Journal of Environmental Management 324 (2022) 116415

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Review

Potential use of algae for the bioremediation of different types of wastewater and contaminants: Production of bioproducts and biofuel for green circular economy

Motasem Y.D. Alazaiza [a,*], Ahmed Albahnasawi [b], Zulfiqar Ahmad [c], Mohammed J.K. Bashir [d], Talal Al-Wahaibi [a], Mohammed Shadi S. Abujazar [e], Salem S. Abu Amr [f], Dia Eddin Nassani [g]

[a] Department of Civil and Environmental Engineering, College of Engineering, A'Sharqiyah University, 400, Ibra, Oman
[b] Department of Environmental Engineering, Gebze Technical University, 41400, Kocaeli, Turkey
[c] Department of Environmental Sciences, University of California, Riverside, CA, 92521, USA
[d] Department of Environmental Engineering, Faculty of Engineering and Green Technology (FEGT), Universiti Tunku Abdul Rahman, 31900, Kampar, Perak, Malaysia
[e] Al-aqsa Community Intermediate College, Al-aqsa University, Gaza, Palestine, P.B.4051
[f] International College of Engineering and Management, P.O. Box 2511, C.P.O Seeb, P.C. 111, Oman
[g] Department of Civil Engineering, Hasan Kalyoncu University, 27500, Gaziantep, Turkey

ARTICLE INFO

Keywords:
Phycoremediation
Wastewater treatment
Algal biomass
Biofuel production
Value-added products

ABSTRACT

Remediation by algae is a very effective strategy for avoiding the use of costly, environmentally harmful chemicals in wastewater treatment. Recently, industries based on biomass, especially the bioenergy sector, are getting increasing attention due to their environmental acceptability. However, their practical application is still limited due to the growing cost of raw materials such as algal biomass, harvesting and processing limitations. Potential use of algal biomass includes nutrients recovery, heavy metals removal, COD, BOD, coliforms, and other disease-causing pathogens reduction and production of bioenergy and valuable products. However, the production of algal biomass using the variable composition of different wastewater streams as a source of growing medium and the application of treated water for subsequent use in agriculture for irrigation has remained a challenging task. The present review highlights and discusses the potential role of algae in removing beneficial nutrients from different wastewater streams with complex chemical compositions as a biorefinery concept and subsequent use of produced algal biomass for bioenergy and bioactive compounds. Moreover, challenges in producing algal biomass using various wastewater streams and ways to alleviate the stress caused by the toxic and high concentrations of nutrients in the wastewater stream have been discussed in detail. The technology will be economically feasible and publicly accepted by reducing the cost of algal biomass production and reducing the loaded or attached concentration of micropollutants and pathogenic microorganisms. Algal strain improvement, consortium development, biofilm formation, building an advanced cultivation reactor system, biorefinery concept development, and life-cycle assessment are all possible options for attaining a sustainable solution for sustainable biofuel production. Furthermore, producing valuable compounds, including pharmaceutical, nutraceutical and pigment contents generated from algal biomass during biofuel production, could also help reduce the cost of wastewater management by microalgae.

1. Introduction

Large volumes of wastewater are produced daily due to population growth, urbanization, expanded access to sanitation, and industrialization (Choudhary et al., 2020; Kapoore et al., 2021; Maurya et al., 2022a; Ungureanu et al., 2019), which resulted in a freshwater shortage in the communities living in urban and suburban areas (Abd-Elaty et al., 2022). Therefore, ways are being sought to alleviate the stress of the freshwater supply. One of the most effective sustainable strategies to reduce water scarcity and lessen the burden on our natural environment is recycling and reusing wastewater from different points and non-point sources (Garg et al., 2021). Industrial wastewater (municipal, textile,

* Corresponding author.
E-mail address: my.azaiza@gmail.com (M.Y.D. Alazaiza).

https://doi.org/10.1016/j.jenvman.2022.116415
Received 9 August 2022; Received in revised form 21 September 2022; Accepted 28 September 2022
Available online 4 October 2022

swine, molasses, piggery, and aquaculture) contributes considerably to the pollution in fresh water and traditional water streams (Ahmad et al., 2022). According to the nature of the industry, the majority of wastewater produced includes a range of contaminants, such as metals, oils and grease, insecticides/pesticides, volatile chemical compounds and minerals. In addition, industrial or sewage wastewater is nutrient-rich, and the accumulation of specific contaminants (N and P) may substantially impact the ecosystem (freshwater and saltwater). The heavy reliance on synthetic inputs in modern agriculture has severely impacted vegetation, soil composition, and even water quality (Yong et al., 2021). Agricultural processing facilities for soluble coffee, cassava, and dairy products also contain significant amounts of both organic and inorganic chemicals such as carbohydrates, ammonia, calcium, chloride, inorganic phosphate, magnesium, nitrate, organic carbon, organic phosphorus, potassium, salt, and sulfate (Selvan et al., 2019). These chemicals pose a significant environmental danger (Panchangam and Janakiraman, 2015). Moreover, the industrial and agricultural wastewaters contain up to three orders of magnitude more nitrogen (N) and phosphorus (P) than natural water bodies (Kowthaman et al., 2022; Ungureanu et al., 2019). Total nitrogen and total phosphorus concentrations in aquatic environments (such as rivers and lakes) must be below 0.5 mg/L and 0.03 mg/L, respectively, in order to avoid eutrophication (Smith et al., 1999; Xu et al., 2015). A study conducted in 23 countries with sample data from 269 sewage treatment facilities indicated the concentrations of TN and TP in the effluent in sewage treatment facilities varied widely between 5 and 20 mg/L and 1–4 mg/L.

Strategies for removing or remediation of the contaminants from aquatic bodies have been developed using a variety of physicochemical and biological treatment processes. Membrane filtration, ion exchange, electrochemical treatment, osmosis, precipitation, and evaporation are a few typical physicochemical approaches for wastewater treatment. The majority of these methods, however, are not environmentally friendly or economically sustainable. Additionally, the energy used in wastewater treatment operations accounts for 2–4% of the nation's total electricity consumption. Additionally, specialized labour is required to manage the treatment plants, which have substantial infrastructure capital costs (Castellaños-Estupiñan et al., 2018; Quintero-Dallos et al., 2019; Sparn and Hunsberger, 2015). For these reasons, scientists are looking at microalgae-based wastewater treatment and resource recovery systems. Phytoremediation is a method for employing algae to remediate contaminated water (Phang et al., 2015). In phycoremediation, microalgae can remove or degrade various environmental contaminants, both organic and inorganic, in addition to the nutrients for their growth, such as nitrogen and phosphorus (Phang et al., 2015). However, high organic carbon contents are a limiting factor in the growth of most microalgal species. In that case consortium of microalgae and bacteria is employed, in which heterotrophic bacteria may utilize the organic matter to produce carbon dioxide, which is consumed later by microalgae for biomass production. The method also prevents the adsorption of harmful substances by the algae, which would otherwise transfer them to the treatment areas (Krishnamoorthy and Manickam, 2021). Effluents from various agricultural, industrial, and domestic wastewaters are treated using algae while producing microalgal biomass. Then, this biomass is transformed into useful products (such as bioenergy products, pharmaceuticals, food supplements, pigments, etc.) for their practical use in animal feeding, medicine, food coloring, and fertilizers (Kurniawan et al., 2022; Rodríguez-Rangel et al., 2022). It is the environmentally friendly conversion of algal biomass into various useful and commercial goods (Kumar and Singh, 2019). The numerous high-value products such as proteins, carbohydrates, lipids, medicinal compounds, and distinctive biomass biorefinery products are driving the expansion of the algae-based industry (Mutanda et al., 2020). Compared to conventional bacteria-based bioremediation methods, using algae has several benefits. Due to their advantages over bacterial treatment, microalgae are a better option for treating different types of wastewater. According to Maizatul et al. (2017), microalgae can effectively remove nutrients (70–90%), have a high seasonal tolerance, grow more quickly on nutrients found in wastewater, are environmentally friendly and sustainable processes, produce high-value end products, form less sludge, and are simple to integrate into current wastewater systems (Roostaei and Zhang, 2017). Microalgae are also believed to have a significantly better drug tolerance than bacteria.

Regarding removing harmful heavy metals and organic pollutants, recent research indicates that microalgae-bacteria consortia may be a great option for municipal wastewater treatment (Touliabah et al., 2022; Znad et al., 2022). However, the efficiency with which microalgae remove the nutrients from wastewater might vary depending on many biotic and abiotic environmental factors. Therefore, it is necessary to undertake pilot-scale research and investigate the complexity of pollutants in complex environments. There have been several reports published that illustrates the potential use of algal biomass to produce bioenergy products like biofuels., antibacterial and antiviral compounds, biofuels, biofertilizer, food additives, and value-added chemicals, including PUFAs, pigments, carbohydrate-derived chemicals, etc. (Ahmad et al., 2022; Zhou et al., 2022).

Since microalgae are photosynthetic entities, thus environmental conditions like light, temperature, and pH significantly impact how effectively they can clean up wastewater. The main challenges in algal-based wastewater treatment include maintaining optimal temperature, pH range, and light intensity and duration (Chawla et al., 2020; Rajamohan et al., 2021; Umamaheswari and Shanthakumar, 2021). Biological pollutants, including pathogenic microorganisms, may significantly impact the quality of treated wastewater in addition to abiotic components. The wastewater procedures must properly detect and eliminate them to meet the health standards (Rani et al., 2021; Vieira et al., 2022).

Limited knowledge is available on the utilization of microalgae for different bioremediating types of wastewater (industrial, agricultural, dairy, etc.) loaded with high nutrients under laboratory conditions (Ansari et al., 2021; Cavieres et al., 2021; Cristina et al., 2022; Wiatrowski et al., 2022a). However, those reviews call into question the reliability of laboratory-scale systems results. The conceptual gap between laboratory findings and practical applications makes it noteworthy that the commercial usage of microalgae for bioremediating industrial and agricultural wastewater in actual field conditions remains unclear. To bring out the microalgae-based bioremediation of wastewater with variable composition and sources to commercial-scale systems, this review, for the first time, explores the problems and potential solutions. The main bottlenecks of microalgae cultivation on a large scale, outdoor conditions and high contamination in the wastewater for algal biomass production and subsequently bioenergy and valuable products have been covered in this review.

2. Algae for industrial wastewater treatments

Industrial wastewaters such as refineries wastewater and produced water from pharmaceutical, leather, paint and textile industries pose a significant threat to the environment as it contains a high concentration of hazardous contaminants like heavy metals, organic pollutants, micropollutants, and biological contaminants (Kinidi et al., 2018). Treatment of such wastewater contaminated with hazardous materials is challenging as it may contain a high level of pollutants (Chia et al., 2021; Khan et al., 2017). Recently, algae-based wastewater treatment has shown high potential for treating such industrial pollutants (Hariz et al., 2019; Heidarpour et al., 2019; Smječanin et al., 2022; Zhou et al., 2021) that involves the use of different microalgal species on various compositions of industrial wastewater effluents that perform treatments differently and have different rates of microalgae growth (Chiu et al., 2015; Wu et al., 2014). Compared to the traditional industrial wastewater treatment procedure, microalgae-based industrial wastewater treatment offers reduced operating costs and environmentally friendly choices (Yong et al., 2021). The reduction of biological oxygen demand (BOD), total suspended solids (TSS), pathogens organisms, and lastly, the concentration of nitrogen and phosphorus in the wastewater have all been successfully demonstrated in several studies as evidence for industrial wastewater treatment using microalgae (Table S1) (Khoo et al., 2021). The algal species can accumulate significant amounts of lipids and starch from sewage, which leads to the conclusion that it is possible to remediate wastewater biologically using microalgae. Nutrients removal (N, P, C) efficiency in an industrial wastewater treatment facility by microalgae is highly dependent not only on the type of algal strain, selection of economically feasible bioreactor system but also on speciation and kind of specific nutrient and its concentration in industrial effluent (Mohsenpour et al., 2021a).

The primary process involved in the algal-based industrial wastewater treatment includes adsorption, accumulation, immobilization, and nutrient utilization (Yadav et al., 2021a). Likewise, the composition of industrial wastewater varies, and the diversity of microalgae species present in different environments is also considerable. Critical issues in algae cultivation in an industrial effluent are low biomass productivity, toxicity at high contaminant concentration, high energy demand and financial viability. Therefore, the selection of suitable microalgal strains which can grow at a high concentration of nutrients, are flexible to adopt at extreme experimental/environmental conditions, and variability of contaminant accumulation and biomass production is of utmost importance. Generally, a single algal species might not gain all favorable conditions, but maximum suitability for biomass production could be achieved through proper experimental setup and optimization of affecting parameters. High biomass production for subsequent biofuel is an index for high adaptability and nutrient removal rate. Strategies that lead to increased biomass production include the selection of efficient algal strains, optimizing biotic and abiotic environmental conditions, and advancing algae-based wastewater treatment systems.

Moreover, wastewater composition may significantly affect algal species' capability for biofuel production. For instance, species having a composition rich in carbohydrates are prominent in bioethanol or biohydrogen production, while species dominant in lipids contents are more suitable for biodiesel production. Therefore, the proportion of each nutrient in wastewater may affect the product's amount and kind. The application of an integrated system (heterotrophic and mixotrophic mode) could be a suitable strategy in microalgae cultivation and a high nutrient removal rate for maximum biomass production (Mubashar et al., 2021). Although various studies employed microalgae for high nutrient removal rate and biomass production, the mechanism involved in treating industrial wastewater by microalgae is still much to explore. The biotechnological and genetic engineering strategies should achieve a high growth rate, intensifying the nutrient removal rate for the selected microalgae.

