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Article Sub-Title		
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Schedule	Received	16 Oct 2023
	Revised	17 Sep 2024
	Accepted	8 Oct 2024

Abstract	Industrialisation, population growth, and concomitant demand for fresh water have immensely impacted water quality and scarcity. In particular, wastewater generated from industries generally produces high amounts of nutrients, heavy metals, and chemicals that degrade the environment. Several algal species have been studied and utilized for their role in the treatment of various types of wastewater. Conventional wastewater treatment options are often expensive and energy-demanding, and generally ineffective at completely removing contaminants. Conversely, phycoremediation technology is an emerging green approach used to remove various types of pollutants from the environment while producing valuable compounds. Compared to conventional methods, phycoremediation presents as an eco-friendly and economically attractive alternative. This paper serves as a review of an algal-based treatment technology in wastewater remediation for industry, describing the most common microalgal consortia used for this purpose. Phycoremediation challenges and strategies to urgently accelerate steps towards achieving a clean and safe environment are presented, while examples of applications in industries are also provided.

Keywords (separated by '-')	Bioremediation - Industrial effluents - Metal pollution - Microalgae - Wastewater treatment
Footnote Information	Editorial responsibility: M.Shabani.

International Journal of Environmental Science and Technology
https://doi.org/10.1007/s13762-024-06130-5

REVIEW

Phycoremediation of industrial wastewater: review of algae consortia

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Received: 16 October 2023 / Revised: 17 September 2024 / Accepted: 8 October 2024

Abstract

Industrialisation, population growth, and concomitant demand for fresh water have immensely impacted water quality and scarcity. In particular, wastewater generated from industries generally produces high amounts of nutrients, heavy metals, and chemicals that degrade the environment. Several algal species have been studied and utilized for their role in the treatment of various types of wastewater. Conventional wastewater treatment options are often expensive and energy-demanding, and generally ineffective at completely removing contaminants. Conversely, phycoremediation technology is an emerging green approach used to remove various types of pollutants from the environment while producing valuable compounds. Compared to conventional methods, phycoremediation presents as an eco-friendly and economically attractive alternative. This paper serves as a review of an algal-based treatment technology in wastewater remediation for industry, describing the most common microalgal consortia used for this purpose. Phycoremediation challenges and strategies to urgently accelerate steps towards achieving a clean and safe environment are presented, while examples of applications in industries are also provided.

Keywords Bioremediation · Industrial effluents · Metal pollution · Microalgae · Wastewater treatment

Introduction

Uncontrolled population growth, urban migration, and industrialisation are among the most urgent 21st-century challenges globally, exacerbated in Africa where sanitation services and infrastructure are already under severe pressure (UN Habitat 2008; Meso et al. 2016; Brikké and Vairavamoorthy 2016; Nansubunga et al. 2016; Saghir and Santoro 2018). The availability of fresh water is scarce and environmental problems are more severe due to rapid industrialisation and urbanization. The global water demand of various sectors (particularly agriculture, industries, and municipalities) is expected to increase by as much as 30% by 2050 (Boretti and Rosa 2019), while the annual global waste production is expected to increase from 2.01 to 3.40 billion tonnes (Koul et al. 2022). This will further impact people and ecosystem services.

Conventional techniques of wastewater treatment and remediation treatment processes involve several steps including preliminary, primary, secondary, tertiary, and disinfection processes; and these processes are often ineffective at removing all contaminants present in wastewater. To negate the harmful impact of various pollutants, alternative treatment options are required. Phycoremediation using either macroalgae (multicellular and macroscopic) or microalgae (unicellular and microscopic) has become a promising method for biological purification and treatment of wastewater (Olgui'n 2003; Gani et al. 2015). Phycoremediation offers various advantages over other traditional methods (e.g., low cost, carbon sequestration). Microalgae are of increasing interest in various sectors, including renewable energy, food, environmental management, water purification, and the production of biofertilizers, and can provide an alternative low-cost and low-energy solution to nutrient recovery from wastewater streams in developing countries.

