDG-12 (sustainable consumption and production), and SDG-13 (climate action), this initiative makes a significant contribution to the attainment of these global goals. This underscores the potential of microalgae-based solutions to promote sustainability and address environmental challenges [258].

Microalgae-based feeds are increasingly recognized as the future of aquaculture nutrition, offering numerous advantages for large-scale production. These feeds act as bedrock for feeding on lower-trophic organisms, such as fish and zooplankton. These, in turn, provide sustenance for the higher trophic species in the food chain. Microalgae are rich in essential nutrients, and their biomass composition can exhibit notable variations. Depending on the conditions and species, some microalgae contain up to 60 % carbohydrates, 70 % oils, or 60 % proteins. This highlights the nutritional versatility of microalgae and their potential role in sustainable food production systems [259]. Beyond nourishment, microalgae release essential substances, such as hormones, growth stimulants, pigments, and secondary metabolites. These natural compounds have antimicrobial, immunostimulatory, antioxidant, and anti-inflammatory effects that are critical for the well-being of aquatic animals [260]. The promotion of microalgal cultivation in unsuitable arable lands or coastal areas is essential for photosynthesis. The transformation of atmospheric CO_2 into renewable nutrients reduces water usage and fosters nutrient recycling in wastewater and seawater. It enhances both terrestrial and aquatic ecosystems, supporting a sustainable bioindustry in aquaculture [261]. Microalgae play a pivotal role in addressing several SDGs, including SDG-1 (no poverty), SDG-2 (zero hunger), SDG-12 (responsible consumption and production), and SDG-14 (life below water). Microalgae contribute to the creation of biodegradable bioproducts by fostering environmentally friendly value chains that minimize carbon emissions and optimize resource utilization. They also provide a nutritious diet for the aquaculture industry. This underscores the significant potential of microalgae to promote sustainability and contribute to global development goals [262,263].

The potential of microalgae as a source of omega-3 fatty acids has been a subject of considerable interest in the field of nutritional science. Omega-3 fatty acids, recognized for their crucial role in strengthening immune health, optimizing cardiovascular function, and protecting against chronic diseases, are in high demand globally [264,265]. The global need for omega-3 currently surpasses production capacity by an estimated 85 %, underscoring the substantial role that microalgae can play in meeting human nutrition and aquaculture demands. In the realm of aquaculture, several microalgal species, including *Tetraselmis*, *Spirulina*, *Chlorella*, and *Euglena*, have shown antibacterial properties against pathogens that impact shrimp and fish, leading to increased survival rates in controlled experiments. For example, when diets are supplemented with *Euglena* or *Chlorella*, it enhances the immune response and growth performance of freshwater species such as rohu, gibel carp, and giant freshwater prawns, thereby strengthening their resistance against pathogens such as *Aeromonas hydrophila* [266,267]. Recent advances in biotechnology have paved the way for new applications for microalgae in aquaculture. Genetically modified microorganisms can produce recombinant bioactive compounds, including growth promoters, vaccines, antimicrobial agents, and immune stimulators. These innovations offer cost-effective strategies for managing diseases, potentially reducing reliance on labor-intensive techniques such as intramuscular or intraperitoneal vaccine injections, which are particularly challenging for small fish and juveniles on a large scale [268–270]. Current advances in microalgae-based aquaculture feeds show great potential for expanding and enhancing the effectiveness of oral medications in this field. By harnessing their natural bioactive properties and utilizing advanced biotechnologies, microalgae can promote sustainable aquaculture practices. This, in turn, can lead to better nutritional outcomes and increased disease resistance in aquatic species.

3.7. SDG 15: life on land

Microalgae play a crucial role in enhancing soil fertility and quality through nutrient solubilization and mineralization processes. They release polysaccharides, hormones, antimicrobial compounds, and other metabolites that promote plant growth and optimize nutrient utilization in the soil [271]. As green and cost-effective biostimulants, microalgae enhance nutrient concentrations, improve soil-quality traits, and increase plant resilience to environmental stressors. These properties make them attractive choices for environmentally conscious farmers and gardeners [272]. Biostimulants derived from microalgae can be applied in various contexts, from laboratory seedlings to hydroponic, greenhouse, and field experiments [273]. Although macroalgae have already been established as commercial soil additives, microalgae with similar biostimulant characteristics have emerged [274]. Experimental findings demonstrate that microalgae like *Scenedesmus quadricauda* and *Chlorella vulgaris* effectively improve root characteristics and plant biomass in various cultivation systems, including sugar beets and tomatoes. Microalgae produce biologically active compounds that enhance plant resilience to environmental stressors and promote the growth of beneficial bacteria in the rhizosphere. For example, cyanobacteria, such as *Calothrix elenkinii*, enhance rice biomass [275–277]. Microalgae positively affect both plant health and soil quality by improving the soil structure, promoting soil aggregation, and increasing organic carbon levels. These benefits reduce erosion, retain nutrients, and prevent eutrophication in nearby water systems [278]. Microalgae also defend plants against pathogens by secreting antimicrobial agents. Overall, algae-based biostimulants have a significant potential to promote sustainable agriculture and mitigate the environmental damage caused by nutrient runoff and soil degradation [279,280].

Microalgae-based bioproducts offer several advantages because they do not require arable land typically used in agriculture. Consequently, they reduce competition with food production systems and positively affect land use dynamics [281]. Algal cultivation occupies approximately five times less space than land-based plants that are commonly used for oil production [282]. The use of microalgae in agriculture is advantageous because it enhances public acceptance and supports large-scale production systems without compromising agricultural development or food security. However, several obstacles have hindered the widespread application of microalgae in agriculture. These challenges include selecting suitable strains for specific purposes and managing high initial and operational cultivation and harvesting costs [283,284]. Climatic conditions can also affect algal cultivation because moderate to high temperatures are typically required for success [285]. Despite recent advancements in Australia and Europe, the use of algae as feed ingredients and nutritional supplements has been significantly boosted by federal programs and initiatives in these countries [286–288]. The potential of algae to increase agricultural sustainability and nutritional value is gaining recognition. However, significant challenges must be addressed before they can be widely adopted. These advancements highlight the critical need to overcome these obstacles.

4. Technical and economic challenges

The use of microalgae in wastewater treatment shows promise; however, practical and economic challenges have hindered its widespread adoption in industry. A significant obstacle is the substantial amount of energy required for microalgal cultivation. Similar to traditional wastewater treatment methods, microalgae culture often requires aeration and pumping systems. These systems generate turbulent flow, which is necessary to facilitate the exchange of oxygen and carbon dioxide and maintain an optimal environment conducive to microalgal growth. Techno-economic evaluation of microalgal technology in the Arabian Gulf has produced promising financial outcomes, as evidenced by recent findings. This assessment focused on the biofixation of flue gas in conjunction with wastewater treatment. These outcomes indicate promising financial prospects for emerging economies that aim to decrease their reliance on mineral oil-based economies. This highlights the potential of microalgal technology as a sustainable and economically feasible solution for wastewater treatment and energy production, particularly in regions striving to diversify their energy sources [289]. The break-even selling price (BESP) for bio-crude produced has been reported to be $0.544 per kg of biomass. This translates to approximately $0.9 per liter of extracted bio-crude, which covers operational expenditure (OPEX) [77]. High-rate algal ponds (HRAPs) have demonstrated considerable potential for the treatment of municipal wastewater, particularly in regions with abundant solar radiation. A recent life-cycle sustainability assessment comparing algae- and bacteria-based wastewater treatment systems found that HRAPs are more environmentally friendly and economically advantageous. Specifically, the cost was found to be 0.18 €/m^3 for HRAPs compared with 0.26 €/m^3 for conventional systems [196]. These findings highlight the potential of microalgae-based systems, not only in terms of environmental sustainability but also in terms of economic viability. HRAPs contribute to CO_2 sequestration and reduce eutrophication potential, with figures of 146.27 versus 458.27 × 10–3 kg CO_2 equiv./m^3 and 126.14 versus 158.01 × 10–6 kg PO_4 equiv./m^3, respectively. Another study explored HRAPs' potential of HRAPs to produce low-cost biofuels from wastewater by estimating an energy output of 800–1400 GJ/ha/year from harvested algal biomass [290,291].

Life-cycle analyses conducted by [292,293] highlighted the significant operational energy consumption during the cultivation stage of microalgal biomass production. Various studies have indicated that mixing in photobioreactors (PBRs) using pumping and aeration consumes approximately ten times more energy than mixing with paddlewheels in high-rate algae ponds (HRAPs) [294]. Specifically, the recirculation pumps consumed 24 kWh/d per unit, whereas the aeration pumps consumed 96 kWh/d per unit. The higher energy consumption of the recirculation pumps was due to the operation of ten units compared to one unit of the aeration pump. Overall, the energy consumption rate reached 15 kWh/m^3, significantly exceeding that of mechanical and/or aerated mixing in conventional wastewater treatment systems (ranging from 0.15 to 0.62 kWh/m3) [295].

Aeration plays a crucial role in microalgae cultivation. Its primary purpose is to supply carbon in the form of CO_2, which is a vital nutrient for microalgal growth. Additionally, aeration enhances the uptake of inorganic nitrogen and phosphorus, which are crucial elements in microalgal growth and metabolic activities. This process ensures optimal growth conditions and contributes to the efficiency of microalgae cultivation for various applications, including biofuel production and wastewater treatment [235]. However, energy-intensive air compression (with or without CO_2 enrichment) significantly contributes to the high operational costs. To address this, a practical approach involves the direct addition of a dissolved carbon source, such as bicarbonate or glucose, to the culture medium [296–300]. This method aims to optimize microalgae incorporation of additional carbon. Furthermore, incorporating carbon-rich waste materials can bolster microalgae wastewater supply and align with broader environmental goals by promoting resource recovery, minimizing material costs, and adhering to circular economic principles.