3. Algae for agricultural wastewater treatments

In most developing Asian countries like Pakistan, India, Bangladesh, Nepal, etc., agriculture is a vibrant business that generates billions of dollars annually for the country's economy (Nugroho and Lakner, 2022). The agricultural fields are probably the greatest source of diffuse pollution to groundwater and surface water systems in rural regions. Agriculture fields are frequently treated with inorganic fertilizers, insecticides, and farmyard manure, which contains high levels of N, P, K, and organic carbon. Consequently, agricultural runoff contains a variety of pollutants, including pesticides, heavy metals, and nutrients (Zhou et al., 2022). For decades, it has been known that groundwater, which eventually finds its way to surface waterways like rivers and lakes, contains high concentrations of nitrates and some phosphate. Their presence causes algal blooms that poison freshwater life by consuming 100% of the available oxygen and limiting the amount of sunlight to the photosynthetic species in the benthic zone. Other toxic compounds like ammonia may also be present in agricultural runoff water, which may seriously threaten aquatic bodies' environmental quality and be a limiting factor in algal growth.

Technically, there are two types of pollution related to agricultural wastewater (non-point and point source pollution) (Marella et al., 2022). Sediment, nutrient runoff and pesticides are examples of non-point sources of pollution. Point source contamination includes animal waste, silage liquor, dairy farming (milking center) waste, slaughtering waste, vegetable washing water, and firewater. Surface runoff from many farms causes non-point source pollution if it does not handle properly. In contrast, a point source might be readily managed and handled.

Although various conventional physioco-chemical methods have been adopted to treat agricultural wastewater, microalgae-based wastewater treatment technology has emerged as a viable alternative. Microalgae have many characteristics, including high photosynthetic efficiency, fast reproduction, and remarkable environmental adaptation (Abdel-Raouf et al., 2012), as well as a presence in fresh and marine water and a range of wastewaters. They can also convert nutrients in wastewater into algal biomass. It is therefore thought to be the ideal biological entity for efficiently utilizing agricultural wastewater.

Microalgal biomass may also be used as a feedstock to synthesize valuable products for various commercial and industrial markets. As a result, there are several opportunities to use algal biotechnology in environmental and product development settings. Numerous studies have also shown that utilizing microalgae in tertiary wastewater treatment is viable because of their excellent nutrient removal efficiencies in different kinds of wastewater (Kumar et al., 2010; Wang et al., 2010).

To treat agricultural runoff from irrigation channels in rural areas, García-Galán et al. (2018) developed a new horizontal tubular hybrid photobioreactor employing *Pediastrum* sp., *Chlorella* sp., *Scenedesmus* sp., and *Gloeothece* sp. A 4-day experiment observed a 22.8% increase in algal biomass production. Additionally, they found the removal of various emerging organic pollutants (up to 72%). In another study, Bzdusek et al. (2006) designed an integrated system to treat agricultural stormwater and biofuel production by sequentially cultivating filamentous algae and lipid-producing microalgae *Chlorella sorokiniana*. At loading rates as high as 5 g VS/L-day, 0.2 L methane per gVS was generated by the entire biomass and lipid-extracted algal residues. Results indicate that filamentous algae polyculture is ideal for successfully implementing the design to produce biofuel from algal feedstock and recover waste nutrients.

Similar findings were reported in a study by Castellanos-Estupiñan et al. (2022) to evaluate the capability of two algae strains (*Chlorella* and *Scenedesmus* sp.) and one cyanobacterium (*Hapalosyphon* sp.) to eliminate surplus nutrients and pesticides in agricultural runoff water. Different concentrations of wastewater and carbon sources (Na_2CO_3 and $NaHCO_3$) were measured. The results demonstrated that all three strains could grow at 100% biomass in wastewater without dilution. There was no difference between the three algal strains in reductions of Na_2CO_3 and $NaHCO_3$ and the concentrations of NO_3 and PO_4 (95 and 85%, respectively). Finally, *Chlorella* sp. had the maximum pesticide removal efficacy (Chlorpyrifos), followed by *Scenedesmus* and *Hapalosyphon* sp. (100, 75, and 50%, respectively). The results suggest the potential use of an algal consortium for the treatment and remediation of pesticide-contaminated water and the utilization of such waste to serve as an alternative source of nutrients for algal biomass and, subsequently, the production of biofuels.

Periphyton biofilm-based technologies comprising microalgae and bacteria (Marella et al., 2022) have been used to control sediments loaded nutrient pollution in agricultural watersheds. They assessed the efficiency of the outdoor single-pass algae floway technique. Average biomass concentration of 11.73 $g/m^2/d$ at steady state was attained, along with removal rates of 0.60 $g/m^2/d$ for nitrogen, 0.27 $g/m^2/d$ for phosphorus, 9.26 $mg/m^2/d$ for arsenic, 255.3 $mg/m^2/d$ for chromium, and 238.6 $mg/m^2/d$ for lead. They suggested that applied Periphytic biofilms containing microalgae and bacteria may be essential for nitrogen fixation, nutrient cycling, heavy metal adsorption, and phosphorus and nitrogen uptake.

4. Application of microalgae in treatment of agro-industrial wastewater

The agricultural industry produces a huge quantity of water and wastewater and is a major source of many organic and inorganic contaminants (Markou and Georgakakis, 2011). Environmental problems caused by the discharge of such contaminated water into drains and agricultural fields include eutrophication, surface and groundwater contamination, odor pollution, gas emissions, etc. (Zilberman et al., 1999). Several agro-based industries produce tremendous amounts of wastewater with contaminates based on their nature and processed raw material. Recent top five agro-industrial wastewater include: 1) Palm Oil Mill Effluent, 2) Rubber Mill Effluent, 3) Olive oil mill wastewater, 4) Animal manures: animal farm industries (Swine manure, Cattle Manure and Pig manure), and 5) Molasses. Previously, several studies indicated the usefulness of microalgae culture in reducing the nutrient load of agro-industries wastewater and the production of algal biomass for subsequent use for biofuel production and valuable products. As a substitute medium for lipid and biomass synthesis, *T. suecica* and *N. oculata*, two microalgae, were grown in palm mill oil effluent. Maximum lipid content (39%) and *N. oculata* and *T. suecica* growth rates (0.21 and 0.20 per day) were observed. Removal of 95% of COD, 97% of BOD, 75% of TOC, 91% of TN, and 91% of the oil was recorded when the algal culture was added to effluents (palm mill oil) as a growth medium (Jafarinejad, 2016). Another study found that using *N. oculata* and *Chlorella* sp. resulted in the maximum COD (95–98%), BOD (90–98%), TOC (80–86%) and TN (80%) removal being achieved compared to the treatment where microalgae were not applied (Ahmad et al., 2014).

The efficacy of three microalgal species, *Arthrospira platensis, Haematococcus pluvialis*, and *Botryococcus braunii*, growing on palm oil mill effluent under various nutritional circumstances was examined and evaluated by (Nur et al., 2022). The findings revealed that *Botryococcus braunii* produced the greatest polyhydroxybutirate concentration compared to *Arthrospira platensis* and *Haematococcus pluvialis*. Up to 20 mg/L per day of polyhydroxybutirat productivity was enhanced by supplementation of glucose and glycerol. The best conditions were 50% palm oil mill effluent mixed with high glycerol and Fe-EDTA concentration to produce 33% polyhydroxybutirate.

A large volume of wastewater comprises latex concentrate and serum with a high BOD content. Most rubber industries typically produce sulfate due to their extensive water use in their unique product manufacturing processes. When released into aquatic bodies, these pollutants have serious negative impacts. Since microalgae are a natural component of a waste stabilization process, they can be the most effective treatment option for rubber mill effluent. *Chlorella vulgaris* successfully removed significant nutrients from wastewater, including 79.33% of total Kjeldahl nitrogen and 93.39% of COD (Phang et al., 2001). Additionally, compared to standard BG 11 medium, *Oscillatoria salina* and *Micocystis aeruginosa* cultured in rubber-mill wastewater produce more fatty acids (Shanthala et al., 2008).

Wastes from olive mills pose a serious environmental issue in countries where olive processing production and processing is high. These wastes become phytotoxic due to their high levels of phenol, lipid, and organic acid. Still, they also include useful resources like a significant amount of organic matter and various nutrients that can be recycled. Lindner and Pleissner (2019) conducted a study on the biotic removal of phenolic chemicals in various quantities of wastewater from an olive mill using *Chlorella vulgaris, Acutodesmus obliquus,* and *Monoraphidium braunii*. They discovered that all examined species eliminated phenolic compounds by 7–21% when phenolic compounds were added to the culture medium at a concentration of 1% (v/v) from olive mill wastewater.

A significant amount of nitrogen and a high level of organic pollutants are present in animal manure. Wang et al. (2022) conducted a study and culture *Chlorella* sp. (FACHB-8) and *Kirchneriella obesa* (FACHB2104) utilizing unsterilized cattle farm wastewater filtered through maize stover. The production of algal biomass supplemented with filtered cattle farm wastewater was considerably greater than those of microalgae supplied with unfiltered cattle farm wastewater by 14%–57% (FACHB-8) and 12%–78% (FACHB-2104) and was equivalent to those with pure blue-green algae medium (BG11). Under optimized conditions, the maximum yields of FACHB-8 and FACHB-2104 were 1.26 and 1.22 g/L, respectively, as well as removal efficiencies for N, P and COD that were more than 95%, 99%, and 82%, respectively. The microalgae-driven approach may treat swine wastewater in an ecologically responsible and cost-effective way. *Chlorella vulgaris* and activated sludge eliminated 99.7% of the phosphorus, 94% nitrogen, and 97.2% of the COD when grown with pre-treated swine manure digestate (Wang et al., 2019).

Some animal wastes, such as pigs, have high levels of ammonia, which can inhibit the growth of microalgal species. Because the free form of ammonia is poisonous, wastewaters must first be diluted before they may be utilized as growth media. Ciardi et al. (2022) utilized pig slurry as the sole fertilizer source to culture *Scenedesmus almeriensis* in a lab-scale bubble column photobioreactor. To process the pig slurry, the optimal dilution of the slurry per liter was 5%, resulting in biomass productivity of 0.68 g/L/d, equivalent to the standard growth medium made from pure chemicals (0.70 g/L/d). About 180 mg/L of $N–NH_4^+$ was present at the inlet, and inhibitory effects started to show up at values over 200 mg/L. The removal rates for $N–NH_4^+$, $N–NO_3^-$, $P\text{-}PO_4^{-3}$, and COD were 34.1, 0.5, 2.1, and 519.3 mg/L/d, respectively.

Although using algae to treat agricultural and agro-industrial wastewater is a viable option, there are still some limitations in its application until this technology is more developed. A significant drawback of employing wastewater for the cultivation of microalgae from these agro-industries is the diversity in composition among the various types of agro-industrial wastewater, even within the same type, which relies on physiological and managerial factors. Because of this, it is difficult to predict the algal biomass content without first examining the wastewater composition and then modifying the medium composition favorable for the cultivated microalgal species. The seasonality and seasonal volatility in the volume of agro-industrial wastewater generated is an additional serious drawback. Additionally, high organic contents and nitrite/free nitrous acid present in different agro-industrial wastewater hinder microalgae growth, thus reducing biomass production and other valuable products. The removal of organic matter and nutrients, as well as other major contaminants from different wastewater streams, has been made possible by co-cultivation systems, which could be comprised of microalgae-bacteria, microalgae-microalgae, microalgae-fungi and microalgae-yeast (Aparicio et al., 2022). Microalgae and other heterotrophic microorganisms, including bacteria, yeast, fungus, and other algae/microalgae, mutually interact during co-cultivation. During co-cultivation, bacteria or fungi can oxidize organic material that the microalgae cannot consume while generating CO_2 for microalgae growth. As a result of photosynthesis, microalgae provide oxygen to support aerobic bacterial or fungal oxidation (Maurya et al., 2022b).

Several studies illustrate the usefulness and application of co-cultivation technology (microalgae-bacteria) in wastewater treatment containing a high concentration of organic carbons and other contaminants to produce significant-high biomass production for bioenergy and valuable by-products(Bankston et al., 2020; Mujtaba and Lee, 2017). Ryu et al. (2014) investigated the potential of *C. vulgaris* consortia with indigenous bacteria cultivated in municipal wastewater for sewage treatment. Their findings demonstrated that >95% of the nitrogen and phosphorus sources in wastewater were eliminated by consortia. In a similar study, *Scenedesmus* sp. and *Chlorella sorokiniana* were co-cultivated to remove 90–97% of NH_3, TN, and P while removing 78% of organic contaminants from brewery effluent. The generated biomass yielded 16 mg/L of chlorophyll, 9.57 mg/L of carotenoids, and 30.4 mg/L of carbs (Han et al., 2021). Similarly (Yang et al., 2019), treated molasses wastewater using fungus, fungal-microalgae consortiums, and microalgae. COD removal efficiencies were 25, 59, and 70.68%, respectively. It was observed that co-cultivation of algae and fungus was more effective at removing nutrients than monoculture. A consortium of microalgae and yeast could also prove superior to a single application of either candidate in wastewater treatment. *Spirulina platensis* and *R. glutinis* co-culture system was studied by Xue et al. (2010) for biomass and lipid accumulation. They observed that COD (73%) and nitrogen (35%) simultaneously reduced while total lipid and total biomass accumulation increased considerably when compared to monocultures. More recent co-cultivation studies results involving the treatment of various types of wastewater are summarized in Table S6.

To overcome the cost barrier, economical dewatering, separating, and drying technologies must be developed. Moreover, the simultaneous production of energy and biofuels from microalgae cultivation and potential biomass can also help the system consume less electrical power (Das et al., 2021). The most expensive step is the attainment of algal biomass from the treated effluent (Gupta et al., 2016). To maintain a sufficient level of wastewater treatment, microalgae biomass must be collected frequently and, if done incorrectly, can be more expensive than the wastewater treatment techniques already described. For this purpose, High Rate Algal Ponds demonstrated good efficiency. When bacterial systems were used, harvesting the microalgae biomass employed for wastewater treatment was significantly simpler (Abinandan and Shanthakumar, 2015).

Various chemical flocculants have been used to improve algae harvesting efficiency, which has several environmental concerns as they add specific chemicals to water bodies. Bio-flocculants such as fungal assisted bio-flocculation and biosurfactant assisted flocculation may prove helpful as they reduce harvesting expenses, improve the cost-effectiveness of wastewater treatment, and provide higher disposal efficiency of pollutants than monoculture (Liu and Hong, 2021). Because microalgae can tolerate and grow in various climatic conditions and can fix CO_2, their biomass also helps to rehabilitate the environment and natural resources (Sharma et al., 2019). The microalgae-based agricultural system for treating wastewater is an economical option for effluent treatment. Its use benefits the environment, as it treats wastewater and emits no carbon dioxide, as well as the economy, as it produces biomass, by-products of other products, and generates electricity. Table S2 summarizes recent microalgae remediation studies for agriculture and agro-industrial wastewater treatment.

5. Algae for remediation of petroleum products

Petrochemicals comprised various chemicals produced from natural gas and petroleum and utilized for various chemical processes (Borup and Joe Middlebrooks, 2018). These petrochemical plants produce various chemical substances like hydrogen, carbon monoxide, ethylene, benzene, toluene, etc. Generally, petrochemical wastewater comprises suspended particles, phenolic compounds, PAHs, aliphatic compounds, nitrogen, sulfide, cyanides, and heavy metals (Cr, Cu, Mo, Se, Fe, Hg, Pb, Ag and Zn) (Asatekin and Mayes, 2009).

Wastewater from the petroleum sector is referred to as "petrochemical wastewater." There are various sources of petrochemical wastewater (Ghimire and Wang, 2019). Some wastewaters are produced directly from manufacturing procedures, including aromatic plants, vapour condensation processes, etc. Others come from pump and compressor cooling, cooling tower blow down, and so on. Another important source of environmental pollutants from petrochemical wastewater plants is runoff from surface fields of drains that collects such wastes as contaminated wastewater (Bhat et al., 2010; Jafarinejad, 2016; Multilateral Investment Guarantee Agency, 2004; US EPA, 1995). Depending on its scale, the volume of crude oil to be processed, the high-value products it produces (more than 2500 goods), and the complexity of its operations, a petrochemical refinery may consume a huge quantity of water (33.6 million barrels per day globally) (Hodges et al., 2017). Typically include suspended particles, organic pollutants such as alkanes and aromatic compounds, and petrochemical wastewater (Huo et al., 2018). The eutrophication impact from high nitrogen and phosphorus concentrations in petrochemical effluent has been a substantial cause of aquatic environmental contamination. Free hydrogen in petrochemical effluent reduces the pH of the water, prevents microbial growth, decreases water's capacity to purify itself, corrodes structures like ships and buildings, and makes water harder. It will also impact groundwater and drinking water quality if petrochemical wastewater seepage occurs into the soil (Andreides et al., 2021; Priyadarshini et al., 2021; Shiri et al., 2015; Verma et al., 2022).

Chemical (oxidation), physical (gravity precipitation, membrane separation, and air flotation), and biological (bacteria, fungus, algae, and plants) treatments are the three broad groups into which petrochemical wastewater treatment technology can be broadly categorized (Wei et al., 2019). Generally, effluent from the refinery plant is first subjected to primary treatment that involves the physical separation (suspended particles, oil) from water, followed by a secondary treatment process (Das et al., 2021). In biological wastewater treatment technology that generally involves the application of bacteria or fungi to remediate these wastewaters, neither the bacterial nor the fungal biomass produced at the end of the treatment process has any apparent economic value. Additionally, these microorganisms are sensitive to harsh environmental conditions and could not perform well under toxic heavy metals, high concentrations of pollutants and in wastewater having varied chemical compositions. Previously, petrochemical effluent, biological anaerobic, anoxic, and aerobic digestion (or a mix of them) has been used (Wei et al., 2019). Yet, these technologies are expensive and challenging to apply in real-world situations (Ugya et al., 2019).

In contrast, growing algae with petrochemical wastewater produce plenty of lipids that may be utilized in the biosynthesis of bioenergy and valuable products (Madadi et al., 2021). Microalgae are likely more effective in treating organic pollutants and removing N and P than conventional methodologies such as built wetlands (Li et al., 2020) and aerobic-activated sludge processes (de Godos et al., 2014). Additionally, it has been discovered that algal biomass exhibited a great tendency as sorbent material for removing heavy metals, which is a cost-efficient, environmentally friendly, and efficient approach for treating petrochemical wastewater(Gurumurthy et al., 2022; Santos et al., 2018).

Therefore, the application of microalgae in treating petrochemical effluent has recently gained popularity due to the environmentally friendly synthesis of lipids and other high-value biomolecules (Yadav et al., 2021b). *Scenedesmus abundans* and a bacterial co-cultured were used in a study by Ashwaniy et al. (2020) to reduce organic compounds in petroleum refinery wastewater. They observed maximum growth/-productivity of microalgae, chlorophyll, and carotenoid content (2.78 and 1.365 g m/L, respectively) as useful by-products when cultured in 50% petroleum refinery effluent. The study demonstrated that a highly loaded organic compound wastewater might be reduced by employing microalgae growing in petroleum refinery effluent. Similarly, in another study, filamentous microalgae *Tribonema* sp. was employed to remediate petrochemical wastewater effluent (Huo et al., 2019). They found that *Tribonema* sp. grown in anaerobic effluent showed the highest growth and was most effective in removing contaminants from wastewater. Total nitrogen removal rates, chemical oxygen demand, and biomass concentrations were found to be 4.4 g/L, 98.4%, and 96.8%, respectively.

Additionally, the anaerobic effluent exhibited the highest potential to enhance microalgal oil content (36.1%) and remove total phosphorus and organic contaminants. *Chlorella vulgaris* efficacy in the bioremediation of petrochemical effluent was also studied by Madadi et al. (2016). Their study removed up to 100% nitrogen and phosphorus completely.

However, varied composition and highly loaded wastewater with high organic carbon and N could hinder the efficacy of certain microalgal species that could be improved by employing co-culturing technology. Hodges et al. (2017) studied treating effluent from petroleum refining, removing nutrients and suspended particulates. Rotating algal biofilm reactors with mixed microalgae culture showed a statistically significant increase in suspended particles, nutrient removal, and biomass productivity. This study showed that growing mixed culture microalgae is ideal for biomass production and petro-wastewater treatment. Several studies that employed microalgae remediation for petrochemical wastewater and heavy metals removal have been summarized in Table S3.

Among the technological and economic hurdles to scale up are the poor sedimentation of the process's generated biomass and the lack of absolute supervision of algal species (de Godos et al., 2014). In this regard, using filamentous algae with large colony size and poorly digestible cell wall have potential advantages over the application of unicellular microalgae in petrochemical wastewater treatment (Gupta et al., 2016).

6. Algae for treatment and removal of micropollutants from wastewater streams

Micro-pollutants (MPs) are biological or chemical contaminants that enter the ground and surface waters in a minor quantity (at or below the microgram per liter concentration). They are produced primarily due to anthropogenic activities (Khan et al., 2022). These contaminants included a wide range of organic compounds (OMP), both natural and manufactured, many of which are classified as "emerging" (EMP) primarily because they were not previously monitored or controlled in environmental samples but have recently become a public health concern. MPs can come from various sources, such as agriculture, homes, traffic networks, or factories, and they enter the water bodies through multiple means (Stamm et al., 2016). MPs Chemicals detection in water and wastewater effluents results from the production, use, and subsequent disposal of pharmaceuticals and personal care products, perfluoroalkyl substances, cleaning detergents, steroid hormones, and pesticides, among other industrial chemicals (Abbasi et al., 2022). Like the above example, the microplastic contaminated water bodies result from our reliance on plastic products.

Additionally, bacteria and viruses act as biological MPs and contaminate source waters. In some cases, chemicals are added to source water to make the drinking water safe to drink for the end-user, but doing so also produces undesirable compounds, specifically disinfection by-products. These pollutants (and many others) have emerged as a problem of national and international concern because of their potential to negatively affect health, the economy, and the environment (Spindola Vieira et al., 2022). Additional factors contributing to the possible dangers of MPs include bioaccumulation, toxicity, and resistance to degradation (Wang et al., 2020).

To effectively degrade and remove these MPs from wastewaters and other water systems, a wide variety of treatment solutions have been put forth, reducing unfavorable environmental risks. Treatment of MPs polluted wastewater involves a variety of physical and chemical techniques, including adsorption, irradiation, flocculation, precipitation, membrane filtration, and chemical oxidation (also known as Fenton's oxidation) (Bagheri et al., 2020, 2021; Muhammad et al., 2021; Munir et al., 2020; Nawaz et al., 2020; Zeb et al., 2020). Although these techniques can work effectively, they have several limitations/drawbacks, including inefficiency, a high overall cost of the process, the production of a lot of sludge, and the creation of very poisonous by-products (Ali et al., 2020; Khan et al., 2020). The development of alternative technology that is effectively smarter, greener, and environmentally responsible has thus become important and necessary.

Recently, a variety of biological techniques have been used for the remediation of MPs, including those involving bacteria, algae, and fungi (Adnan et al., 2016; Al Farraj et al., 2019; He et al., 2013; Ratnasari et al., 2021; Sathishkumar et al., 2010; Syafiuddin et al., 2021, 2020). Since algae cells' composition is a polysaccharide, they may adsorb MPs more efficiently than other biological entities like bacteria and fungi (Synytsya et al., 2015). Algae has unique properties for removing MPs as it has a higher surface area, binding affinity for adsorbing substances, and effectiveness. As a biological treatment, algae effectively eliminates organic micropollutants (OMPs), heavy metals and dyes from textile industries, and pharmaceutically active compounds. Algal-based treatment of MPs is effective in terms of manufacturing and maintenance. Additionally, it can produce valuable products, utilize nitrogen and phosphorus as a growth medium, provide cheap and abundant energy through photosynthesis, and reproduce biofuels while incredibly resilient to toxic environments (Papazi et al., 2019).

Practically, none of the industries generate a single MP; there is always a combination of several organic and inorganic pollutants. Hence, microalgae species that can eliminate/remediate multiple MPs are ideal for practical application in wastewater treatment processes. In a study conducted by (Cheng and Wang, 2022), microalgae *Scenedesmus abundans* were used to remove a variety of microplastics (MPs), including polystyrene, poly(methyl methacrylate), and polylactide. They discovered that more than 84% removal efficiency for all MPs was attained. *S. abundans* among these MPs had a high removal efficiency of PMMA microparticles (around 98%). They further found that pre-exposure was necessary for the other two types of MPs to maximize the removal effectiveness of more than 70%.

Exopolymer substances may facilitate hetero-aggregation, a well-documented phenomenon in removing MPs by microalgae. In a study conducted by Cunha et al. (2019), two EPS-producing freshwater microalgae (*Microcystis panniformis* and *Scenedesmus* sp.) and two marine microalgae (*Tetraselmis* sp. and *Gloeocapsa* sp.) were exposed to different kinds of microplastics. The results showed that *Microcystis panniformis* and *Scenedesmus* sp. had smaller EPS, a higher tendency to disaggregate, and a lesser capacity to aggregate microplastics. *Tetraselmis* sp. showed a greater capacity to aggregate both low and high-density microplastics. Exceptional EPS generation and excellent microplastic aggregation skills were exhibited by *Gloeocapsa* sp. The outcomes demonstrated microalgae's potential as biocompatible approaches to the remediation of water microplastics.

The use of a freshwater *Cyanothece* sp. strain in treating wastewater contaminated with nano- and microplastics was examined by (Cunha et al., 2019). They found that the presence of nano- and microplastics had an adverse effect on the microalgae's growth (up to 47%). Exopolysaccharides have facilitating role in bioflocculation and subsequently in the removal of MPs. They further investigated that *Cyanothece* sp. EPS has a strong bioflocculant activity even at low concentrations. The study emphasized the potential of microalgae with the capability to produce exopolysaccharides for the removal of nano- and microplastic. However, microplastic pollution in wastewater may exert a toxic effect on aquatic organisms, thus hindering the efficiency of certain microalgae species in the treatment and production of biomass for bioenergy and other valuable products. Wu et al. (2022) conducted a study to comprehend the effects of polystyrene microplastics on the ability of *C. vulgaris* to degrade/remove endocrine-disrupting antibiotics in freshwater aquaculture effluent. The findings demonstrated that PS-MP stress greatly decreased *C. vulgaris* growth. Polystyrene microplastics predominantly affected the removal of endocrine-disrupting antibiotics by *C. vulgaris* by altering adsorption, enrichment, and enzyme degradation. Hence, a suitable alternate strategy such as co-cultivation (microalgae-bacteria, microalgae-fungi, microalgae-yeast, microalgae-microalgae) should be designed for the complete removal and degradation of these MPs. That way, the generation of enhanced biomass for bioenergy and valuable products could be possible. Several studies that employed microalgae remediation for micropollutants have been summarized in Table S4.