The extent to which microalgae can be effectively integrated into wastewater treatment processes depends heavily on the specific stage at which they are added. Traditionally, microalgae have been utilized in tertiary treatment stages, which follow an energy-intensive secondary treatment phase, further reducing the concentrations of inorganic nitrogen and phosphorus. However, this approach does not significantly lower the overall energy demand because it requires additional mixing and aeration. A more efficient alternative could be to incorporate microalgae earlier in the treatment process, specifically as a secondary biological treatment step, when applied to primary-settled wastewater. This approach can optimize energy usage and improve treatment efficiency by leveraging microalgae's ability to assimilate nutrients and pollutants. While many studies have investigated various microalgal species in wastewater treatment, they often do so under different environmental and cultivation conditions. Implementing standardized protocols and consistent environmental conditions could yield more robust insights into microalgae's role in wastewater treatment, paving the way for more effective and sustainable wastewater management strategies.

5. Challenges and future perspectives

Microalgae are frequently acclaimed for their rapid growth rates and outstanding carbon sequestration capabilities. Consequently, it is imperative to evaluate these claims thoroughly. Microalgae are known for their accelerated growth and effective carbon capture; however, this does not necessarily make them suitable for all applications. Their ability to flourish in various environments, including infertile land and wastewater, is noteworthy; however, it does not guarantee their survival under all conditions. Furthermore, although microalgae can process both organic and inorganic carbon sources to enhance their carbon sequestration potential, the efficiency of this process under different environmental conditions remains to be investigated thoroughly. Although promising, microalgae capabilities should be evaluated using a critical eye [301]. Additionally, microalgal biomass contains various secondary metabolites, including lipids, pigments, proteins, and carbohydrates [302,303]. These compounds have diverse applications in various industries, ranging from energy and health to cosmetics [304]. *Dunaliella*, *Tetraselmis*, and *Spirulina* are widely recognized for their natural antioxidant properties. In particular, *Schizochytrium* sp. is renowned for its omega-3 fatty acids used in the production of yogurt beverages. Furthermore, *Chlorella* sp. has also been utilized to create nutritious snacks [305].

Despite these potential benefits, the economic viability of microalgae as a means of carbon dioxide sequestration remains a significant hurdle. Open-pond cultivation systems tend to exhibit low productivity, and outdoor cultivation is susceptible to bacterial and fungal contamination [306]. The significance of microalgae in carbon sequestration has been highlighted by various factors, emphasizing the need for technological advancements and improved cultivation methods to increase efficiency and lower production costs. This could unlock the full potential of microalgae in carbon sequestration and other applications.

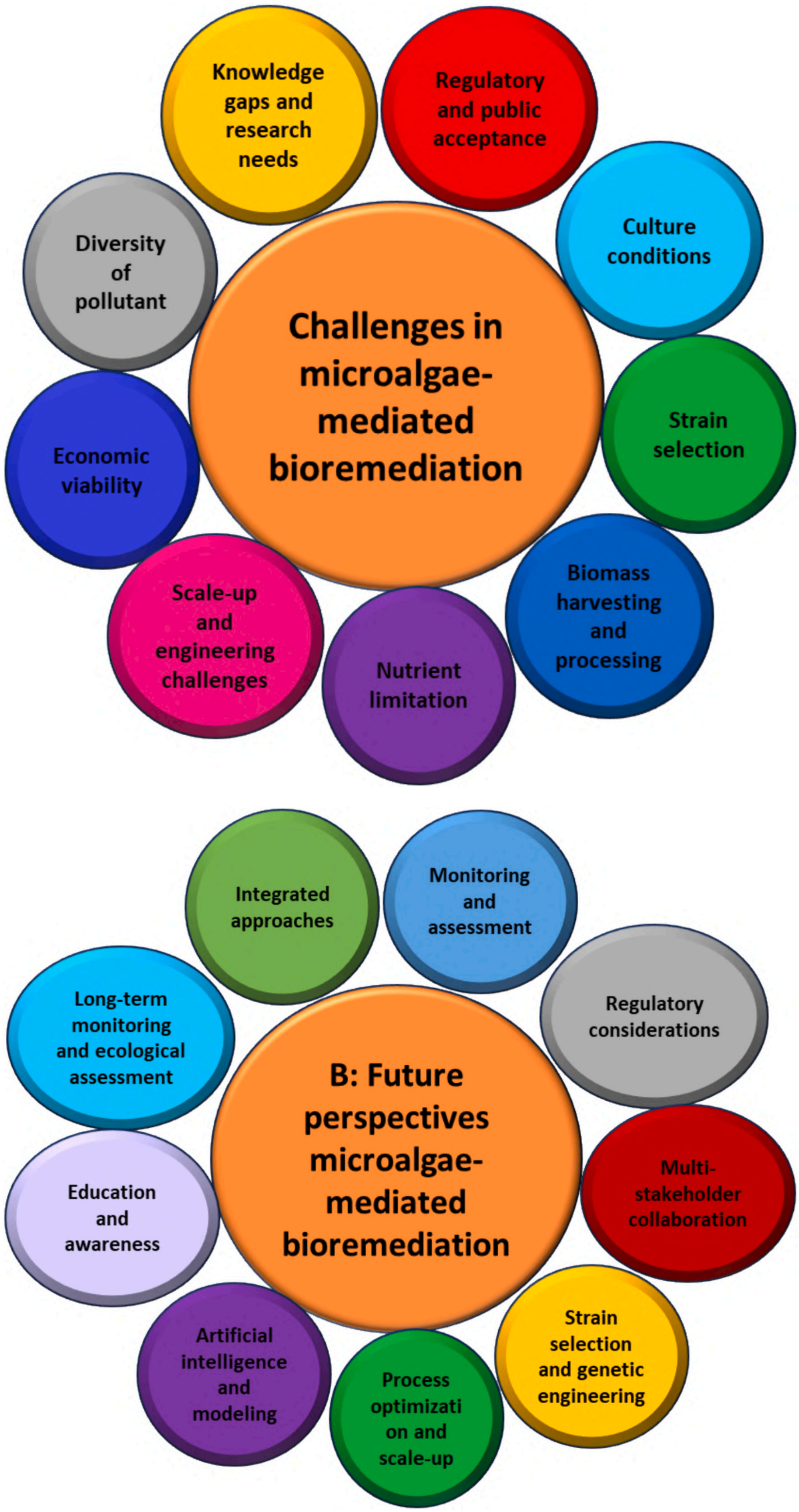

Fig. 6. Challenges and future perspectives of microalgae-mediated bioremediation of wastewater.

Unfortunately, closed photobioreactors are associated with high operational costs [307]. Over the past two decades, several large-scale facilities have been developed to treat industrial flue gas using microalgae. Although microalgae-mediated bioremediation offers great potential as a sustainable solution for environmental pollution, several challenges, illustrated in Fig. 6, must be overcome for its successful implementation.

Notable examples include Termizo Inc. and Fukushima Municipal Waste Treatment Plants, which collectively process over 90,000 tons of waste annually. These plants utilize waste gas and water to cultivate microalgae harvested for biodiesel production. The Fukushima plant, in particular, produces 60.55 metric tons of dry microalgal biomass each year and recycles 83.3 metric tons of CO_2 annually [113]. However, the direct use of flue gas poses challenges because of the high concentrations of NO_X and SO_X, which can harm microalgal cells and inhibit their growth. Therefore, capturing CO_2 directly from flue gas is not the preferred approach. Most microalgae-based carbon sequestration studies have been conducted in laboratory settings, with only a limited number of experiments conducted outdoors in natural environments. Although phytohormones can boost efficiency, the additional costs associated with their use could pose a significant barrier to large-scale cultivation. However, promising innovations such as microbubble systems, low-cost adsorbents, and genetic engineering techniques that are intended to improve CO_2 fixation by microalgae have emerged on the horizon. Several steps must be taken to harness the potential of microalgae for carbon sequestration on a commercial scale. These include deepening our understanding of the mechanisms underlying carbon fixation, selecting strains that produce high levels of biomass, developing effective cultivation and harvesting techniques, integrating carbon fixation with the development of value-added products, and conducting comprehensive techno-economic analyses [308].

Genetic engineering presents significant potential for creating microalgal strains that thrive under elevated CO_2 levels and adverse environmental conditions while maintaining efficient carbon fixation. Considering the potential benefits and obstacles that may surface, it is crucial to evaluate these advancements carefully and analytically [309]. This review highlighted the significant contribution of microalgae to sustainable development and climate resilience. This underscores the importance of microalgae as a sustainable alternative to traditional farming methods by demonstrating their ability to supply essential nutrients, purify wastewater, and sequester carbon. Additionally, we illustrate how microalgal biofuels can facilitate the transition to a low-carbon economy while enhancing environmental remediation and waste management practices. Cross-disciplinary collaboration and research can fully harness the potential of microalgae to address critical global challenges and make substantial progress towards achieving the United Nations' SDGs. Ultimately, this study advocates further exploration and innovation in microalgae utilization, setting the foundation for a more sustainable future.

6. Conclusions

This review highlights the pivotal role of microalgae in wastewater remediation and ecological restoration. The cultivation of microalgae in wastewater facilitates bioenergy generation and highlights their significant environmental and economic value. Delving into specifics

1. Microalgae utilize nutrients from wastewater for growth, reduce pollutants, and aid in ecological restoration by cleaning contaminated environments and generating biomass.
2. Cultivating microalgae in wastewater systems contributes to environmental remediation and serves as a source of bioenergy through biomass production, supporting sustainable water management and renewable energy generation.
3. Microalgae can rehabilitate degraded land, enhance soil fertility, and promote plant growth. They can be integrated into sustainable agriculture by producing biofertilizers and bioactive compounds to improve crop yield.
4. Microalgae absorb CO_2 during growth and contribute to climate-change mitigation. Their role in large-scale biomass production is crucial for bioenergy generation, as they offer an alternative to fossil fuels and enhance energy security.
5. Despite their potential, high production costs have hindered their widespread application, particularly in harvesting and processing. Microalgae are sensitive to environmental variables, which poses challenges for consistent large-scale cultivation. Technological innovations and cost-effective strategies are required to overcome these limitations.
6. Microalgae contribute to SDG 7 (Clean Energy) as a renewable biofuel source. They supported SDGs 8, 9, and 12 by fostering sustainable economic growth, innovation in bio-based industries, and responsible production practices. Their environmental impact aligns with SDGs 6, 11, 13, 14, and 15, which promote water purification, sustainable cities, climate action, and biodiversity conservation.
7. Microalgae produce high-value bioactive compounds, biofuels, and biofertilizers, supporting various industries, reducing reliance on nonrenewable resources, and promoting sustainability across multiple sectors.
8. Future study is required to reduce production costs through innovations in cultivation, harvesting, and processing technologies. Expanding field-based studies is crucial for understanding the real-world application of micro-algal systems in diverse environments. Investment in interdisciplinary research, policy support, and public-private partnerships is essential to maximize the socio-environmental benefits of microalgae.