Depending on the type and nature of PM, many biodegradation mechanisms have been proposed, such as biosorption, bioaccumulation, biodegradation, and photodegradation (Gondi et al., 2022a, 2022b; Hom-Diaz et al., 2022). Compared to direct photolysis, indirect photolysis is mainly utilized to eliminate organic particles (Wei et al., 2022). The main determinants of algal-based MP removal are pH, temperature, hydraulic retention duration, and MP concentration (Gondi et al., 2022b).

Algal bioremediation has many advantages, but it also carries several limitations that could impair the ability of microalgae to perform their function effectively (Sonone et al., 2020). Microalgae should be screened and employed for wastewater treatment because of their ability to adapt to challenging environmental conditions, high rate of carbon dioxide sequestration, increased tolerance, and remediation capacity (Rempel et al., 2021). Since they can enhance the adsorption of several emerging MPs, microalgal consortiums with specific adsorption properties should be screened and employed in wastewater treatment (Ryu et al., 2017). Additionally, it is important to consider the function of microalgae using such wastewater contaminated with MPs as a medium of growth while developing a specific wastewater treatment plan. Algal bioremediation might be more practical for mass culture and cultivation if biotechnological approaches are used to improve the growth and selectivity of algal strains towards particular MPs.Figs. 1 and 2

7. Algae for resource recovery and biofuel production

Resource recovery is the process of separating materials from waste that can be used to synthesize new valuable products or as an alternative to fossil fuel energy sources. The main purpose of the process is to restore nutrients and valuable products as much as possible from waste streams and re-establish a balance between the scarcity of resources and the over-production of waste (Gregson et al., 2016). The concept is also a part of the global objective to ensure a waste-free and more sustainable environment for future generations. Resource recovery from wastewaters assures a sustainable water supply and the availability of numerous important bioactive compounds and energy products. Furthermore, the green circular economy concept is connected to the generation of algal biomass and valuable products using wastewater.

Algae are a promising candidate for resource recoveries such as nutrient recovery for further use in agriculture, bioactive compounds, and energy products such as bioethanol, biodiesel, biohydrogen, biomethane, and bio-oil (Acién Fernández et al., 2018). The nutrients (N and P) present in these effluents at variable concentrations can be recovered by growing microalgae using effluents from different industries as valuable feedstock. Algae have a unique property of biomass production and accumulation of nutrients with limited space and resources under harsh environmental conditions, thus making them suitable for resource recovery. One m^3 of nutrient-rich effluent can produce 1 kg of dry biomass (algae). Acién Fernández et al., 2018 reported maximum theoretical biomass (10 t N/ha and 2 t P/ha annually), indicating that the greater the biomass, the higher the nutrient restoration. In certain cases, bacteria and algae work together to oxidize organic substances into inorganic nutrients, which algae then use to produce biomass, bioenergy, and valuable products. To develop, grow, and generate biomass, microalgae must meet a variety of requirements, including the amount of light available (solar radiation), the efficiency of photosynthetic processes, and the depth of the culture. Microalgae have been employed successfully to recover useful mineral elements for several decades. Thus, it is one of the promising and rapidly expanding fields which gaining much attention even recently. Due to the tremendous potential of microalgae-based processes and the diverse use of algal biomass, several research organizations and businesses are currently engaged in this subject.

As mentioned above, in addition to bioenergy products production and nutrients recoveries, microalgae are also capable of producing co-products that are extremely relevant to the food, pharmaceutical, and chemical industries, such as proteins, polysaccharides, and pigments contents (e.g., violaxanthin/neoxanthin, astaxanthin, vaucheriaxanthin, lutein/zeaxanthin, canthaxanthin, phycocyanin, allophycocyanin, phycoerythrin, Fucoxanthin (Liu and Hong, 2021). Microalgae harvesting methods had a severe impact on the production of pigment contents produced in different ways. For instance, Baierle et al. (2015) observed that samples subjected to electrocoagulation during harvesting marine *Nannochloropsis* sp. had much less pigment. Furthermore, several environmental pollutants, such as the accumulation of heavy metals (Pb, Cu, Cd, and Ti), are linked to toxicity and significantly inhibit microalgae growth and pigment production. Extraction of pigment contents could be done by grounding the microalgae sample in acetone with glass beads at room temperature (22 °C), followed by stirring, and subsequent supernatant is subjected for analysis and quantification. Further research should be conducted to ensure that the bioproducts don't pose

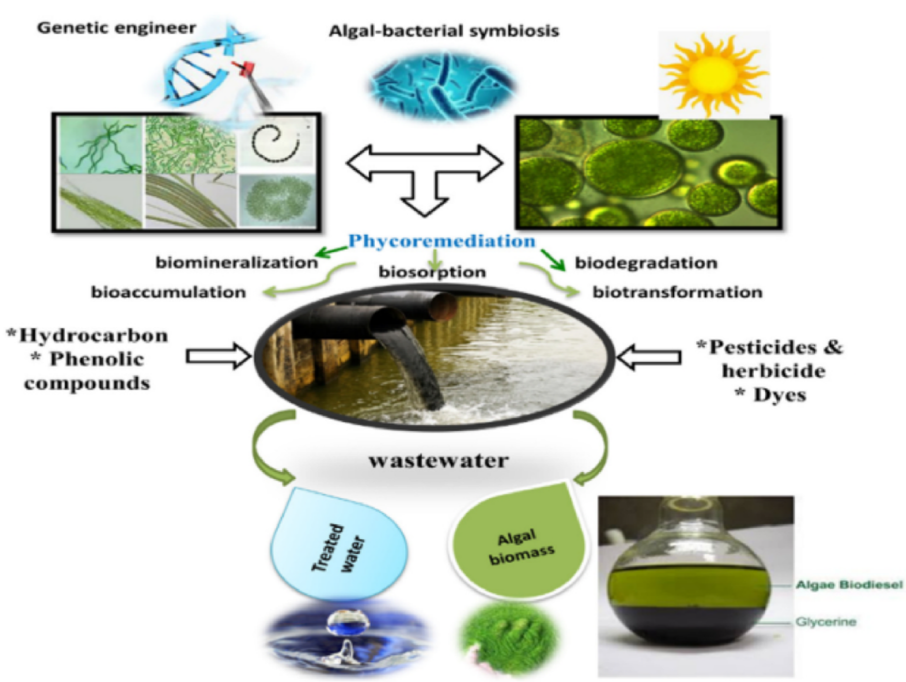

Fig. 1. Algae-base bioremediation for organic pollutant removal(Touliabah et al., 2022).

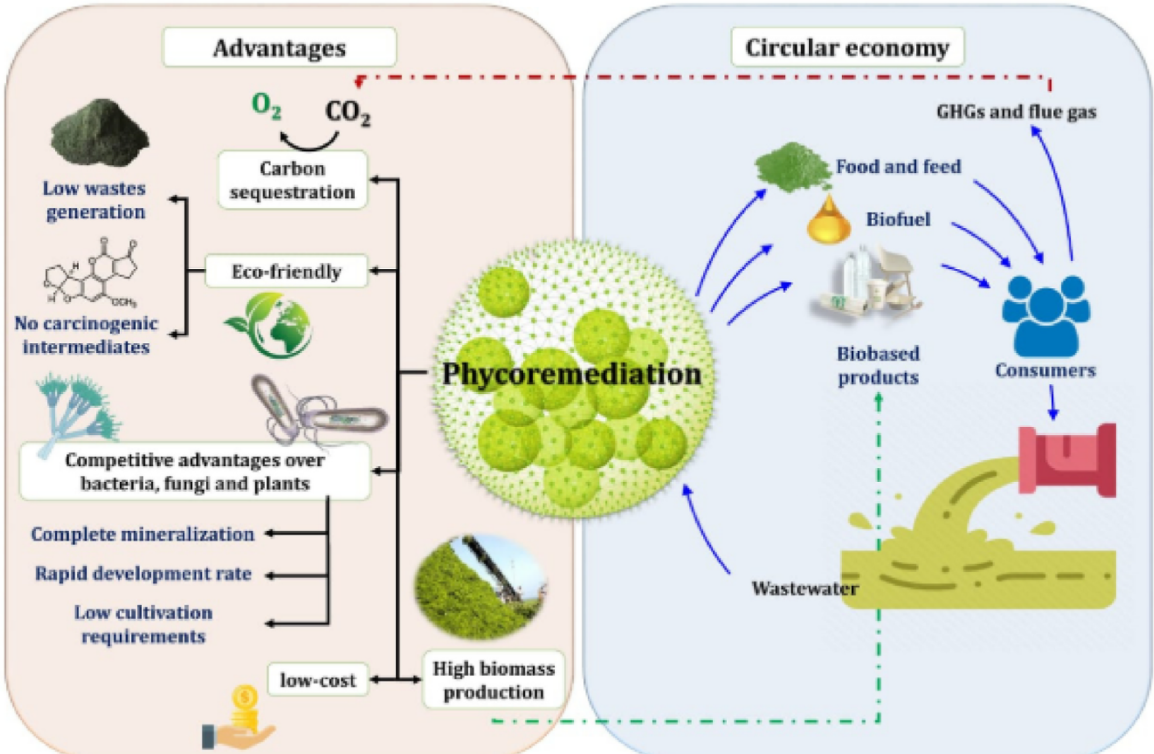

Fig. 2. The advantages and effective roles of algae in phycoremediation of wastewater (Touliabah et al., 2022).

any potential risks depending on the intended use of the pigments (Arashiro et al., 2020). To satisfy the cost-effective strategy for biofuel production for the green circular economy, more research and development with a holistic approach are required to explore other synergetic potentials related to pigment content production. Table S5 summarizes the results of previous studies that used microalgae to produce fuel with added value.

Despite potential resource recovery and bio-refinery strategy, microalgae culture in wastewater faces many challenges, such as contamination, a low biomass yield, a complicated nutrient removal process, and contaminants in the biomass after downstream processing (Javed et al., 2019). In addition, a few practical examples of this technology at a field scale are currently in use worldwide. The performance limitations of the current technology are the main reason behind its field-scale application. The wastewater treatment method based on microalgae still has a corner of improvement. The actual process of microalgae cultivation needs a longer hydraulic resident time, nearly around 7–10 days and 10 m^2 per equivalent person surface area (Matamoros et al., 2015). A suitable strategy that includes optimizing the parameters, reducing hydraulic retention time and surface area, and selecting genetically efficient algal strains could solve the problem (Acién Fernández et al., 2018). Table S5 shows recent studies that employed microalgae for added value product production.

8. Techno-economic and life cycle analysis of biofuels/bioproducts from microalgae biomass

The Techno-Economic Analysis (TEA) determines any new technological development's technical functioning and industrial viability. At the same time, from the extraction of starting material to their disposal, the Life Cycle Analysis (LCA) analyzes the possible influence on the environment associated with production systems. In other words, Life Cycle Assessment (LCA) provides a framework for assessing the environmental impacts of a product, extraction, processing, transportation, use, and disposal of raw materials (Muralikrishna and Manickam, 2017). Numerous studies indicate that TEA and LCA are helpful tools in the development and implementation of bioprocesses or product development based on algae biomass (Beal et al., 2015; Dutta et al., 2016; Kern et al., 2017; Kushwaha et al., 2022; Wiatrowski et al., 2022b). There is a need to perform LCA more efficiently to reduce the time and cost involved and inspire a broader audience to encourage them to use LCA. The LCA consists of four linked stages.

Definition of objectives and scope, describes the objectives and expected results of the LCA, the study's limitations (what is included and what is not included), and the key assumptions.

Life Cycle Inventory: measures the energy, raw materials, and environmental emissions used in each production stage.

Impact analysis: determining how energy and resource inputs and the inventory of quantified environmental emissions affect human health and the environment.

Improvement analysis: Find ways to lower power consumption and resource use or environmental impact at each stage of the product life cycle.

In both methodologies, the desired objective and scope of the study are specified, inventory data (often related to the mass and energy balances of the systems under consideration) are collected, and the inventory data is converted into proper environmental or economic measures. Finally, the findings of the proposed method are explained and recorded. Technology developers must consider potential ecological implications and technical and financial factors when developing new technologies for sustainable design. For technology assessment, TEA and LCA are usually made individually. Sustainable process design depends on understanding the adjustment between environmental performance and the economics of the process, which is not entirely possible if TEA and LCA are carried out independently. The economic, environmental, and technical effectiveness relationship could be systematically analyzed when TEA and LCA are integrated simultaneously. It also gives technology developers more data for compensation analysis. Using an integrated TEA-LCA tool might eliminate the inconsistencies that can arise when individual TEA and LCA are used in decision-making.

However, the main methodological problems related to the integration of LCA and TEA are the deficiency of uniform technological directions and suitable computational tools, the varying selection of system boundaries and functional units, the restricted availability of data, and uncertainty. These technical tools would be easy to use by developing integrated TEA-LCA tools, defining a technique for incorporating optimization into the tool and creating a plan to effectively communicate the tool's results to various stakeholders and relevant parties.

9. Recommendation and future prospective

Bioenergy derived from microalgae has long been regarded as a possible alternative to fossil fuels on a large scale. Numerous limitations still need to be minimized to attain large-scale microalgal bioenergy production. These limitations are high costs, poor efficiency, inadequate sedimentation of the generated biomass, and lack of control over the microalgae species. Possible solutions may include cultivation in wastewater, reuse of water and nutrients, use of the entire biomass, co-cultivation, selection of indigenous microalgal and bacterial strain, supplementation of inexpensive organic substrates, optimization of the metabolic pathway, and attachment of the cells to the suspended materials. Some other limitations and their possible solutions are recommended as follows:

One of the most challenging aspects of using wastewater for the growth of algae is the variability in the content of the wastewater, which may have an excess or a shortage of critical nutrients. This issue influences algal biomass production and the development of valuable bioactive compounds. Various solutions have been proposed to tackle this issue. According to previous studies, organic carbon sources and bound algal biofilms can encourage algal development in wastewater of various kinds with various concentrations of contaminants (Choi et al., 2018; Ummalyma and Sukumaran, 2014; Zhao et al., 2021).

Commercially marketable algal biofuel from wastewater is only possible if three critical conditions are met: high biomass with high lipid content production, increased algae strain tolerance for concentrated wastewater and efficient harvesting technology. The increased productivity of biomass and lipids contributes, thus reducing the number of resources and energy consumed in biomass cultivation and processing. High tolerance for wastewater adds to the developing system's health and stability. The potential output of a culture system is determined by the selection of algal strains and variety; however, actual production is mainly driven by culture conditions. Optimal growth conditions, genetically efficient algal strains, and sophisticated harvesting technologies such as new bio-flocculation and auto-flocculation might provide a means to increase algal biomass output for subsequent application in the production of biofuel and bioactive chemical creation. Furthermore, more studies at a higher advanced level are required to understand the variables that prevent lipid formation during the combined growth of algal species in wastewater.

Another issue with using wastewater as a growing medium for algae is that it is not sterile. Research should be directed toward the co-cultivation of natural communities of microalgae to produce a more stable and efficient consortium while also testing all ecological niches that limit the risks of culture death and contamination to reduce further operating costs and treatment efficiency (Mohsenpour et al., 2021b). The form of culture and associated process parameters must be examined for the large-scale cultivation of microalgae in wastewater systems.

Dilution is another significant limitation in wastewater usage, which would need additional water supply expenses. To prevent the cost of dilution, wastewater that satisfies the nutritional need of microalgae must be evaluated.

The economic feasibility of any biorefinery in producing bioactive compounds involving wastewater is critical. Protein and enzyme extraction are costly due to their tiny size and difficulty extracting. To progress in the valorization of valuable bioproducts, highly advanced biotechnical approaches such as ultrafiltration and microfiltration, as well as a deeper investigation of the operating conditions and the selection of non-toxic algae strains, are required.

It is well documented that even if high biomass yields were reported in the lab, outside the full scale, culture units typically did not provide high outputs over an extended period. This is probably brought on by limits on mass transfer, light, temperature, mixing, and growth rate. The light limitation is typically solved by exposing dense cultures. High amounts of mixing are required to achieve a turbulent flow of the culture to acquire the best light regime. Additional culture heating at low ambient temperatures and cooling at high temperatures could overcome the issue of unforeseen, abrupt temperature changes.

Additionally, when using wastewater as the culture broth, careful pH modification can be done to avoid contamination by grazers like zooplankton. A detergent and phenol process can also be used to avoid bacterial contamination.

The critical issue in scaling downstream operations (harvesting, extraction, and fuel conversion) are always uneconomical due to high operating costs and energy needs. To lessen the total price for biofuel and valuable product generation, life cycle and techno-economic analysis must consider all relevant factors, such as solar energy consumption, wastewater cultivation, biorefineries, and bioenergy production.

In general, the tolerance of the species to environmental stress, the cultural conditions affecting the survival of microalgae in wastewater, metabolic engineering, and genetic modification could be viable options to improve the quality and quantity of bioenergy and bioactive compounds. Microalgae production utilizing wastewater can address microalgae culture's water and nutrient availability. More efforts are still required to connect algal-based clean technologies. There are numerous prospects in this field for researchers to discover possible alternative uses of biomass from microalgae and to produce unique, revenue-generating microalgae products.

10. Conclusion

A wastewater treatment system's long-term development must be technically possible, environmentally safe, and economically viable. According to present research findings, alternative biological wastewater remediation using microalgae seems both technologically feasible and ecologically safe. The capability of algae in various environments, including autotrophic, mixotrophic, and heterotrophic environments, is well documented. It's also cost-effective, considering the cost of producing a microalgae plant might be an "installation" charge. Still, standard systems also carry an installation cost as well. Compared to conventional biological wastewater treatment techniques, microalgal-based treatment systems for eliminating N, P and carbonaceous substances may reduce energy usage and greenhouse gas production. Toxic contaminants, including organic compounds such as petroleum hydrocarbons, heavy metals, and micropollutants, can be degraded/or removed by algae. Scaling up the process of algae cultivation for biomass and, subsequently, bioenergy and bioactive compounds production depends on optimizing process parameters, appropriate choice of wastewater, selection of efficient algal strain, and design of the culturing system.

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.

Data availability

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

Acknowledgement

The research leading to these results has received funding from the Ministry of Higher Education, Research, and Innovation (MoHERI) of the Sultanate of Oman under the Block Funding Program, MoHERI Block Funding Agreement No. MoHERI/BFP/ASU/01/2021.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116415.

References

Abbasi, N.A., Shahid, S.U., Majid, M., Tahir, A., 2022. Ecotoxicological risk assessment of environmental micropollutants. Environ. Micropollutants 331–337. https://doi.org/10.1016/B978-0-323-90555-8.00004-0.

Abd-Elaty, I., Kuriqi, A., Shahawy, A. El, 2022. Environmental rethinking of wastewater drains to manage environmental pollution and alleviate water scarcity. Nat. Hazards 110, 2353–2380. https://doi.org/10.1007/S11069-021-05040-W/TABLES/4.

Abdel-Raouf, N., Al-Homaidan, A.A., Ibraheem, I.B.M., 2012. Microalgae and wastewater treatment. Saudi J. Biol. Sci. 19, 257–275. https://doi.org/10.1016/J.SJBS.2012.04.005.

Abinandan, S., Shanthakumar, S., 2015. Challenges and opportunities in application of microalgae (Chlorophyta) for wastewater treatment: a review. Renew. Sustain. Energy Rev. 52, 123–132. https://doi.org/10.1016/J.RSER.2015.07.086.

Acién Fernández, F.G., Gómez-Serrano, C., Fernández-Sevilla, J.M., 2018. Recovery of nutrients from wastewaters using microalgae. Front. Sustain. Food Syst. 2, 59. https://doi.org/10.3389/FSUFS.2018.00059/BIBTEX.

Adnan, L.A., Hadibarata, T., Sathishkumar, P., Mohd Yusoff, A.R., 2016. Biodegradation pathway of acid red 27 by white-rot fungus armillaria sp. F022 and phytotoxicity evaluation. Clean: Soil, Air, Water 44, 239–246. https://doi.org/10.1002/CLEN.201400249.

Ahmad, A., Banat, F., Alsafar, H., Hasan, S.W., 2022. Algae biotechnology for industrial wastewater treatment, bioenergy production, and high-value bioproducts. Sci. Total Environ. 806, 150585 https://doi.org/10.1016/J.SCITOTENV.2021.150585.

Ahmad, A., Shah, S.M.U., Othman, M.F., Abdullah, M.A., 2014. Aerobic and anaerobic co-cultivation of Nannochloropsis oculata with oil palm empty fruit bunch for enhanced biomethane production and palm oil mill effluent treatment. New pub Balaban 56, 2055–2065. https://doi.org/10.1080/19443994.2014.960458.

Al Farraj, D.A., Hadibarata, T., Yuniarto, A., Syafiuddin, A., Surtikanti, H.K., Elshikh, M. S., Al Khulaifi, M.M., Al-Kufaidy, R., 2019. Characterization of pyrene and chrysene degradation by halophilic Hortaea sp. B15. Bioproc. Biosyst. Eng. 42, 963–969. https://doi.org/10.1007/S00449-019-02096-8/FIGURES/4.

Ali, N., Khan, A., Nawaz, S., Bilal, M., Malik, S., Badshah, S., Iqbal, H.M.N., 2020. Characterization and deployment of surface-engineered chitosan-triethylenetetramine nanocomposite hybrid nano-adsorbent for divalent cations decontamination. Int. J. Biol. Macromol. 152, 663–671. https://doi.org/10.1016/J.IJBIOMAC.2020.02.218.

Andreides, D., Varga, Z., Pokorna, D., Zabranska, J., 2021. Performance evaluation of sulfide-based autotrophic denitrification for petrochemical industry wastewater. J. Water Proc. Eng. 40, 101834 https://doi.org/10.1016/J.JWPE.2020.101834.

Ansari, F.A., Nasr, M., Rawat, I., Bux, F., 2021. Meeting Sustainable Development Goals (SDGs) through Progression of Pilot-Scale Algal System to Commercial Raceway Pond (300 000 L).

Aparicio, S., Robles, Á., Ferrer, J., Seco, A., Borrás Falomir, L., 2022. Assessing and modeling nitrite inhibition in microalgae-bacteria consortia for wastewater treatment by means of photo-respirometric and chlorophyll fluorescence techniques. Sci. Total Environ. 808, 152128 https://doi.org/10.1016/J.SCITOTENV.2021.152128.

Arashiro, L.T., Boto-Ordóñez, M., Van Hulle, S.W.H., Ferrer, I., Garfí, M., Rousseau, D.P. L., 2020. Natural pigments from microalgae grown in industrial wastewater. Bioresour. Technol. 303, 122894 https://doi.org/10.1016/j.biortech.2020.122894.

Asatekin, A., Mayes, A.M., 2009. Oil industry wastewater treatment with fouling resistant membranes containing amphiphilic comb copolymers. Environ. Sci. Technol. 43, 4487–4492. https://doi.org/10.1021/ES803677K/ASSET/IMAGES/LARGE/ES-2008-03677K_0002 (JPEG).

Ashwaniy, V.R.V., Perumalsamy, M., Pandian, S., 2020. Enhancing the synergistic interaction of microalgae and bacteria for the reduction of organic compounds in petroleum refinery effluent. Environ. Technol. Innovat. 19, 100926 https://doi.org/10.1016/J.ETI.2020.100926.

Bagheri, A.R., Aramesh, N., Khan, A.A., Gul, I., Ghotekar, S., Bilal, M., 2020. Molecularly imprinted polymers-based adsorption and photocatalytic approaches for mitigation of environmentally-hazardous pollutants — A review. J. Environ. Chem. Eng. 9, 104879 https://doi.org/10.1016/J.JECE.2020.104879.

Bagheri, A.R., Aramesh, N., Sher, F., Bilal, M., 2021. Covalent organic frameworks as robust materials for mitigation of environmental pollutants. Chemosphere 270, 129523. https://doi.org/10.1016/J.CHEMOSPHERE.2020.129523.

Baierle, F., John, D.K., Souza, M.P., Bjerk, T.R., Moraes, M.S.A., Hoeltz, M., Rohlfes, A.L. B., Camargo, M.E., Corbellini, V.A., Schneider, R.C.S., 2015. Biomass from microalgae separation by electroflotation with iron and aluminum spiral electrodes. Chem. Eng. J. 267, 274–281. https://doi.org/10.1016/J.CEJ.2015.01.031.

Bankston, E., Wang, Q., Higgins, B.T., 2020. Algae support populations of heterotrophic, nitrifying, and phosphate-accumulating bacteria in the treatment of poultry litter anaerobic digestate. Chem. Eng. J. 398, 125550 https://doi.org/10.1016/J.CEJ.2020.125550.

Beal, C.M., Gerber, L.N., Sills, D.L., Huntley, M.E., Machesky, S.C., Walsh, M.J., Tester, J. W., Archibald, I., Granados, J., Greene, C.H., 2015. Algal biofuel production for fuels and feed in a 100-ha facility: a comprehensive techno-economic analysis and life cycle assessment. Algal Res. 10, 266–279. https://doi.org/10.1016/J.ALGAL.2015.04.017.

Bhat, N., Chandni, T., Babu, M., Babu, S., Vangeti, C., Thomas, S.B., Mall, I.D., Rajagopalan, V., Garg, R.K., Tyagi, P.C., Gautam, S.P., Chkrabarti, T., Nyati, K.P., Pandey, G.K., Subramaniam, G.V., Sengupta, B., Trivedi, R.C., Joglekar, H.G., Sharma, P.N., Babu, N.S., 2010. Technical Eia Guidance Manual for Petrochemical Complexes.

Borup, B.M., Joe Middlebrooks, E., 2018. Pollution control in the petrochemicals industry. Pollut. Control Petrochemicals Ind 1–180. https://doi.org/10.1201/9781351075862.