CRediT authorship contribution statement

Ashfaq Ahmad: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Syed Salman Ashraf:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors extend their gratitude to Khalifa University, Abu Dhabi, United Arab Emirates, for the support received through ASPIRE, the Technology Program Management pillar of Abu Dhabi's Advanced Technology Research Council (ATRC), under the ASPIRE Research Institute program (VRI-FS grant 8434000459).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2024.106506.

Data availability

No data was used for the research described in the article.

References

[1] R. Stekelorum, et al., Green supply chain management practices and third-party logistics providers' performances: a fuzzy-set approach, Int. J. Prod. Econ. 235 (2021) 108093.

[2] O.A. Ogbolumani, N.I. Nwulu, Multi-objective optimisation of constrained food-energy-water-nexus systems for sustainable resource allocation, Sustain Energy Technol Assess 44 (2021) 100967.
[3] M. Goncharenko, et al., Sustainable Development Goals 2030 and Ways of Achieving Them in a Global Dimension, 2023.
[4] C.W. Tong, W.H. Chen, Guest Editorial for the Special Issue on Sustainable Energy Technologies, Wiley Online Library, 2022, p. 5.
[5] M. Shahbaz, et al., Exploring the growth of sustainable energy technologies: a review, Sustain Energy Technol Assess 57 (2023) 103157.
[6] D.L. Sutherland, et al., How microalgal biotechnology can assist with the UN sustainable development goals for natural resource management, Current Research in Environmental Sustainability 3 (2021) 100050.
[7] Z.L. Lau, et al., A review on the diverse interactions between microalgae and nanomaterials: growth variation, photosynthetic performance and toxicity, Bioresour. Technol. 351 (2022) 127048.
[8] R. Kholssi, et al., 2Biotechnological uses of microalgae: a review on the state of the art and challenges for the circular economy, Biocatal. Agric. Biotechnol. 36 (2021) 102114.
[9] Y. Chisti, Biodiesel from microalgae, Biotechnol. Adv. 25 (3) (2007) 294–306.
[10] A.E.-F. Abomohra, et al., Microalgal biomass production as a sustainable feedstock for biodiesel: current status and perspectives, Renew. Sustain. Energy Rev. 64 (2016) 596–606.
[11] G. Muhammad, et al., Modern developmental aspects in the field of economical harvesting and biodiesel production from microalgae biomass, Renew. Sustain. Energy Rev. 135 (2021) 110209.
[12] C.Y.B. Oliveira, et al., Synergistic effect of growth conditions and organic carbon sources for improving biomass production and biodiesel quality by the microalga Choricystis minor var. minor, Sci. Total Environ. 759 (2021) 143476.
[13] D.M.d.M. Dantas, et al., Evaluation of antioxidant and antibacterial capacity of green microalgae Scenedesmus subspicatus, Food Sci. Technol. Int. 25 (4) (2019) 318–326.
[14] K. Singh, et al., Microalgae from wastewaters to wastelands: leveraging microalgal research conducive to achieve the UN sustainable development goals, Renew. Sustain. Energy Rev. 188 (2023) 113773.
[15] L.D.A. Purba, et al., Enhanced cultivation and lipid production of isolated microalgae strains using municipal wastewater, Environmental Technology & Innovation 27 (2022) 102444.
[16] M. Han, C. Zhang, S.-H. Ho, Immobilized microalgal system: an achievable idea for upgrading current microalgal wastewater treatment, Environmental Science and Ecotechnology 14 (2023) 100227.
[17] F. Hussain, et al., Microalgae an ecofriendly and sustainable wastewater treatment option: biomass application in biofuel and bio-fertilizer production. A review, Renew. Sustain. Energy Rev. 137 (2021) 110603.
[18] K.K. Jaiswal, et al., Microalgae fuel cell for wastewater treatment: recent advances and challenges, Journal of Water Process Engineering 38 (2020) 101549.
[19] X. Li, et al., Advanced wastewater treatment with microalgae-indigenous bacterial interactions, Environmental Science and Ecotechnology 20 (2024) 100374.
[20] J.I. Mardones, et al., Disentangling the environmental processes responsible for the world's largest farmed fish-killing harmful algal bloom: Chile, 2016, Sci. Total Environ. 766 (2021) 144383.
[21] C.Y.B. Oliveira, et al., A Scientometric overview of global dinoflagellate research, Publications 8 (4) (2020) 50.
[22] A. Ahmad, et al., Algae biotechnology for industrial wastewater treatment, bioenergy production, and high-value bioproducts, Sci. Total Environ. 806 (2022) 150585.
[23] R. Raman, et al., Aligning sustainable aviation fuel research with sustainable development goals: trends and thematic analysis, Energy Rep. 12 (2024) 2642–2652.
[24] A. Ahmad, A. Buang, A.H. Bhat, Renewable and sustainable bioenergy production from microalgal co-cultivation with palm oil mill effluent (POME): a review, Renew. Sustain. Energy Rev. 65 (2016) 214–234.
[25] A.G. Olabi, et al., Role of microalgae in achieving sustainable development goals and circular economy, Sci. Total Environ. 854 (2023) 158689.
[26] M.I. Khan, J.H. Shin, J.D. Kim, The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products, Microb. Cell Fact. 17 (2018) 36, https://doi.org/10.1186/s12934-018-0879-x.
[27] B. Elisabeth, F. Rayen, T. Behnam, Microalgae culture quality indicators: a review, Crit. Rev. Biotechnol. 41 (4) (2021) 457–473.
[28] M.I. Khan, J.H. Shin, J.D. Kim, The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products, Microb. Cell Fact. 17 (1) (2018) 36.
[29] F. Khavari, et al., Microalgae: therapeutic potentials and applications, Mol. Biol. Rep. 48 (5) (2021) 4757–4765.
[30] N. Yan, et al., The potential for microalgae as bioreactors to produce pharmaceuticals, Int. J. Mol. Sci. 17 (6) (2016) 962.
[31] O. Nam, et al., A protein blueprint of the diatom CO₂−fixing organelle, Cell 187 (21) (2024) 5935–5950.e18.
[32] Choudhary, M.P. and V. Garg. Causes, consequences and control of air pollution. in All India seminar on methodologies for air pollution control, held at MNIT. 2013.
[33] H. Paramesh, Current scenario of air pollution in relation to respiratory health, Curr. Sci. 116 (8) (2019) 1289–1292.
[34] J. Sentian, et al., Long-term air pollution trend analysis in Malaysia, International Journal of Environmental Impacts 2 (4) (2019) 309–324.
[35] S. Batterman, R. Ganguly, P. Harbin, High resolution spatial and temporal mapping of traffic-related air pollutants, Int. J. Environ. Res. Public Health 12 (4) (2015) 3646–3666.
[36] Z. Dong, et al., Regional transport in Beijing-Tianjin-Hebei region and its changes during 2014–2017: the impacts of meteorology and emission reduction, Sci. Total Environ. 737 (2020) 139792.
[37] F. Dong, et al., Combined effects of CO2-driven ocean acidification and Cd stress in the marine environment: enhanced tolerance of Phaeodactylum tricornutum to Cd exposure, Mar. Pollut. Bull. 150 (2020) 110594.
[38] E. Sanidas, et al., Air pollution and arterial hypertension. A new risk factor is in the air, J. Am. Soc. Hypertens. 11 (11) (2017) 709–715.
[39] O.A. Olalere, et al., Leveraging microalgae utilization for anthropogenic CO2 emission abatement in Malaysian urban Centre: revisiting the sustainable development goal (SDG-13), Physics and Chemistry of the Earth, Parts A/B/C 129 (2023) 103356.
[40] J. Laherrère, C.A. Hall, R. Bentley, How much oil remains for the world to produce? Comparing assessment methods, and separating fact from fiction, Current Research in Environmental Sustainability 4 (2022) 100174.
[41] A. Ahmad, K.A. Amin, S.S. Ashraf, Biological effects of culture medium on Tetraselmis chuii and Dunaliella tertiolecta: implications for emerging pollutants degradation, Chemosphere 363 (2024) 142868.
[42] Y. Cai, et al., Sequencing batch reactor (SBR) and anoxic and oxic process (a/O) display opposite performance for pollutant removal in treating digested effluent of swine wastewater with low and high COD/N ratios, J. Clean. Prod. 372 (2022) 133643.
[43] A. Bora, et al., Microalgae to bioenergy production: recent advances, influencing parameters, utilization of wastewater – a critical review, Sci. Total Environ. 946 (2024) 174230.
[44] R. Kholssi, et al., Microalgae as a sustainable energy source: growth and lipids production of Nitzschia sp., Nannochloropsis sp., and Tetraselmis sp. from Mediterranean seawater. Biocatalysis and agricultural, Biotechnology 50 (2023) 102720.
[45] A. Abdelfattah, et al., Microalgae-based wastewater treatment: mechanisms, challenges, recent advances, and future prospects, Environmental Science and Ecotechnology 13 (2023) 100205.
[46] C. Zhang, et al., Revealing the role of microalgae-bacteria niche for boosting wastewater treatment and energy reclamation in response to temperature, Environmental Science and Ecotechnology 14 (2023) 100230.
[47] I. Josa, M. Garfí, Social life cycle assessment of microalgae-based systems for wastewater treatment and resource recovery, J. Clean. Prod. 407 (2023) 137121.
[48] S.A. Vaz, et al., Recent reports on domestic wastewater treatment using microalgae cultivation: towards a circular economy, Environmental Technology & Innovation 30 (2023) 103107.
[49] A.F.M. Udaiyappan, et al., A review of the potentials, challenges and current status of microalgae biomass applications in industrial wastewater treatment, Journal of Water Process Engineering 20 (2017) 8–21.
[50] A. Ahmad, A.H. Bhat, A. Buang, Biosorption of transition metals by freely suspended and ca-alginate immobilised with Chlorella vulgaris: kinetic and equilibrium modeling, J. Clean. Prod. 171 (2018) 1361–1375.
[51] V. Nambukrishna, J. Singaram, Investigation on tannery wastewater as feedstock for marine microalgae in biofuel production, Tierarztl. Prax. 40 (2020).
[52] A. Rajalakshmi, T. Silambarasan, R. Dhandapani, Small scale photo bioreactor treatment of tannery wastewater, heavy metal biosorption and CO2 sequestration using microalga Chlorella sp.: a biodegradation approach. Applied water, Science 11 (7) (2021) 108.
[53] A. Azarpour, et al., A review on microalgal biomass and biodiesel production through co-cultivation strategy, Energ. Conver. Manage. 267 (2022) 115757.
[54] P. Li, Y. Luo, X. Yuan, Life cycle and techno-economic assessment of source-separated wastewater-integrated microalgae biofuel production plant: a nutrient organization approach, Bioresour. Technol. 344 (2022) 126230.
[55] X. Li, et al., Co-cultivation of microalgae-activated sludge for municipal wastewater treatment: exploring the performance, microbial co-occurrence patterns, microbiota dynamics and function during the startup stage, Bioresour. Technol. 374 (2023) 128733.
[56] C.E. Najar-Almanzor, et al., Microalgae-assisted green bioremediation of food-processing wastewater: a sustainable approach toward a circular economy concept, J. Environ. Manage. 345 (2023) 118774.
[57] K.K. Jaiswal, et al., Bio-flocculation of oleaginous microalgae integrated with municipal wastewater treatment and its hydrothermal liquefaction for biofuel production, Environmental Technology & Innovation 26 (2022) 102340.
[58] Z. Li, L. Zhu, The scientometric analysis of the research on microalgae-based wastewater treatment, Environ. Sci. Pollut. Res. 28 (20) (2021) 25339–25348.
[59] M. Jain, et al., Current perspective of innovative strategies for bioremediation of organic pollutants from wastewater, Bioresour. Technol. 344 (2022) 126305.
[60] S.J. Varjani, E. Gnansounou, A. Pandey, Comprehensive review on toxicity of persistent organic pollutants from petroleum refinery waste and their degradation by microorganisms, Chemosphere 188 (2017) 280–291.
[61] S.R. Subashchandrabose, et al., Mixotrophic cyanobacteria and microalgae as distinctive biological agents for organic pollutant degradation, Environ. Int. 51 (2013) 59–72.
[62] A. Fernández, et al., Recovery of nutrients from wastewaters using microalgae, Frontiers in Sustainable Food Systems 2 (59) (2018).
[63] J.T. da Fontoura, et al., Influence of light intensity and tannery wastewater concentration on biomass production and nutrient removal by microalgae