Bzdusek, P.A., Christensen, E.R., Lee, C.M., Pakdeesusuk, U., Freedman, D.L., 2006. PCB congeners and dechlorination in sediments of Lake Hartwell, South Carolina, determined from cores collected in 1987 and 1998. Environ. Sci. Technol. 40, 109–119. https://doi.org/10.1021/ES0501940/SUPPL_FILE/ES050194OSI20051018_065917.PDF.

Castellanos-Estupiñan, M.A., Carrillo-Botello, A.M., Rozo-Granados, L.S., Becerra-Moreno, D., García-Martínez, J.B., Urbina-Suarez, N.A., López-Barrera, G.L., Barajas-Solano, A.F., Bryan, S.J., Zuorro, A., 2022. Removal of nutrients and pesticides from agricultural runoff using microalgae and cyanobacteria. Water 2022 14, 558. https://doi.org/10.3390/W14040558. Page 558 14.

Castellaños-Estupiñan, M.A., Sánchez-Galvis, E.M., García-Martínez, J.B., Barajas-Ferreira, C., Zuorro, A., Barajas-Solano, A.F., 2018. Design of an electroflotation system for the concentration and harvesting of freshwater microalgae. Chem. Eng. Trans. 64, 1–6. https://doi.org/10.3303/CET1864001.

Cavieres, L., Bazaes, J., Marticorena, P., Riveros, K., Medina, P., Sepúlveda, C., Riquelme, C., 2021. Pilot-scale Phycoremediation Using Muriellopsis Sp. For Wastewater Reclamation in the Atacama Desert: Microalgae Biomass Production and Pigment Recovery 331–343. https://doi.org/10.2166/wst.2020.576.

Chawla, P., Malik, A., Sreekrishnan, T.R., Dalvi, V., Gola, D., 2020. Selection of optimum combination via comprehensive comparison of multiple algal cultures for treatment of diverse wastewaters. Environ. Technol. Innovat. 18, 100758 https://doi.org/10.1016/j.eti.2020.100758.

Cheng, Y.R., Wang, H.Y., 2022. Highly effective removal of microplastics by microalgae Scenedesmus abundans. Chem. Eng. J. 435, 135079 https://doi.org/10.1016/J.CEJ.2022.135079.

Chia, S.R., Chew, K.W., Leong, H.Y., Ho, S.H., Munawaroh, H.S.H., Show, P.L., 2021. CO2 mitigation and phycoremediation of industrial flue gas and wastewater via microalgae-bacteria consortium: possibilities and challenges. Chem. Eng. J. 425, 131436 https://doi.org/10.1016/j.cej.2021.131436.

Chiu, S.Y., Kao, C.Y., Chen, T.Y., Chang, Y., Bin, Kuo C.M., Lin, C.S., 2015. Cultivation of microalgal Chlorella for biomass and lipid production using wastewater as nutrient resource. Bioresour. Technol. 184, 179–189. https://doi.org/10.1016/J.BIORTECH.2014.11.080.

Choi, Y.K., Jang, H.M., Kan, E., 2018. Microalgal biomass and lipid production on dairy effluent using a novel microalga, Chlorella sp. isolated from dairy wastewater. Biotechnol. Bioproc. Eng. 333–340. https://doi.org/10.1007/S12257-018-0094-Y, 2018 233 23.

Choudhary, P., Assemany, P.P., Naaz, F., Bhattacharya, A., Castro, J. de S., Couto, E. de A. do C., Calijuri, M.L., Pant, K.K., Malik, A., 2020. A review of biochemical and thermochemical energy conversion routes of wastewater grown algal biomass. Sci. Total Environ. 726, 137961 https://doi.org/10.1016/j.scitotenv.2020.137961.

Ciardi, M., Gómez-Serrano, C., Lafarga, T., González-Céspedes, A., Acién, G., López-Segura, J.G., Fernández-Sevilla, J.M., 2022. Pilot-scale annual production of Scenedesmus almeriensis using diluted pig slurry as the nutrient source: reduction of water losses in thin-layer cascade reactors. J. Clean. Prod. 359, 132076 https://doi.org/10.1016/J.JCLEPRO.2022.132076.

Cristina, M., Palacio, R., Bernardo, R., Cabrera, E., Cesar, J., Aguilar, R., 2022. The cultivation of five microalgae species and their potential for biodiesel production. Energy. Sustain. Soc. 1–6. https://doi.org/10.1186/s13705-022-00337-5.

Cunha, C., Faria, M., Nogueira, N., Ferreira, A., Cordeiro, N., 2019. Marine vs freshwater microalgae exopolymers as biosolutions to microplastics pollution. Environ. Pollut. 249, 372–380. https://doi.org/10.1016/J.ENVPOL.2019.03.046.

Das, P.K., Rani, J., Rawat, S., Kumar, S., 2021. Microalgal Co-cultivation for biofuel production and bioremediation: current status and benefits. BioEnergy Res 1–26. https://doi.org/10.1007/S12155-021-10254-8, 2021 151 15.

de Godos, I., Vargas, V.A., Guzmán, H.O., Soto, R., García, B., García, P.A., Muñoz, R., 2014. Assessing carbon and nitrogen removal in a novel anoxic–aerobic cyanobacterial–bacterial photobioreactor configuration with enhanced biomass sedimentation. Water Res. 61, 77–85. https://doi.org/10.1016/J.WATRES.2014.04.050.

Dutta, S., Neto, F., Coelho, M.C., 2016. Microalgae biofuels: a comparative study on techno-economic analysis & life-cycle assessment. Algal Res. 20, 44–52. https://doi.org/10.1016/J.ALGAL.2016.09.018.

García-Galán, M.J., Gutiérrez, R., Uggetti, E., Matamoros, V., García, J., Ferrer, I., 2018. Use of full-scale hybrid horizontal tubular photobioreactors to process agricultural runoff. Biosyst. Eng. 166, 138–149. https://doi.org/10.1016/J.BIOSYSTEMSENG.2017.11.016.

Garg, S., Rumjit, N.P., Thomas, P., Lai, C.W., 2021. Bioremediation of agricultural wastewater. Appl. Water Sci. 565–579. https://doi.org/10.1002/9781119725282.CH17.

Ghimire, N., Wang, S., 2019. Biological treatment of petrochemical wastewater. Pet. Chem. - Recent Insight. https://doi.org/10.5772/INTECHOPEN.79655.

Gondi, R., Kavitha, S., Yukesh Kannah, R., Parthiba Karthikeyan, O., Kumar, G., Kumar Tyagi, V., Rajesh Banu, J., 2022a. Algal-based system for removal of emerging pollutants from wastewater: a review. Bioresour. Technol. 344, 126245 https://doi.org/10.1016/j.biortech.2021.126245.

Gondi, R., Kavitha, S., Yukesh Kannah, R., Parthiba Karthikeyan, O., Kumar, G., Kumar Tyagi, V., Rajesh Banu, J., 2022b. Algal-based system for removal of emerging pollutants from wastewater: a review. Bioresour. Technol. 344, 126245 https://doi.org/10.1016/J.BIORTECH.2021.126245.

Gregson, N., Crang, M., Botticello, J., Calestani, M., Krzywoszynska, A., 2016. Doing the 'dirty work'of the green economy: resource recovery and migrant labour in the EU. journals.sagepub.com 23, 541–555. https://doi.org/10.1177/0969776414554489.

Gupta, P.L., Lee, S.M., Choi, H.J., 2016. Integration of microalgal cultivation system for wastewater remediation and sustainable biomass production. World J. Microbiol. Biotechnol. 32, 1–11. https://doi.org/10.1007/S11274-016-2090-8/TABLES/5.

Gurumurthy, H., Mahadevan, G.D., Mulla, S.I., 2022. Biosorption of Industrial Wastewater by Microalgae, pp. 163–175. https://doi.org/10.1007/978-981-16-4574-7_8.

Han, X., Hu, X., Yin, Q., Li, S., Song, C., 2021. Intensification of brewery wastewater purification integrated with CO2 fixation via microalgae co-cultivation. J. Environ. Chem. Eng. 9, 105710 https://doi.org/10.1016/J.JECE.2021.105710.

Hariz, H.B., Takriff, M.S., Mohd Yasin, N.H., Ba-Abbad, M.M., Mohd Hakimi, N.I.N., 2019. Potential of the microalgae-based integrated wastewater treatment and CO2 fixation system to treat Palm Oil Mill Effluent (POME) by indigenous microalgae; Scenedesmus sp. and Chlorella sp. J. Water Proc. Eng. 32 https://doi.org/10.1016/j.jwpe.2019.100907.

He, P.J., Mao, B.L.-F., Shao, L.M., Lee, D.J., Chang, J.S., 2013. The combined effect of bacteria and Chlorella vulgaris on the treatment of municipal wastewaters. Bioresour. Technol. 146, 562–568. https://doi.org/10.1016/J.BIORTECH.2013.07.111.

Heidarpour, A., Aliasgharzad, N., Khoshmanzar, E., khoshru, B., Asgari Lajayer, B., 2019. Bio-removal of Zn from contaminated water by using green algae isolates. Environ. Technol. Innovat. 16, 100464 https://doi.org/10.1016/j.eti.2019.100464.

Hodges, A., Fica, Z., Wanlass, J., VanDarlin, J., Sims, R., 2017. Nutrient and suspended solids removal from petrochemical wastewater via microalgal biofilm cultivation. Chemosphere 174, 46–48. https://doi.org/10.1016/J.CHEMOSPHERE.2017.01.107.

Hom-Diaz, A., Jaén-Gil, A., Rodríguez-Mozaz, S., Barceló, D., Vicent, T., Blánquez, P., 2022. Insights into removal of antibiotics by selected microalgae (Chlamydomonas reinhardtii, Chlorella sorokiniana, Dunaliella tertiolecta and Pseudokirchneriella subcapitata). Algal Res. 61, 102560 https://doi.org/10.1016/J.ALGAL.2021.102560.

Huo, S., Chen, J., Zhu, F., Zou, B., Chen, X., Basheer, S., Cui, F., Qian, J., 2019. Filamentous microalgae Tribonema sp. cultivation in the anaerobic/oxic effluents of petrochemical wastewater for evaluating the efficiency of recycling and treatment. Biochem. Eng. J. 145, 27–32. https://doi.org/10.1016/J.BEJ.2019.02.011.

Huo, S., Zhu, F., Zou, B., Xu, L., Cui, F., You, W., 2018. A two-stage system coupling hydrolytic acidification with algal microcosms for treatment of wastewater from the manufacture of acrylonitrile butadiene styrene (ABS) resin. Biotechnol. Lett. 40, 689–696. https://doi.org/10.1007/S10529-018-2513-8/FIGURES/3.

Jafarinejad, S., 2016. Petroleum waste treatment and pollution control. Pet. Waste Treat. Pollut. Control 1–362.

Javed, F., Aslam, M., Rashid, N., Shamair, Z., Khan, A.L., Yasin, M., Fazal, T., Hafeez, A., Rehman, F., Rehman, M.S.U., Khan, Z., Iqbal, J., Bazmi, A.A., 2019. Microalgae-based biofuels, resource recovery and wastewater treatment: a pathway towards sustainable biorefinery. Fuel 255, 115826. https://doi.org/10.1016/J.FUEL.2019.115826.

Kapoore, R.V., Wood, E.E., Llewellyn, C.A., 2021. Algae biostimulants: a critical look at microalgal biostimulants for sustainable agricultural practices. Biotechnol. Adv. 49, 107754 https://doi.org/10.1016/j.biotechadv.2021.107754.

Kern, J.D., Hise, A.M., Characklis, G.W., Gerlach, R., Viamajala, S., Gardner, R.D., 2017. Using life cycle assessment and techno-economic analysis in a real options framework to inform the design of algal biofuel production facilities. Bioresour. Technol. 225, 418–428. https://doi.org/10.1016/J.BIORTECH.2016.11.116.

Khan, A., Ali, J., Jamil, S.U.U., Zahra, N., Tayaba, T.B., Iqbal, M.J., Waseem, H., 2022. Removal of micropollutants. Environ. Micropollutants 443–461. https://doi.org/10.1016/B978-0-323-90555-8.00012-X.

Khan, H., Iram, Gul K., Ara, B., Khan, A., Ali, Nauman, Ali, Nisar, Bilal, M., 2020. Adsorptive removal of acrylic acid from the aqueous environment using raw and chemically modified alumina: batch adsorption, kinetic, equilibrium and thermodynamic studies. J. Environ. Chem. Eng. 8, 103927 https://doi.org/10.1016/J.JECE.2020.103927.

Khan, S., Shamshad, I., Waqas, M., Nawab, J., Ming, L., 2017. Remediating industrial wastewater containing potentially toxic elements with four freshwater algae. Ecol. Eng. 102, 536–541. https://doi.org/10.1016/j.ecoleng.2017.02.038.

Khoo, K.S., Chia, W.Y., Chew, K.W., Show, P.L., 2021. Microalgal-bacterial consortia as future prospect in wastewater bioremediation, environmental management and bioenergy production. Indian J. Microbiol. 61, 262–269. https://doi.org/10.1007/s12088-021-00924-8.

Kinidi, L., Tan, I.A.W., Abdul Wahab, N.B., Tamrin, K.F. Bin, Hipolito, C.N., Salleh, S.F., 2018. Recent development in ammonia stripping process for industrial wastewater treatment. Int. J. Chem. Eng. https://doi.org/10.1155/2018/3181087, 2018.