Scenedesmus sp, Process Safety and Environmental Protection 111 (2017) 355–362.
[64] S. Begum, et al., Phycoremediation of tannery dye wastewater using green microalga: bioremediation of tannery dye wastewater, History 1 (3) (2015) 192–197.
[65] N. Kottangodan, et al., Phycoremediation of hazardous mixed industrial effluent by a marine strain of Phormidium sp. CLEAN–Soil, Air, Water 47 (6) (2019) 1800264.
[66] C. Das, et al., Bioremediation of tannery wastewater by a salt-tolerant strain of Chlorella vulgaris, J. Appl. Phycol. 29 (1) (2017) 235–243.
[67] A.C. Pena, et al., Influence of period light on cultivation of microalgae consortium for the treatment of tannery wastewaters from leather finishing stage, J. Clean. Prod. 263 (2020) 121618.
[68] K.V. Ajayan, et al., Phycoremediation of tannery wastewater using microalgae Scenedesmus species, Int. J. Phytoremediation 17 (10) (2015) 907–916.
[69] S. Mirza, et al., Biosorption of chromium from tannery effluent using carbon-activated algae granules of Chlorella vulgaris and Scenedesmus obliquus, Int. J. Environ. Sci. Technol. (2021) 1–10.
[70] B. Lekshmi, et al., Studies on reduction of inorganic pollutants from wastewater by Chlorella pyrenoidosa and Scenedesmus abundans, Alex. Eng. J. 54 (4) (2015) 1291–1296.
[71] G.K.S.H. Nishshanka, et al., Sustainable cultivation of Haematococcus pluvialis and Chromochloris zofingiensis for the production of astaxanthin and co-products, Can. J. Chem. Eng. 100 (10) (2022) 2835–2849.
[72] D. Nagarajan, et al., Resource recovery from wastewaters using microalgae-based approaches: a circular bioeconomy perspective, Bioresour. Technol. 302 (2020) 122817.
[73] L. Shen, et al., The critical utilization of active heterotrophic microalgae for bioremoval of Cr (VI) in organics co-contaminated wastewater, Chemosphere 228 (2019) 536–544.
[74] S. Gupta, S.B. Pawar, R.A. Pandey, Current practices and challenges in using microalgae for treatment of nutrient rich wastewater from agro-based industries, Sci. Total Environ. 687 (2019) 1107–1126.
[75] M. Kube, et al., The impact of wastewater characteristics, algal species selection and immobilisation on simultaneous nitrogen and phosphorus removal, Algal Research 31 (2018) 478–488.
[76] W. Kong, et al., Review on carbon dioxide fixation coupled with nutrients removal from wastewater by microalgae, J. Clean. Prod. 292 (2021) 125975.
[77] S.F. Mohsenpour, et al., Integrating micro-algae into wastewater treatment: a review, Sci. Total Environ. 752 (2021) 142168.
[78] L.E. de-Bashan, Y. Bashan, Immobilized microalgae for removing pollutants: review of practical aspects, Bioresour. Technol. 101 (6) (2010) 1611–1627.
[79] I. Moreno-Garrido, Microalgae immobilization: current techniques and uses, Bioresour. Technol. 99 (10) (2008) 3949–3964.
[80] N. Mallick, Biotechnological potential of immobilized algae for wastewater N, P and metal removal: a review, Biometals 15 (4) (2002) 377–390.
[81] G.C. de Jesus, R. Gaspar Bastos, M. Altenhofen da Silva, Production and characterization of alginate beads for growth of immobilized Desmodesmus subspicatus and its potential to remove potassium, carbon and nitrogen from sugarcane vinasse. Biocatalysis and agricultural, Biotechnology 22 (2019) 101438.
[82] A. Alhumairi, R. Hamouda, A. Saddiq, Comparative study between immobilized and suspended Chlorella sp in treatment of pollutant sites in Dhiba port Kingdom of Saudi Arabia, Heliyon 8 (9) (2022) e10766.
[83] G. Mujtaba, et al., Removal of nutrients and COD through co-culturing activated sludge and immobilized Chlorella vulgaris, Chem. Eng. J. 343 (2018) 155–162.
[84] Huang, F., et al., Recognition of typical antibiotic residues in environmental media related to groundwater in China (2009–2019). J. Hazard. Mater., 2020. 399: p. 122813.
[85] M. Kumar, et al., Antibiotics bioremediation: perspectives on its ecotoxicity and resistance, Environ. Int. 124 (2019) 448–461.
[86] L. Leng, et al., Use of microalgae based technology for the removal of antibiotics from wastewater: a review, Chemosphere 238 (2020) 124680.
[87] K. Reddy, et al., Algae-mediated processes for the treatment of antiretroviral drugs in wastewater: prospects and challenges, Chemosphere 280 (2021) 130674.
[88] J. Lu, C. Zhang, J. Wu, Removal of steroid hormones from mariculture system using seaweed Caulerpa lentillifera, Front. Environ. Sci. Eng. 16 (2) (2021) 15.
[89] W. Ahmad, H.C. Joshi, S. Kumar, Algae mediated photodegradation of fluroquinolone antibiotic: Ofloxacin, Current Research in Green and Sustainable Chemistry 5 (2022) 100269.
[90] M. Sun, et al., Bioaccumulation and biodegradation of sulfamethazine in Chlorella pyrenoidosa, J. Ocean Univ. China 16 (2017) 1167–1174.
[91] Q. Xiong, et al., Co-metabolism of sulfamethoxazole by a freshwater microalga Chlorella pyrenoidosa, Water Res. 175 (2020) 115656.
[92] K.L. Grimes, et al., Evaluating the efficacy of an algae-based treatment to mitigate elicitation of antibiotic resistance, Chemosphere 237 (2019) 124421.
[93] I. Moro, et al., Morpho-physiological responses by Isochrysis galbana Parke to different concentrations of oxytetracycline, Environ. Pollut. 262 (2020) 114273.
[94] C. Kiki, et al., Dissipation of antibiotics by microalgae: kinetics, identification of transformation products and pathways, J. Hazard. Mater. 387 (2020) 121985.
[95] L. Ferrando, V. Matamoros, Attenuation of nitrates, antibiotics and pesticides from groundwater using immobilised microalgae-based systems, Sci. Total Environ. 703 (2020).
[96] J.-C. Lee, J.K. Jang, H.-W. Kim, Sulfonamide degradation and metabolite characterization in submerged membrane photobioreactors for livestock excreta treatment, Chemosphere 261 (2020).
[97] X.L. Bai, K. Acharya, Removal of trimethoprim, sulfamethoxazole, and triclosan by the green alga Nannochloris sp, J. Hazard. Mater. 315 (2016) 70–75.
[98] X.L. Bai, K. Acharya, Algae-mediated removal of selected pharmaceutical and personal care products (PPCPs) from Lake Mead water, Sci. Total Environ. 581 (2017) 734–740.
[100] J.Q. Xiong, M.B. Kurade, B.H. Jeon, Ecotoxicological effects of enrofloxacin and its removal by monoculture of microalgal species and their consortium, Environ. Pollut. 226 (Jul.) (2017) 486.
[101] R. Lopez-Serna, et al., Photobioreactors based on microalgae-bacteria and purple phototrophic bacteria consortia: a promising technology to reduce the load of veterinary drugs from piggery wastewater, Sci. Total Environ. 692 (2019) 259–266.
[102] C.F. Song, et al., Biodegradability and mechanism of florfenicol via Chlorella sp UTEX1602 and L38: experimental study, Bioresour. Technol. 272 (2019) 529–534.
[103] P. Xie, et al., Dual purpose microalgae-based biorefinery for treating pharmaceuticals and personal care products (PPCPs) residues and biodiesel production, Sci. Total Environ. 688 (2019) 253–261.
[104] J.C. Prata, et al., Influence of microplastics on the toxicity of the pharmaceuticals procainamide and doxycycline on the marine microalgae Tetraselmis chuii, Aquat. Toxicol. 197 (2018) 143–152.
[105] R. Jiang, et al., Degradation of cefradine in alga-containing water environment: a mechanism and kinetic study, Environ. Sci. Pollut. Res. 26 (9) (2019) 9184–9192.
[106] IPCC, Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, D.C.R. H.-O. Pörtner, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.), Editor. 2022, Cambridge University Press: Cambridge, UK and New York. p. 3056.
[107] S.V. Hanssen, et al., The climate change mitigation potential of bioenergy with carbon capture and storage, Nat. Clim. Chang. 10 (11) (2020) 1023–1029.
[108] W.Y. Cheah, et al., Biosequestration of atmospheric CO2 and flue gas-containing CO2 by microalgae, Bioresour. Technol. 184 (2015) 190–201.
[109] V. Bhola, et al., Overview of the potential of microalgae for CO2 sequestration, International Journal of Environmental Science and Technology 11 (7) (2014) 2103–2118.
[110] X. Xu, et al., Progress, challenges and solutions of research on photosynthetic carbon sequestration efficiency of microalgae, Renew. Sustain. Energy Rev. 110 (2019) 65–82.
[111] Y. Yang, S. Tang, J.P. Chen, Carbon capture and utilization by algae with high concentration CO2 or bicarbonate as carbon source, Sci. Total Environ. 918 (2024) 170325.
[112] J. Shi, et al., Enzymatic conversion of carbon dioxide, Chem. Soc. Rev. 44 (17) (2015) 5981–6000.
[113] R. Prasad, et al., Role of microalgae in global CO2 sequestration: physiological mechanism, recent development, challenges, and future prospective, Sustainability 13 (23) (2021) 13061.
[114] B. Zhao, Y. Su, Process effect of microalgal-carbon dioxide fixation and biomass production: a review, Renew. Sustain. Energy Rev. 31 (2014) 121–132.
[115] A.F. Alshalif, et al., A systematic review on bio-sequestration of carbon dioxide in bio-concrete systems: a future direction, Eur. J. Environ. Civ. Eng. 26 (3) (2022) 1209–1228.
[116] X.-T. Bui, et al., RETRACTED: Effects of nutrient ratios and carbon dioxide bio-sequestration on biomass growth of Chlorella sp, in: Bubble Column Photobioreactor, Elsevier, 2018.
[117] L. Yan, et al., Effect of excess CO2 on semi-continuous microalgae systems: carbon biofixation, Environmental Technology & Innovation 35 (2024) 103645.
[118] G. Huang, et al., Rapid screening of microalgae by a 96-hole air-flowing device, Bioprocess Biosyst. Eng. 45 (5) (2022) 943–953.
[119] Z. Wang, et al., Comprehensive understanding of regulatory mechanisms, physiological models and key enzymes in microalgal cells based on various concentrations of CO2, Chem. Eng. J. 454 (2023) 140233.
[120] V.K. Bhola, et al., Physiological responses of carbon-sequestering microalgae to elevated carbon regimes, Eur. J. Phycol. 51 (4) (2016) 401–412.
[121] J.-C. Lee, et al., Isolation and screening of indigenous microalgae species for domestic and livestock wastewater treatment, biodiesel production, and carbon sequestration, J. Environ. Manage. 318 (2022) 115648.
[122] C. Chiellini, et al., Remediation capacity of different microalgae in effluents derived from the cigarette butt cleaning process, Plants 11 (13) (2022) 1770.
[123] A. Ghorbani, et al., A review of carbon capture and sequestration in Iran: microalgal biofixation potential in Iran, Renew. Sustain. Energy Rev. 35 (2014) 73–100.
[124] M. Murakami, M. Ikenouchi, The biological CO2 fixation and utilization project by rite (2)—screening and breeding of microalgae with high capability in fixing CO2—, Energ. Conver. Manage. 38 (1997) S493–S497.
[125] H. Dahai, et al., The application of magical microalgae in carbon sequestration and emission reduction: removal mechanisms and potential analysis, Renew. Sustain. Energy Rev. 197 (2024) 114417.
[126] T. Iglina, P. Iglin, D. Pashchenko, Industrial CO2 capture by algae: a review and recent advances, Sustainability 14 (7) (2022) 3801.
[127] S. Paul, et al., Review on the recent structural advances in open and closed systems for carbon capture through algae, Energy Nexus 4 (2021) 100032.
[128] D. Tang, et al., CO2 biofixation and fatty acid composition of Scenedesmus obliquus and Chlorella pyrenoidosa in response to different CO2 levels, Bioresour. Technol. 102 (3) (2011) 3071–3076.