Kowthaman, C.N., Kumar, P.S., Mozhi, V.A., Ganesh, D., 2022. A comprehensive insight from microalgae production process to characterization of biofuel for the sustainable energy. Fuel 310, 122320. https://doi.org/10.1016/j.fuel.2021.122320.

Krishnamoorthy, S., Manickam, P., 2021. Phycoremediation of industrial wastewater: challenges and prospects. Bioremediation Environ. Sustain. 99–123. https://doi.org/10.1016/B978-0-12-820318-7.00005-8.

Kumar, A., Yuan, X., Sahu, A.K., Ergas, S.J., Van Langenhove, H., Dewulf, J., 2010. A hollow fiber membrane photo-bioreactor for CO2 sequestration from combustion gas coupled with wastewater treatment: a process engineering approach. J. Chem. Technol. Biotechnol. 85, 387–394. https://doi.org/10.1002/JCTB.2332.

Kumar, D., Singh, B., 2019. Algal biorefinery: an integrated approach for sustainable biodiesel production. Biomass Bioenergy 131, 105398. https://doi.org/10.1016/J.BIOMBIOE.2019.105398.

Kurniawan, S.B., Ahmad, A., Imron, M.F., Abdullah, S.R.S., Othman, A.R., Hasan, H.A., 2022. Potential of microalgae cultivation using nutrient-rich wastewater and harvesting performance by biocoagulants/bioflocculants: mechanism, multi-conversion of biomass into valuable products, and future challenges. J. Clean. Prod. 365, 132806 https://doi.org/10.1016/J.JCLEPRO.2022.132806.

Kushwaha, A., Yadav, A.N., Singh, B., Dwivedi, V., Kumar, S., Goswami, L., Hussain, C. M., 2022. Life cycle assessment and techno-economic analysis of algae-derived biodiesel: current challenges and future prospects. Waste-to-Energy Approaches Towar. Zero Waste 343–372. https://doi.org/10.1016/B978-0-323-85387-3.00003-3.

Li, X., Wu, S., Yang, C., Zeng, G., 2020. Microalgal and duckweed based constructed wetlands for swine wastewater treatment: a review. Bioresour. Technol. 318, 123858 https://doi.org/10.1016/J.BIORTECH.2020.123858.

Lindner, A.V., Pleissner, D., 2019. Utilization of phenolic compounds by microalgae. Algal Res. 42, 101602 https://doi.org/10.1016/J.ALGAL.2019.101602.

Liu, X. ya, Hong, Y., 2021. Microalgae-based wastewater treatment and recovery with biomass and value-added products: a brief review. Curr. Pollut. Reports 7, 227–245. https://doi.org/10.1007/S40726-021-00184-6/TABLES/3.

Madadi, R., Pourbabaee, A.A., Tabatabaei, M., Zahed, M.A., Naghavi, M.R., 2016. Treatment of petrochemical wastewater by the green algae Chlorella vulgaris. Int. J. Environ. Res. 10, 555–560. https://doi.org/10.22059/IJER.2016.59684.

Madadi, R., Zahed, M.A., Pourbabaee, A.A., Tabatabaei, M., Naghavi, M.R., 2021. Simultaneous phycoremediation of petrochemical wastewater and lipid production by Chlorella vulgaris. SN Appl. Sci. 3, 1–10. https://doi.org/10.1007/s42452-021-04511-w.

Maizatul, A.Y., Radin Mohamed, R.M.S., Al-Gheethi, A.A., Hashim, M.K.A., 2017. An overview of the utilisation of microalgae biomass derived from nutrient recycling of wet market wastewater and slaughterhouse wastewater. Int. Aquat. Res. 9, 177–193. https://doi.org/10.1007/S40071-017-0168-Z/TABLES/8.

Marella, T.K., Saxena, A., Tiwari, A., Datta, A., Dixit, S., 2022. Treating agricultural non-point source pollutants using periphyton biofilms and biomass volarization. J. Environ. Manag. 301, 113869 https://doi.org/10.1016/J.JENVMAN.2021.113869.

Markou, G., Georgakakis, D., 2011. Cultivation of filamentous cyanobacteria (blue-green algae) in agro-industrial wastes and wastewaters: a review. Appl. Energy 88, 3389–3401. https://doi.org/10.1016/J.APENERGY.2010.12.042.

Matamoros, V., Gutiérrez, R., Ferrer, I., García, J., Bayona, J.M., 2015. Capability of microalgae-based wastewater treatment systems to remove emerging organic contaminants: a pilot-scale study. J. Hazard Mater. 288, 34–42. https://doi.org/10.1016/J.JHAZMAT.2015.02.002.

Maurya, R., Zhu, X., Valverde-Pérez, B., Ravi Kiran, B., General, T., Sharma, S., Kumar Sharma, A., Thomsen, M., Venkata Mohan, S., Mohanty, K., Angelidaki, I., 2022a. Advances in microalgal research for valorization of industrial wastewater. Bioresour. Technol. 343 https://doi.org/10.1016/j.biortech.2021.126128.

Maurya, R., Zhu, X., Valverde-Pérez, B., Ravi Kiran, B., General, T., Sharma, S., Kumar Sharma, A., Thomsen, M., Venkata Mohan, S., Mohanty, K., Angelidaki, I., 2022b. Advances in microalgal research for valorization of industrial wastewater. Bioresour. Technol. 343, 126128 https://doi.org/10.1016/J.BIORTECH.2021.126128.

Mohsenpour, S.F., Hennige, S., Willoughby, N., Adeloye, A., Gutierrez, T., 2021a. Integrating micro-algae into wastewater treatment: a review. Sci. Total Environ. 752, 142168 https://doi.org/10.1016/j.scitotenv.2020.142168.

Mohsenpour, S.F., Hennige, S., Willoughby, N., Adeloye, A., Gutierrez, T., 2021b. Integrating micro-algae into wastewater treatment: a review. Sci. Total Environ. 752, 142168 https://doi.org/10.1016/J.SCITOTENV.2020.142168.

Mubashar, M., Ahmad, Z., Li, C., Zhang, H., Xu, C., Wang, G., Qiu, D., Song, L., Zhang, X., 2021. Carbon-negative and high-rate nutrient removal using mixotrophic microalgae. Bioresour. Technol. 340, 125731 https://doi.org/10.1016/J.BIORTECH.2021.125731.

Muhammad, Z., Ali, F., Sajjad, M., Ali, N., Bilal, M., Shaik, M.R., Adil, S.F., Sharaf, M.A. F., Awwad, E.M., Khan, M., 2021. Zirconium-doped chromium IV oxide nanocomposites: synthesis, characterization, and photocatalysis towards the degradation of organic dyes. Catal. 2021 11, 117. https://doi.org/10.3390/CATAL11010117. Page 117 11.

Mujtaba, G., Lee, K., 2017. Treatment of real wastewater using co-culture of immobilized Chlorella vulgaris and suspended activated sludge. Water Res. 120, 174–184. https://doi.org/10.1016/J.WATRES.2017.04.078.

Multilateral Investment Guarantee Agency, 2004. Environmental guidelines for petrochemicals manufacturing. Pollut. Prev. Abat. Handb. 371–376.

Munir, H., Mumtaz, A., Rashid, R., Najeeb, J., Zubair, M.T., Munir, S., Bilal, M., Cheng, H., 2020. Eucalyptus camaldulensis gum as a green matrix to fabrication of zinc and silver nanoparticles: characterization and novel prospects as antimicrobial and dye-degrading agents. J. Mater. Res. Technol. 9, 15513–15524. https://doi.org/10.1016/J.JMRT.2020.11.026.

Muralikrishna, I.V., Manickam, V., 2017. Life cycle assessment. Environ. Manag. 57–75. https://doi.org/10.1016/B978-0-12-811989-1.00005-1.
Mutanda, T., Naidoo, D., Bwapwa, J.K., Anandraj, A., 2020. Biotechnological applications of microalgal oleaginous compounds: current trends on microalgal bioprocessing of products. Front. Energy Res. 8, 299. https://doi.org/10.3389/FENRG.2020.598803/BIBTEX.
Nawaz, A., Khan, A., Ali, Nisar, Ali, Nauman, Bilal, M., 2020. Fabrication and characterization of new ternary ferrites-chitosan nanocomposite for solar-light driven photocatalytic degradation of a model textile dye. Environ. Technol. Innovat. 20, 101079 https://doi.org/10.1016/J.ETI.2020.101079.
Nugroho, A.D., Lakner, Z., 2022. Impact of economic globalisation on agriculture in developing countries: a review. Agric. Econ. 68 (2022), 180–188. https://doi.org/10.17221/401/2021-AGRICECON.
Nur, M.M.A., Yuliestyan, A., Irfandy, F., Setyoningrum, T.M., 2022. Nutritional factors influence polyhydroxybutyrate in microalgae growing on palm oil mill effluent. J. Appl. Phycol. 34, 127–133. https://doi.org/10.1007/S10811-021-02654-2/FIGURES/3.
Panchangam, S.C., Janakiraman, K., 2015. Decolorization of aqueous coffee and tea infusions by chemical coagulation. New pub Balaban 53, 119–125. https://doi.org/10.1080/19443994.2013.860401.
Papazi, A., Karamanli, M., Kotzabasis, K., 2019. Comparative biodegradation of all chlorinated phenols by the microalga Scenedesmus obliquus — the biodegradation strategy of microalgae. J. Biotechnol. 296, 61–68. https://doi.org/10.1016/J.JBIOTEC.2019.03.010.
Phang, S.-M., Chu, W.-L., Rabiei, R., 2015. Phycoremediation. Algae World. Springer, pp. 357–389. https://doi.org/10.1007/978-94-017-7321-8_13.
Phang, S., Hashim, M.A., 2001. High rate algal ponds for treatment of wastewater. In%3A Photosynthetic microorganisms in environmental biotechnology&publication_year=2001&author=S.M. Phang&author=Y. (accessed 9.18.22). https://scholar.google.com/scholar_lookup?title=High rate algal ponds for treatment of wastewater%3A a case study for the rubber industry [WWW Document]. URL.
Priyadarshini, M., Ahmad, A., Das, S., Ghangrekar, M.M., 2021. Application of microbial electrochemical technologies for the treatment of petrochemical wastewater with concomitant valuable recovery: a review. Environ. Sci. Pollut. Res. 2021, 1–20. https://doi.org/10.1007/S11356-021-14944-W.
Quintero-Dallos, V., García-Martínez, J.B., Contreras-Ropero, J.E., Barajas-Ferrerira, C., Barajas-Solano, A.F., Lavecchia, R., Zuorro, A., 2019. Distillery Wastewater as a Sustainable Medium for Microalgae Production. https://doi.org/10.20944/PREPRINTS201906.0184.V1.
Rajamohan, N., Senthil Kumar, P., Rajasimman, M., Qasmi, F. Al, 2021. Treatment of methanol industry effluent using algal biomass,Gelidium omanense- kinetic modeling. Chem. Eng. J. Adv. 5, 100068 https://doi.org/10.1016/j.ceja.2020.100068.
Rani, S., Gunjyal, N., Ojha, C.S.P., Singh, R.P., 2021. Review of challenges for algae-based wastewater treatment: strain selection, wastewater characteristics, abiotic, and biotic factors. J. Hazardous, Toxic, Radioact. Waste 25, 03120004. https://doi.org/10.1061/(asce)hz.2153-5515.0000578.
Ratnasari, A., Zaidi, N.S., Syafiuddin, A., Boopathy, R., Kueh, A.B.H., Amalia, R., Prasetyo, D.D., 2021. Prospective biodegradation of organic and nitrogenous pollutants from palm oil mill effluent by acidophilic bacteria and archaea. Bioresour. Technol. Reports 15, 100809. https://doi.org/10.1016/J.BITEB.2021.100809.
Rempel, A., Gutkoski, J.P., Nazari, M.T., Biolchi, G.N., Cavanhi, V.A.F., Treichel, H., Colla, L.M., 2021. Current advances in microalgae-based bioremediation and other technologies for emerging contaminants treatment. Sci. Total Environ. 772, 144918 https://doi.org/10.1016/J.SCITOTENV.2020.144918.
Rodríguez-Rangel, H., Arias, D.M., Morales-Rosales, L.A., Gonzalez-Huitron, V., Partida, M.V., García, J., 2022. Machine learning methods modeling carbohydrate-enriched cyanobacteria biomass production in wastewater treatment systems. Energies 2022 15, 2500. https://doi.org/10.3390/EN15072500. Page 2500 15.
Roostaei, J., Zhang, Y., 2017. Spatially explicit life cycle assessment: opportunities and challenges of wastewater-based algal biofuels in the United States. Algal Res. 24, 395–402. https://doi.org/10.1016/J.ALGAL.2016.08.008.
Ryu, B.G., Kim, E.J., Kim, H.S., Kim, J., Choi, Y.E., Yang, J.W., 2014. Simultaneous treatment of municipal wastewater and biodiesel production by cultivation of Chlorella vulgaris with indigenous wastewater bacteria. Biotechnol. Bioproc. Eng. 19, 201–210. https://doi.org/10.1007/S12257-013-0250-3, 2014 192.
Ryu, B.G., Kim, J., Han, J.I., Yang, J.W., 2017. Feasibility of using a microalgal-bacterial consortium for treatment of toxic coke wastewater with concomitant production of microbial lipids. Bioresour. Technol. 225, 58–66. https://doi.org/10.1016/J.BIORTECH.2016.11.029.
Santos, S.C.R., Ungureanu, G., Volf, I., Boaventura, R.A.R., Botelho, C.M.S., 2018. Macroalgae biomass as sorbent for metal ions. Biomass as renew. Raw mater. To obtain bioprod. High-Tech Value 69–112. https://doi.org/10.1016/B978-0-444-63774-1.00003-X.
Sathishkumar, P., Murugesan, K., Palvannan, T., 2010. Production of laccase from Pleurotus Florida using agro-wastes and efficient decolorization of Reactive blue 198. J. Basic Microbiol. 50, 360–367. https://doi.org/10.1002/JOBM.200900407.
Selvan, S.T., Govindasamy, B., Muthusamy, S., Ramamurthy, D., 2019. Exploration of green integrated approach for effluent treatment through mass culture and biofuel production from unicellular alga. Acutodesmus obliquus RDS01 21, 1305–1322. https://doi.org/10.1080/15226514.2019.1633255.
Shanthala, M., Hosmani, S.P., Hosetti, B.B., 2008. Diversity of phytoplanktons in a waste stabilization pond at Shimoga Town, Karnataka State, India. Environ. Monit. Assess. 437–443. https://doi.org/10.1007/S10661-008-0287-5, 2008 1511 151.
Sharma, N., Singh, A., Lalremruati, F., Vanlalmalsawmi, Sharma R., 2019. Diverse application and future prospects for commercial cultivation of microalgae species: a review. Plant Sci. Today 6, 427–432. https://doi.org/10.14719/PST.2019.6.4.581.
Shiri, Z., Kermanshahi, R.K., Soudi, M.R., Farajzadeh, D., 2015. Isolation and characterization of an n-hexadecane degrading Acinetobacter baumannii KSS1060 from a petrochemical wastewater treatment plant. Int. J. Environ. Sci. Technol. 12, 455–464. https://doi.org/10.1007/S13762-014-0702-0/TABLES/2.
Smith, V.H., Tilman, G.D., Nekola, J.C., 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environ. Pollut. 100, 179–196. https://doi.org/10.1016/S0269-7491(99)00091-3.
Smječanin, N., Bužo, D., Mašić, E., Nuhanović, M., Sulejmanović, J., Azhar, O., Sher, F., 2022. Algae-based green biocomposites for uranium removal from wastewater: kinetic, equilibrium and thermodynamic studies. Mater. Chem. Phys. 283, 125998 https://doi.org/10.1016/j.matchemphys.2022.125998.
Sonone, S.J., Ms, S., R, K., 2020. Water contamination by heavy metals and their toxic effect on aquaculture and human health through food chain. Lett. Appl. NanoBioScience 10, 2148–2166. https://doi.org/10.33263/LIANBS102.21482166.
Sparn, B., Hunsberger, R., 2015. Opportunities and Challenges for Water and Wastewater Industries to Provide Exchangeable Services. https://doi.org/10.2172/1227107.
Stamm, C., Räsänen, K., Burdon, F.J., Altermatt, F., Jokela, J., Joss, A., Ackermann, M., Eggen, R.I.L., 2016. Unravelling the impacts of micropollutants in aquatic ecosystems: interdisciplinary studies at the interface of large-scale ecology. Adv. Ecol. Res. 55, 183–223. https://doi.org/10.1016/BS.AECR.2016.07.002.
Syafiuddin, A., Boopathy, R., Hadibarata, T., 2020. Challenges and solutions for sustainable groundwater usage: pollution control and integrated management. Curr. Pollut. Reports 6, 310–327. https://doi.org/10.1007/S40726-020-00167-Z/FIGURES/6.
Syafiuddin, A., Boopathy, R., Mehmood, M.A., 2021. Recent advances on bacterial quorum quenching as an effective strategy to control biofouling in membrane bioreactors. Bioresour. Technol. Reports 15, 100745. https://doi.org/10.1016/J.BITEB.2021.100745.
Synytsya, A., Copíková, J., Kim, W.J., Park, Y.I., 2015. Cell Wall Polysaccharides of Marine Algae. Springer Handb. https://doi.org/10.1007/978-3-642-53971-8_22/COVER/. Mar. Biotechnol. 543–590.
Touliabah, H.E., El-sheekh, M.M., Ismail, M.M., El-kassas, H., 2022. A Review of Microalgae- and Cyanobacteria-Based Biodegradation of Organic Pollutants.
Ugya, A.Y., Hua, X., Ma, J., 2019. Biosorption of Cr3+ and Pb2+ from tannery wastewater using combined fruit waste. Appl. Ecol. Environ. Res. 17, 1773–1787. https://doi.org/10.15666/AEER/1702_17731787.
Umamaheswari, J., Shanthakumar, S., 2021. Paddy-soaked rice mill wastewater treatment by phycoremediation and feasibility study on use of algal biomass as biofertilizer. J. Chem. Technol. Biotechnol. 96, 394–403. https://doi.org/10.1002/jctb.6551.
Ummalyma, S.B., Sukumaran, R.K., 2014. Cultivation of microalgae in dairy effluent for oil production and removal of organic pollution load. Bioresour. Technol. 165, 295–301. https://doi.org/10.1016/J.BIORTECH.2014.03.028.
Ungureanu, N., Vlăduț, V., Biriș, S., Zăbavă, B., Popa, M., 2019. Microalgal systems for wastewater treatment-review. Res. People Actual Tasks Multidiscip. Sci.
US EPA, 1995. Profile of the petroleum refining industry. EPA off. Compliance Sect. Noteb. Proj. 59.
Verma, S., Kumar, P., Srivastava, V.C., Štangar, U.L., 2022. Application of advanced oxidation processes (AOPs) for the treatment of petrochemical industry wastewater. Environ. Sci. Eng. 103–128. https://doi.org/10.1007/978-3-030-83811-9_6/COVER/.
Vieira, H., Mendonça, D., Henrique, M., Marchão, L., Lomeu, A., Salvador, D., Souza, D., Reis, A., 2022. Biofuel recovery from microalgae biomass grown in dairy wastewater treated with activated sludge : the next step in sustainable production. Sci. Total Environ. 824, 153838 https://doi.org/10.1016/j.scitotenv.2022.153838.
Wang, L., Addy, M., Liu, J., Nekich, C., Zhang, R., Peng, P., Cheng, Y., Cobb, K., Liu, Y., Wang, H., Ruan, R., 2019. Integrated process for anaerobically digested swine manure treatment. Bioresour. Technol. 273, 506–514. https://doi.org/10.1016/J.BIORTECH.2018.11.050.
Wang, L., Li, Y., Chen, P., Min, M., Chen, Y., Zhu, J., Ruan, R.R., 2010. Anaerobic digested dairy manure as a nutrient supplement for cultivation of oil-rich green microalgae Chlorella sp. Bioresour. Technol. 101, 2623–2628. https://doi.org/10.1016/J.BIORTECH.2009.10.062.
Wang, T., Wang, L., Chen, Q., Kalogerakis, N., Ji, R., Ma, Y., 2020. Interactions between microplastics and organic pollutants: effects on toxicity, bioaccumulation, degradation, and transport. Sci. Total Environ. 748, 142427 https://doi.org/10.1016/J.SCITOTENV.2020.142427.
Wang, Zhongjiang, Wang, Ziyue, Wang, G., Zhou, Z., Hao, S., Wang, L., 2022. Microalgae cultivation using unsterilized cattle farm wastewater filtered through corn stover. Bioresour. Technol. 352, 127081 https://doi.org/10.1016/J.BIORTECH.2022.127081.
Wei, J., Chong, R., Tan, X., Shiong, K., Suan, H., Jonglertjunya, W., Yong, G., Loke, P., 2022. Microalgae-based bioplastics : future solution towards mitigation of plastic wastes. Environ. Res. 206, 112620 https://doi.org/10.1016/j.envres.2021.112620.
Wei, X., Zhang, S., Han, Y., Wolfe, F.A., 2019. Treatment of petrochemical wastewater and produced water from oil and gas. Water Environ. Res. 91, 1025–1033. https://doi.org/10.1002/WER.1172.
Wiatrowski, M., Klein, B.C., Davis, R.W., Arita, C.Q., Tan, E.C.D., Hunt, R.W., Davis, R.E., 2022a. Biotechnology for Biofuels Techno - economic assessment for the production of algal fuels and value - added products : opportunities for high - protein microalgae conversion. Biotechnol. Biofuels Bioprod. 1–14. https://doi.org/10.1186/s13068-021-02098-3.

Wiatrowski, M., Klein, B.C., Davis, R.W., Quiroz-Arita, C., Tan, E.C.D., Hunt, R.W., Davis, R.E., 2022b. Techno-economic assessment for the production of algal fuels and value-added products: opportunities for high-protein microalgae conversion. Biotechnol. Biofuels Bioprod. 15, 1–14. https://doi.org/10.1186/S13068-021-02098-3/FIGURES/3.

Wu, X., Wu, H., Zhang, A., Sekou, K., Li, Z., Ye, J., 2022. Influence of polystyrene microplastics on levofloxacin removal by microalgae from freshwater aquaculture wastewater. J. Environ. Manag. 301, 113865 https://doi.org/10.1016/J.JENVMAN.2021.113865.

Wu, Y.H., Hu, H.Y., Yu, Y., Zhang, T.Y., Zhu, S.F., Zhuang, L.L., Zhang, X., Lu, Y., 2014. Microalgal species for sustainable biomass/lipid production using wastewater as resource: a review. Renew. Sustain. Energy Rev. 33, 675–688. https://doi.org/10.1016/J.RSER.2014.02.026.

Xu, H., Paerl, H.W., Qin, B., Zhu, G., Hall, N.S., Wu, Y., 2015. Determining critical nutrient thresholds needed to control harmful cyanobacterial blooms in eutrophic Lake Taihu, China. Environ. Sci. Technol. 49, 1051–1059. https://doi.org/10.1021/ES503744Q/SUPPL_FILE/ES503744Q_SI_001.PDF.

Xue, F., Miao, J., Zhang, X., Tan, T., 2010. A new strategy for lipid production by mix cultivation of Spirulina platensis and Rhodotorula glutinis. Appl. Biochem. Biotechnol. 160, 498–503. https://doi.org/10.1007/S12010-008-8376-Z/TABLES/3.

Yadav, G., Shanmugam, S., Sivaramakrishnan, R., Kumar, D., Mathimani, T., Brindhadevi, K., Pugazhendhi, A., Rajendran, K., 2021a. Mechanism and challenges behind algae as a wastewater treatment choice for bioenergy production and beyond. Fuel 285, 119093. https://doi.org/10.1016/j.fuel.2020.119093.

Yadav, G., Shanmugam, S., Sivaramakrishnan, R., Kumar, D., Mathimani, T., Brindhadevi, K., Pugazhendhi, A., Rajendran, K., 2021b. Mechanism and challenges behind algae as a wastewater treatment choice for bioenergy production and beyond. Fuel 285, 119093. https://doi.org/10.1016/J.FUEL.2020.119093.

Yang, L., Li, H., Wang, Q., 2019. A novel one-step method for oil-rich biomass production and harvesting by co-cultivating microalgae with filamentous fungi in molasses wastewater. Bioresour. Technol. 275, 35–43. https://doi.org/10.1016/J.BIORTECH.2018.12.036.

Yong, J.J.J.Y., Chew, K.W., Khoo, K.S., Show, P.L., Chang, J.S., 2021. Prospects and development of algal-bacterial biotechnology in environmental management and protection. Biotechnol. Adv. 47, 107684 https://doi.org/10.1016/j.biotechadv.2020.107684.

Zeb, S., Ali, N., Ali, Z., Bilal, M., Adalat, B., Hussain, S., Gul, S., Ali, F., Ahmad, R., khan, S., Iqbal, H.M.N., 2020. Silica-based nanomaterials as designer adsorbents to mitigate emerging organic contaminants from water matrices. J. Water Proc. Eng. 38, 101675 https://doi.org/10.1016/J.JWPE.2020.101675.

Zhao, Z., Muylaert, K., Szymczyk, A., Vankelecom, I.F.J., 2021. Enhanced microalgal biofilm formation and facilitated microalgae harvesting using a novel pH-responsive, crosslinked patterned and vibrating membrane. Chem. Eng. J. 410, 127390 https://doi.org/10.1016/J.CEJ.2020.127390.

Zhou, H., Zhao, X., Kumar, K., Kunetz, T., Zhang, Y., Gross, M., Wen, Z., 2021. Removing high concentration of nickel (II) ions from synthetic wastewater by an indigenous microalgae consortium with a Revolving Algal Biofilm (RAB) system. Algal Res. 59, 102464 https://doi.org/10.1016/j.algal.2021.102464.

Zhou, Y., Liu, L., Li, M., Hu, C., 2022. Algal biomass valorisation to high-value chemicals and bioproducts: recent advances, opportunities and challenges. Bioresour. Technol. 344, 126371 https://doi.org/10.1016/J.BIORTECH.2021.126371.

Zilberman, D., Templeton, S.R., Khanna, M., 1999. Agriculture and the environment: an economic perspective with implications for nutrition. Food Pol. 24, 211–229. https://doi.org/10.1016/S0306-9192(99)00026-3.

Znad, H., Awual, M.R., Martini, S., 2022. The utilization of algae and seaweed biomass for bioremediation of heavy metal-contaminated wastewater. Molecules 27, 1275. https://doi.org/10.3390/molecules27041275.