[129] R. Chaudhary, A.K. Dikshit, Y.W. Tong, Carbon-dioxide biofixation and phycoremediation of municipal wastewater using Chlorella vulgaris and Scenedesmus obliquus, Environ. Sci. Pollut. Res. 25 (21) (2018) 20399–20406.
[130] H.V. de Mendonça, et al., Biofuel recovery from microalgae biomass grown in dairy wastewater treated with activated sludge: the next step in sustainable production, Sci. Total Environ. 824 (2022) 153838.
[131] T.D. Moshood, G. Nawanir, F. Mahmud, Microalgae biofuels production: a systematic review on socioeconomic prospects of microalgae biofuels and policy implications, Environmental Challenges 5 (2021) 100207.
[132] M. Rohit, S.V. Mohan, Tropho-metabolic transition during Chlorella sp. cultivation on synthesis of biodiesel, Renew. Energy 98 (2016) 84–91.
[133] A. Raheem, et al., A review on sustainable microalgae based biofuel and bioenergy production: recent developments, J. Clean. Prod. 181 (2018) 42–59.
[134] S. Bhushan, et al., Current trends and prospects in microalgae-based bioenergy production, J. Environ. Chem. Eng. 8 (5) (2020) 104025.
[135] M. El-Sheekh, et al., Screening of different species of Scenedesmus isolated from Egyptian freshwater habitats for biodiesel production, Renew. Energy 129 (2018) 114–120.
[136] Y. He, et al., Direct enzymatic ethanolysis of potential Nannochloropsis biomass for co-production of sustainable biodiesel and nutraceutical eicosapentaenoic acid, Biotechnol. Biofuels 12 (2019) 1–15.
[137] F.J. Choix, C.G. López-Cisneros, H.O. Méndez-Acosta, Azospirillum brasilense increases CO 2 fixation on microalgae Scenedesmus obliquus, Chlorella vulgaris, and Chlamydomonas reinhardtii cultured on high CO 2 concentrations, Microb. Ecol. 76 (2018) 430–442.
[138] M.H. Spalding, et al., Influence of carbon dioxide concentration during growth on fluorescence induction characteristics of the green alga Chlamydomonas reinhardii, Photosynth. Res. 5 (1984) 169–176.
[139] L. Yahya, R. Harun, L.C. Abdullah, Screening of native microalgae species for carbon fixation at the vicinity of Malaysian coal-fired power plant, Sci. Rep. 10 (1) (2020) 22355.
[140] Y. Bo, et al., The influence of spermidine on the build-up of fucoxanthin in Isochrysis sp. acclimated to varying light intensities, Bioresour. Technol. 387 (2023) 129688.
[141] J.Y. Lee, et al., Enhanced carbon dioxide fixation of Haematococcus pluvialis using sequential operating system in tubular photobioreactors, Process Biochem. 50 (7) (2015) 1091–1096.
[142] L. Li, et al., Red light promotes autotrophic growth of Haematococcus pluvialis with improved carbonic anhydrase activity and CO2 utilization, Aquaculture 571 (2023) 739462.
[143] M. Morales, L. Sánchez, S. Revah, The impact of environmental factors on carbon dioxide fixation by microalgae, FEMS Microbiol. Lett. 365 (3) (2018) fnx262.
[144] X.B. Tan, et al., Cultivation of microalgae for biodiesel production: a review on upstream and downstream processing, Chin. J. Chem. Eng. 26 (1) (2018) 17–30.
[145] Y. Yang, et al., Analysis of photosynthetic pigments pathway produced by CO2-toxicity-induced Scenedesmus obliquus, Sci. Total Environ. 867 (2023) 161309.
[146] A.L. Gonçalves, et al., The effect of increasing CO2 concentrations on its capture, biomass production and wastewater bioremediation by microalgae and cyanobacteria, Algal Res. 14 (2016) 127–136.
[147] E.B. Sydney, et al., Potential carbon dioxide fixation by industrially important microalgae, Bioresour. Technol. 101 (15) (2010) 5892–5896.
[148] T.E. Van Den Berg, et al., Light acclimation of the colonial green alga Botryococcus braunii strain Showa, Plant Physiol. 179 (3) (2019) 1132–1143.
[149] J. Jin, et al., Extracellular hydrocarbon and intracellular lipid accumulation are related to nutrient-sufficient conditions in pH-controlled chemostat cultures of the microalga Botryococcus braunii SAG 30.81, Algal research 17 (2016) 244–252.
[150] F. Abd El-Malek, et al., Microorganism-mediated algal biomass processing for clean products manufacturing: current status, challenges and future outlook, Fuel 311 (2022) 122612.
[151] T. Raj, et al., Recent advances in commercial biorefineries for lignocellulosic ethanol production: current status, challenges and future perspectives, Bioresour. Technol. 344 (2022) 126292.
[152] A. Ahmad, F. Banat, H. AlBlooshi, Algal Biotechnology: Integrated Algal Engineering for Bioenergy, Bioremediation, and Biomedical Applications, Elsevier, 2022.
[153] W. Farooq, et al., Monitoring lipids profile, CO2 fixation, and water recyclability for the economic viability of microalgae Chlorella vulgaris cultivation at different initial nitrogen, J. Biotechnol. 345 (2022) 30–39.
[154] V. Mimouni, et al., Chapter 5 - lipids from microalgae, in: I.A. Levine, J. Fleurence (Eds.), Microalgae in Health and Disease Prevention, Academic Press, 2018, pp. 109–131.
[155] T.E. Devi, R. Parthiban, Hydrothermal liquefaction of Nostoc ellipsosporum biomass grown in municipal wastewater under optimized conditions for bio-oil production, Bioresour. Technol. 316 (2020) 123943.
[156] A.S. Adekunle, et al., Biodiesel potential of used vegetable oils transesterified with biological catalysts, Energy Rep. 6 (2020) 2861–2871.
[157] M. Macias Aragonés, et al., Bioenergy production side-streams availability assessment as decision making driver for sustainable valorisation technologies development. Case study: bioethanol and biodiesel industries, Energy Rep. 8 (2022) 6856–6865.
[158] A.T. Hoang, et al., Biofuel production from microalgae: challenges and chances, Phytochem. Rev. 22 (4) (2023) 1089–1126.
[159] K.R. Bukkarapu, A. Krishnasamy, A critical review on available models to predict engine fuel properties of biodiesel, Renew. Sustain. Energy Rev. 155 (2022) 111925.
[160] X. Yao, et al., Catalytic hydrothermal deoxygenation of lipids and fatty acids to diesel-like hydrocarbons: a review, Green Chem. 23 (3) (2021) 1114–1129.
[161] C. Macombe, et al., Social life cycle assessment of biodiesel production at three levels: a literature review and development needs, J. Clean. Prod. 52 (2013) 205–216.
[162] J. Malça, A. Coelho, F. Freire, Environmental life-cycle assessment of rapeseed-based biodiesel: alternative cultivation systems and locations, Appl. Energy 114 (2014) 837–844.
[163] Z. Shokravi, et al., Impacts of the harvesting process on microalgae fatty acid profiles and lipid yields: implications for biodiesel production, Renew. Sustain. Energy Rev. 161 (2022) 112410.
[164] I.S. Tan, et al., Advances of macroalgae biomass for the third generation of bioethanol production, Chin. J. Chem. Eng. 28 (2) (2020) 502–517.
[165] N. Hossain, et al., Feasibility of microalgae as feedstock for alternative fuel in Malaysia: a review, Energ. Strat. Rev. 32 (2020) 100536.
[166] J.R. Melendez, et al., Perspectives in the production of bioethanol: a review of sustainable methods, technologies, and bioprocesses, Renew. Sustain. Energy Rev. 160 (2022) 112260.
[167] Elkatory, M.R., M.A. Hassaan, and A. El Nemr, Chapter 12 - Algal biomass for bioethanol and biobutanol production, in Handbook of Algal Biofuels, M. El-Sheekh and A.E.-F. Abomohra, Editors. 2022, Elsevier. p. 251–279.
[168] S. Maity, N. Mallick, Trends and advances in sustainable bioethanol production by marine microalgae: a critical review, J. Clean. Prod. 345 (2022) 131153.
[169] J.-B. Beigbeder, J.-M. Lavoie, Effect of photoperiods and CO2 concentrations on the cultivation of carbohydrate-rich P. Kessleri microalgae for the sustainable production of bioethanol, Journal of CO2 Utilization 58 (2022) 101934.
[170] A. Vergara-Fernández, et al., Evaluation of marine algae as a source of biogas in a two-stage anaerobic reactor system, Biomass Bioenergy 32 (4) (2008) 338–344.
[171] A. Constantino, et al., Alternative chemo-enzymatic hydrolysis strategy applied to different microalgae species for bioethanol production, Algal Research 56 (2021) 102329.
[172] H.M. Kim, C.H. Oh, H.-J. Bae, Comparison of red microalgae (Porphyridium cruentum) culture conditions for bioethanol production, Bioresour. Technol. 233 (2017) 44–50.
[173] S. Li, et al., Biohydrogen production from microalgae for environmental sustainability, Chemosphere 291 (2022) 132717.
[174] K. Batyrova, P.C. Hallenbeck, Hydrogen production by a Chlamydomonas reinhardtii strain with inducible expression of photosystem II, Int. J. Mol. Sci. 18 (3) (2017) 647.
[175] S.P. Cuellar-Bermudez, et al., Photosynthetic bioenergy utilizing CO2: an approach on flue gases utilization for third generation biofuels, J. Clean. Prod. 98 (2015) 53–65.
[176] S.K. Bhatia, et al., Renewable biohydrogen production from lignocellulosic biomass using fermentation and integration of systems with other energy generation technologies, Sci. Total Environ. 765 (2021) 144429.
[177] S. Lunprom, et al., A sequential process of anaerobic solid-state fermentation followed by dark fermentation for bio-hydrogen production from Chlorella sp, Int. J. Hydrogen Energy 44 (6) (2019) 3306–3316.
[178] Venkiteshwaran, K., et al., Chapter 8 - Anaerobic digester biogas upgrading using microalgae, in Integrated Wastewater Management and Valorization Using Algal Cultures, G.N. Demirer and S. Uludag-Demirer, Editors. 2022, Elsevier. p. 183–214.
[179] O. Gavaldà, et al., Life cycle cost analysis for industrial bioenergy projects: development of a simulation tool and application to three demand sectors in Africa, Energy Rep. 8 (2022) 2908–2923.
[180] H.M. Zabed, et al., Biogas from microalgae: technologies, challenges and opportunities, Renew. Sustain. Energy Rev. 117 (2020) 109503.
[181] S.S. Ali, et al., Enhanced digestion of bio-pretreated sawdust using a novel bacterial consortium: microbial community structure and methane-producing pathways, Fuel 254 (2019) 115604.
[182] S.S. Ali, et al., Enhanced anaerobic digestion performance by two artificially constructed microbial consortia capable of woody biomass degradation and chlorophenols detoxification, J. Hazard. Mater. 389 (2020) 122076.
[183] S.S. Ali, A.M. Mustafa, J. Sun, Wood-feeding termites as an obscure yet promising source of bacteria for biodegradation and detoxification of creosote-treated wood along with methane production enhancement, Bioresour. Technol. 338 (2021) 125521.
[184] S.S. Ali, et al., Construction of novel microbial consortia CS-5 and BC-4 valued for the degradation of catalpa sawdust and chlorophenols simultaneously with enhancing methane production, Bioresour. Technol. 301 (2020) 122720.
[185] A. Ahmad, et al., Biohydrogen production through dark fermentation: recent trends and advances in transition to a circular bioeconomy, Int. J. Hydrogen Energy 52 (2024) 335–357.
[186] A. Ahmad, et al., Evaluation of aerobic and anaerobic co-digestion of Tetraselmis suecica and oil palm empty fruit bunches by response surface methodology, Adv. Mat. Res. 925 (2014) 243–247.
[187] G. Itskos, et al., Chapter 6 - energy and the environment, in: S.G. Poulopoulos, V. J. Inglezakis (Eds.), Environment and Development, Elsevier, Amsterdam, 2016, pp. 363–452.
[188] A. Ahmad, A.H. Bhat, A. Buang, Immobilized Chlorella vulgaris for efficient palm oil mill effluent treatment and heavy metals removal, Desalin. Water Treat. 81 (2017) 105–117.
[189] B.A. Alagöz, O. Yenigün, A. Erdinçler, Ultrasound assisted biogas production from co-digestion of wastewater sludges and agricultural wastes: comparison with microwave pre-treatment, Ultrason. Sonochem. 40 (2018) 193–200.

[190] F. Ometto, et al., Improving the energy balance of an integrated microalgal wastewater treatment process, Waste Biomass Valoriz. 5 (2014) 245–253.
[191] D. Nagarajan, et al., Recent insights into biohydrogen production by microalgae – from biophotolysis to dark fermentation, Bioresour. Technol. 227 (2017) 373–387.
[192] S. Kavitha, et al., Nanoparticle induced biological disintegration: a new phase separated pretreatment strategy on microalgal biomass for profitable biomethane recovery, Bioresour. Technol. 289 (2019) 121624.
[193] A. Olabi, et al., Assessment of the pre-combustion carbon capture contribution into sustainable development goals SDGs using novel indicators, Renew. Sustain. Energy Rev. 153 (2022) 111710.
[194] K. Obaideen, et al., On the contribution of solar energy to sustainable developments goals: case study on Mohammed bin Rashid Al Maktoum Solar Park, International Journal of Thermofluids 12 (2021) 100123.
[195] N. Shehata, et al., Role of refuse-derived fuel in circular economy and sustainable development goals, Process Safety and Environmental Protection 163 (2022) 558–573.
[196] S. Dhahri, A. Omri, Foreign capital towards SDGs 1 & 2—ending poverty and hunger: the role of agricultural production, Struct. Chang. Econ. Dyn. 53 (2020) 208–221.
[197] L. Campagnolo, M. Davide, Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality, World Dev. 122 (2019) 96–109.
[198] Y. Torres-Tiji, F.J. Fields, S.P. Mayfield, Microalgae as a future food source, Biotechnol. Adv. 41 (2020) 107536.
[199] J.L. Pérez-Lloréns, Microalgae: from staple foodstuff to avant-Garde cuisine, International journal of gastronomy and food science 21 (2020) 100221.
[200] R.C. Anyanwu, et al., Optimisation of tray drier microalgae dewatering techniques using response surface methodology, Energies 11 (9) (2018) 2327.
[201] A. Alaswad, et al., Technologies and developments of third generation biofuel production, Renew. Sustain. Energy Rev. 51 (2015) 1446–1460.
[202] R. Rasheed, et al., Solar cultivation of microalgae in a desert environment for the development of techno-functional feed ingredients for aquaculture in Qatar, Sci. Total Environ. 835 (2022) 155538.
[203] L.-E. Rioux, S.L. Turgeon, Seaweed carbohydrates, in: Seaweed Sustainability, Elsevier, 2015, pp. 141–192.
[204] R. Anyanwu, et al., Micro-Macroalgae Properties and Applications, in Reference Module in Materials Science and Materials Engineering, Elsevier BV, 2018.
[205] T.C. do Nascimento, et al., Exploratory data of the microalgae compounds for food purposes, Data Brief 29 (2020) 105182.
[206] M. Lõhmus, J. Balbus, Making green infrastructure healthier infrastructure, Infection ecology & epidemiology 5 (1) (2015) 30082.
[207] A. Ahmad, S.S. Ashraf, Sustainable food and feed sources from microalgae: food security and the circular bioeconomy, Algal Research 74 (2023) 103185.
[208] A. Ahmad, S.W. Hassan, F. Banat, An overview of microalgae biomass as a sustainable aquaculture feed ingredient: food security and circular economy, Bioengineered 13 (4) (2022) 9521–9547.
[209] E. Jacob-Lopes, et al., Bioactive food compounds from microalgae: an innovative framework on industrial biorefineries, Curr. Opin. Food Sci. 25 (2019) 1–7.
[210] A.K. Koyande, et al., Microalgae: a potential alternative to health supplementation for humans, Food Sci. Human Wellness 8 (1) (2019) 16–24.
[211] R. Katiyar, A. Arora, Health promoting functional lipids from microalgae pool: a review, Algal Research 46 (2020) 101800.
[212] L. Gao, et al., Microalgae as future food: rich nutrients, safety, production costs and environmental effects, Sci. Total Environ. 927 (2024) 172167.
[213] X. Li, et al., Extraction and purification of eicosapentaenoic acid and docosahexaenoic acid from microalgae: a critical review, Algal Research 43 (2019) 101619.
[214] B. Nowruzi, G. Sarvari, S. Blanco, Applications of cyanobacteria in biomedicine, in: Handbook of Algal Science, Technology and Medicine, Elsevier, 2020, pp. 441–453.
[215] J. Pruvost, et al., Microalgae culture in building-integrated photobioreactors: biomass production modelling and energetic analysis, Chem. Eng. J. 284 (2016) 850–861.
[216] M.F. de Jesus Raposo, A.M.M.B. de Morais, Microalgae for the prevention of cardiovascular disease and stroke, Life Sci. 125 (2015) 32–41.
[217] M.M.R. Shah, et al., Astaxanthin-producing green microalga Haematococcus pluvialis: from single cell to high value commercial products, Front. Plant Sci. 7 (2016) 531.
[218] M.C. Pina-Pérez, et al., Microalgae as healthy ingredients for functional foods, in: The Role of Alternative and Innovative Food Ingredients and Products in Consumer Wellness, Elsevier, 2019, pp. 103–137.
[219] M. Le Goff, et al., Microalgal carotenoids and phytosterols regulate biochemical mechanisms involved in human health and disease prevention, Biochimie 167 (2019) 106–118.
[220] U. Nations, ESocialSciences, The sustainable development goals (2016) 2016.
[221] G. Markou, et al., Using agro-industrial wastes for the cultivation of microalgae and duckweeds: contamination risks and biomass safety concerns, Biotechnol. Adv. 36 (4) (2018) 1238–1254.
[222] J. Alcamo, Water quality and its interlinkages with the sustainable development goals, Curr. Opin. Environ. Sustain. 36 (2019) 126–140.
[223] L.-H. Li, et al., Use of microalgae for the treatment of black and odorous water: purification effects and optimization of treatment conditions, Algal research 47 (2020) 101851.
[224] A.P. Batista, et al., Combining urban wastewater treatment with biohydrogen production–an integrated microalgae-based approach, Bioresour. Technol. 184 (2015) 230–235.
[225] Y.K. Leong, J.-S. Chang, Bioremediation of heavy metals using microalgae: recent advances and mechanisms, Bioresour. Technol. 303 (2020) 122886.
[226] F. Fu, Q. Wang, Removal of heavy metal ions from wastewaters: a review, J. Environ. Manage. 92 (3) (2011) 407–418.
[227] A. Ahmad, A.H. Bhat, A. Buang, Enhanced biosorption of transition metals by living Chlorella vulgaris immobilized in ca-alginate beads, Environ. Technol. 40 (14) (2019) 1793–1809.
[228] D. Kotoula, et al., Municipal wastewater treatment by combining in series microalgae Chlorella sorokiniana and macrophyte Lemna minor: preliminary results, J. Clean. Prod. 271 (2020) 122704.
[229] E. Daneshvar, et al., Versatile applications of freshwater and marine water microalgae in dairy wastewater treatment, lipid extraction and tetracycline biosorption, Bioresour. Technol. 268 (2018) 523–530.
[230] D. Nagarajan, et al., Current advances in biological swine wastewater treatment using microalgae-based processes, Bioresour. Technol. 289 (2019) 121718.
[231] D.L. Cheng, et al., Microalgae biomass from swine wastewater and its conversion to bioenergy, Bioresour. Technol. 275 (2019) 109–122.
[232] J.M. Prandini, et al., Enhancement of nutrient removal from swine wastewater digestate coupled to biogas purification by microalgae Scenedesmus spp, Bioresour. Technol. 202 (2016) 67–75.
[233] Y. Wang, et al., Nutrients and COD removal of swine wastewater with an isolated microalgal strain Neochloris aquatica CL-M1 accumulating high carbohydrate content used for biobutanol production, Bioresour. Technol. 242 (2017) 7–14.
[234] A. Ahmad, et al., Recent breakthroughs in integrated biomolecular and biotechnological approaches for enhanced lipid and carotenoid production from microalgae, Phytochemistry Reviews 22 (4) (2023) 993–1013.
[235] J. Liu, et al., Wastewater treatment using filamentous algae – a review, Bioresour. Technol. 298 (2020) 122556.
[236] F. Qie, et al., Biological removal of nitrogen oxides by microalgae, a promising strategy from nitrogen oxides to protein production, Bioresour. Technol. 292 (2019) 122037.
[237] H. Chen, Q. Wang, Microalgae-based nitrogen bioremediation. Algal Research 46 (2020) 101775.
[238] K. Skalska, J.S. Miller, S. Ledakowicz, Trends in NOx abatement: a review, Sci. Total Environ. 408 (19) (2010) 3976–3989.
[239] T. Wilberforce, et al., Developments of electric cars and fuel cell hydrogen electric cars, Int. J. Hydrogen Energy 42 (40) (2017) 25695–25734.
[240] A. Ahmad, et al., Aerobic and anaerobic co-cultivation of Nannochloropsis oculata with oil palm empty fruit bunch for enhanced biomethane production and palm oil mill effluent treatment, Desalination and Water Treatment 56 (8) (2015) 2055–2065.
[241] A. Ahmad, et al., Biomethane production and palm oil mill effluent treatment by co-cultivation of Nannochloropsis oculata, Appl. Mech. Mater. 625 (2014) 818–821.
[242] C. Rodriguez, et al., Waste paper and macroalgae co-digestion effect on methane production, Energy 154 (2018) 119–125.
[243] A.A. Akinsemolu, The role of microorganisms in achieving the sustainable development goals, J. Clean. Prod. 182 (2018) 139–155.
[244] C. Onumaegbu, et al., Pre-treatment methods for production of biofuel from microalgae biomass, Renew. Sustain. Energy Rev. 93 (2018) 16–26.
[245] R. Ganesan, et al., A review on prospective production of biofuel from microalgae, Biotechnology Reports 27 (2020) e00509.
[246] A. Ahmad, et al., Enhanced palm oil mill effluent treatment and biomethane production by co-digestion of oil palm empty fruit bunches with Chlorella Sp, Can. J. Chem. Eng. 92 (9) (2014) 1636–1642.
[247] A. Tanaka, et al., On the scaling of climate impact indicators with global mean temperature increase: a case study of terrestrial ecosystems and water resources, Clim. Change 141 (4) (2017) 775–782.
[248] P.L. Bodelier, Toward understanding, managing, and protecting microbial ecosystems, Front. Microbiol. 2 (2011) 80.
[249] F. Castro Hector, et al., Soil microbial community responses to multiple experimental climate change drivers, Appl. Environ. Microbiol. 76 (4) (2010) 999–1007.
[250] B.K. Singh, et al., Microorganisms and climate change: terrestrial feedbacks and mitigation options, Nat. Rev. Microbiol. 8 (11) (2010) 779–790.
[251] C. Gougoulias, J.M. Clark, L.J. Shaw, The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems, J. Sci. Food Agric. 94 (12) (2014) 2362–2371.
[252] P. Smith, Land use change and soil organic carbon dynamics, Nutr. Cycl. Agroecosyst. 81 (2) (2008) 169–178.
[253] S.-Y. Chiu, et al., Microalgal biomass production and on-site bioremediation of carbon dioxide, nitrogen oxide and sulfur dioxide from flue gas using Chlorella sp. cultures, Bioresour. Technol. 102 (19) (2011) 9135–9142.
[254] E.M. Radmann, et al., Isolation and application of SOX and NOX resistant microalgae in biofixation of CO2 from thermoelectricity plants, Energ. Conver. Manage. 52 (10) (2011) 3132–3136.
[255] D.L. Sutherland, R.J. Craggs, Utilising periphytic algae as nutrient removal systems for the treatment of diffuse nutrient pollution in waterways, Algal Research 25 (2017) 496–506.
[256] W. Mulbry, P. Kangas, S. Kondrad, Toward scrubbing the bay: nutrient removal using small algal turf scrubbers on Chesapeake Bay tributaries, Ecol. Eng. 36 (4) (2010) 536–541.

[257] D. Calahan, D. Blersch, W. Adey, Weeds in the algae garden – a source of biomass for the algae-to-biofuels program, Ecol. Eng. 85 (2015) 275–282.
[258] S. Hydromentia, 154 Pilot Single Stage Algal Turf Scrubber (ATS) Final Report, South Florida Water Management District, 2005.
[259] R.B. Draaisma, et al., Food commodities from microalgae, Curr. Opin. Biotechnol. 24 (2) (2013) 169–177.
[260] M. García-Chavarría, M. Lara-Flores, The use of carotenoid in aquaculture, Res. J. Fish. Hydrobiol. 8 (2) (2013) 38–49.
[261] B. Subhadra, Grinson-George, Algal biorefinery-based industry: an approach to address fuel and food insecurity for a carbon-smart world, J. Sci. Food Agric. 91 (1) (2011) 2–13.
[262] A. Neori, "Green water" microalgae: the leading sector in world aquaculture, Journal of Applied Phycology 23 (1) (2011) 143–149.
[263] M. Carus, L. Dammer, The circular bioeconomy—concepts, opportunities, and limitations, Ind. Biotechnol. 14 (2) (2018) 83–91.
[264] T.C. Adarme-Vega, et al., Microalgal biofactories: a promising approach towards sustainable omega-3 fatty acid production, Microb. Cell Fact. 11 (1) (2012) 96.
[265] D. Swanson, R. Block, S.A. Mousa, Omega-3 fatty acids EPA and DHA: health benefits throughout life, Adv. Nutr. 3 (1) (2012) 1–7.
[266] N. Salem Jr., M. Eggersdorfer, Is the world supply of omega-3 fatty acids adequate for optimal human nutrition? Current Opinion in Clinical Nutrition & Metabolic Care 18 (2) (2015).
[267] J. Yarnold, et al., Microalgal Aquafeeds as part of a circular bioeconomy, Trends Plant Sci. 24 (10) (2019) 959–970.
[268] P. Charoonnart, S. Purton, V. Saksmerprome, Applications of microalgal biotechnology for disease control in aquaculture, Biology 7 (2) (2018) 24.
[269] M. Madhumathi, R. Rengasamy, Antioxidant status of Penaeus monodon fed with Dunaliella salina supplemented diet and resistance against WSSV, Int. J. Eng. Sci. Technol. 3 (10) (2011) 7249–7259.
[270] Y.K. Leong, J.-S. Chang, Lutein biosynthesis from microalgae — recent advances and circular economy, Environmental Technology & Innovation 30 (2023) 103097.
[271] Alam, M.A., J.-L. Xu, and Z. Wang, Microalgae biotechnology for food, health and high value products. 2020: Springer.
[272] Y. Rouphael, G. Colla, Biostimulants in agriculture, Front. Plant Sci. 11 (2020) 511937.
[273] P. du Jardin, Plant biostimulants: definition, concept, main categories and regulation, Sci. Hortic. 196 (2015) 3–14.
[274] L. Labeeuw, et al., Indole-3-acetic acid is produced by Emiliania huxleyi coccolith-bearing cells and triggers a physiological response in bald cells, Front. Microbiol. 7 (2016) 183686.
[275] P. Chiaiese, et al., Renewable sources of plant biostimulation: microalgae as a sustainable means to improve crop performance, Front. Plant Sci. 9 (2018) 430391.
[276] N. Renuka, et al., Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges, Biotechnol. Adv. 36 (4) (2018) 1255–1273.
[277] V. Barone, et al., Root morphological and molecular responses induced by microalgae extracts in sugar beet (Beta vulgaris L.), Journal of Applied Phycology 30 (2) (2018) 1061–1071.
[278] H. Priya, et al., Influence of cyanobacterial inoculation on the culturable microbiome and growth of rice, Microbiol. Res. 171 (2015) 78–89.
[279] F. Rachidi, et al., Evaluation of microalgae polysaccharides as biostimulants of tomato plant defense using metabolomics and biochemical approaches, Sci. Rep. 11 (1) (2021) 930.
[280] E. Yilmaz, M. Sönmez, The role of organic/bio–fertilizer amendment on aggregate stability and organic carbon content in different aggregate scales, Soil Tillage Res. 168 (2017) 118–124.
[281] E. Gnansounou, J. Kenthorai Raman, Life cycle assessment of algae biodiesel and its co-products, Appl. Energy 161 (2016) 300–308.
[282] M.L.N.M. Carneiro, et al., Potential of biofuels from algae: comparison with fossil fuels, ethanol and biodiesel in Europe and Brazil through life cycle assessment (LCA), Renew. Sustain. Energy Rev. 73 (2017) 632–653.
[283] Y. Shen, et al., Microalgae mass production methods, Trans. ASABE 52 (4) (2009) 1275–1287.
[284] L. Xu, et al., Microalgal bioreactors: challenges and opportunities, Eng. Life Sci. 9 (3) (2009) 178–189.
[285] S. Pankratz, et al., Algae production platforms for Canada's northern climate, Renew. Sustain. Energy Rev. 80 (2017) 109–120.
[286] Wesseler, J. and J. von Braun, Measuring the Bioeconomy: Economics and Policies. Annual Review of Resource Economics, 2017. 9(Volume 9, 2017): p. 275–298.
[287] A.W. Sheppard, et al., Biosecurity and sustainability within the growing global bioeconomy, Curr. Opin. Environ. Sustain. 3 (1) (2011) 4–10.
[288] K. D'Hondt, G. Jiménez-Sánchez, J. Philp, Reconciling food and industrial needs for an Asian bioeconomy: the enabling power of genomics and biotechnology, Asian Biotechnology & Development Review 17 (2) (2015).
[289] A.M.D. Al Ketife, et al., A technoeconomic assessment of microalgal culture technology implementation for combined wastewater treatment and CO2 mitigation in the Arabian gulf, Process Saf. Environ. Prot. 127 (2019) 90–102.
[290] N. Kohlheb, et al., Assessing the life-cycle sustainability of algae and bacteria-based wastewater treatment systems: high-rate algae pond and sequencing batch reactor, J. Environ. Manage. 264 (2020) 110459.
[291] A. Mehrabadi, M.M. Farid, R. Craggs, Potential of five different isolated colonial algal species for wastewater treatment and biomass energy production, Algal Research 21 (2017) 1–8.
[292] A.L. Stephenson, et al., Life-cycle assessment of potential algal biodiesel production in the United Kingdom: a comparison of raceways and air-lift tubular bioreactors, Energy Fuel 24 (7) (2010) 4062–4077.
[293] O. Jorquera, et al., Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors, Bioresour. Technol. 101 (4) (2010) 1406–1413.
[294] F.G. Acién, et al., Production cost of a real microalgae production plant and strategies to reduce it, Biotechnol. Adv. 30 (6) (2012) 1344–1353.
[295] A.K. Plappally, J.H. Lienhard V, Energy requirements for water production, treatment, end use, reclamation, and disposal, Renew. Sustain. Energy Rev. 16 (7) (2012) 4818–4848.
[296] Davis, R., et al., Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion. 2016: United States.
[297] L. Evans, et al., Effect of organic carbon enrichment on the treatment efficiency of primary settled wastewater by Chlorella vulgaris, Algal Res. 24 (2017) 368–377.
[298] M. Kesaano, et al., Dissolved inorganic carbon enhanced growth, nutrient uptake, and lipid accumulation in wastewater grown microalgal biofilms, Bioresour. Technol. 180 (2015) 7–15.
[299] P.L. Gupta, et al., Enhanced biomass production through optimization of carbon source and utilization of wastewater as a nutrient source, J. Environ. Manage. 184 (2016) 585–595.
[300] O. Perez-Garcia, Y. Bashan, M. Esther Puente, Organic carbon supplementation of sterilized municipal wastewater is essential for heterotrophic growth and removing ammonium by the microalga CHLORELLA VULGARIS1, J. Phycol. 47 (1) (2011) 190–199.
[301] J.O. Ighalo, et al., Progress in microalgae application for CO2 sequestration, Cleaner Chemical Engineering 3 (2022) 100044.
[302] R.K. Goswami, et al., Valorisation of organic carbons and organo-solvents by mixotrophic cultivation of methylotrophic Tetraselmis indica for enhanced biomolecules production, Sustain. Chem. Pharm. 36 (2023) 101281.
[303] W. Lu, et al., Enhanced microalgae growth for biodiesel production and nutrients removal in raw swine wastewater by carbon sources supplementation, Waste and Biomass Valorization 12 (2021) 1991–1999.
[304] M.K. Lam, K.T. Lee, A.R. Mohamed, Current status and challenges on microalgae-based carbon capture, International Journal of Greenhouse gas control 10 (2012) 456–469.
[305] K.K. Jaiswal, et al., Photosynthetic microalgae–based carbon sequestration and generation of biomass in biorefinery approach for renewable biofuels for a cleaner environment, Biomass Convers. Biorefinery (2021) 1–19.
[306] H. Onyeaka, et al., Minimizing carbon footprint via microalgae as a biological capture, Carbon Capture Science & Technology 1 (2021) 100007.
[307] L.N. Nguyen, et al., Microalgae-based carbon capture and utilization: a critical review on current system developments and biomass utilization, Crit. Rev. Environ. Sci. Technol. 53 (2) (2023) 216–238.
[308] W. Zhou, et al., Bio-mitigation of carbon dioxide using microalgal systems: advances and perspectives, Renew. Sustain. Energy Rev. 76 (2017) 1163–1175.
[309] S.S. Oncel, A. Kose, D. Oncel, Carbon sequestration in microalgae photobioreactors building integrated, in: Start-Up Creation, Elsevier, 2020, pp. 161–200.