Biological treatment of wastewater, more specifically plant-based green technologies, can assist in supporting the United Nations Sustainable Development Goals

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(SDGs) and contribute significantly to the circular economy (Fig. 1). Phycoremediation is aligned, in particular, to the objectives of SDG-3 "Good health and well-being", SDG-6 "Clean water and sanitation", SDG-7 "Affordable and clean energy", and SDG-13 "Climate action", collectively directed to enhance social, economic, and environmental aspects.

Internationally phycoremediation approaches have already been successfully applied to several industrial wastewater types including paper and pulp (Sasi et al. 2020), distillery (Khrisnamoorthy et al. 2019), and sugar processing (Sailaja and Meti 2014; Zewdie and Ali 2020) effluents. Similarly, phycoremediation has reportedly successfully decreased or eliminated the heavy metal content of wastewater, and reduced antibiotic resistance and other emerging contaminants (Sutherland and Ralph 2019; Leng et al. 2020; Singh et al. 2021; Jha et al. 2023; Atoku et al. 2021; Hejna et al. 2022; Ricky and Shanthakumar 2022). In South Africa specifically, phycoremediation has been applied in municipal and domestic wastewater treatment (Oberholster et al. 2017, 2021; Steyn and Oberholster 2021). Given the current water quality challenges and expected future population growth, phycoremediation presents as a sustainable wastewater management option in support of closing the loop in the circular economy. Figure 2 provides a timeline for phycoremediation globally. This review, therefore, documents the effectiveness of phycoremediation as an alternative technology to treat and remove metals and other toxic pollutants from industrial wastewater, as well as the possible opportunities and challenges facing the phycoremediation of industrial wastewater.

Mechanism of phycoremediation of microalgae

While phycoremediation is not a new concept (John 2003; Abdel-Raouf et al. 2012), it has recently gained significant attention for treating domestic, industrial, agro-industrial, and livestock wastewater (Abdelfattah et al. 2022). Bioremediation using microalgae is favoured above macroalgae due to its simple organization, faster growth rate, and high cell surface-to-volume ratio, as well as being capable of doubling their biomass in less than one day (Demirbas 2011; Lam et al. 2012; Kumar et al. 2018). As a further advantage, Leong and Chang (2020) described the high photosynthetic performance of algae and its ability to adapt to extreme environmental conditions. Bansal et al. (2018) reported that phycoremediation technology generally improved several biochemical parameters of water including pH, colour and odour removal, sludge reduction, biological oxygen demand (BOD) and chemical oxygen demand (COD) reduction, and nutrient removal including ammonia. The reduction of operational costs by up to 90% and better management of R/O rejects were also reported (Bansal et al. 2018). A variety of microalgal species, including *Scenedesmus*, *Chlorella*, *Botryococcus*, *Phormidium*, *Limnospira* (formerly *Arthrospira*, *Spirulina*), and *Chlamydomonas*, have been associated with successful removal of nutrients, heavy metals, emerging pollutants and pathogens from wastewater (Hoh et al. 2016; López-Sánchez et al. 2022; Ahmad et al. 2021). Studies have shown that phycoremediation can reduce eutrophication by 57.4%, ozone by 22.6%, and global warming by 2.7% (Li et al. 2020).

Fig. 1 Phycoremediation in the circular economy in support of the SDGs (adapted from Olabi et al. 2023)

While the exact mechanism of phycoremediation is largely unknown, it is believed that microalgae bind pollutants using cell wall receptor molecules such as lipids, proteins, and polysaccharides (Priyadarshani et al. 2011; Balzano et al. 2020) by creating a negative charge on the cell surface (Anastopoulos and Kyzas 2015). Microalgae-facilitated bioremediation involves mechanisms (Fig. 3) such as biosorption, bioaccumulation, biodegradation, biotransformation, phycovolatilisation, and complexation (Shackira et al. 2022; Abdelfattah et al. 2022). Biosorption is a passive

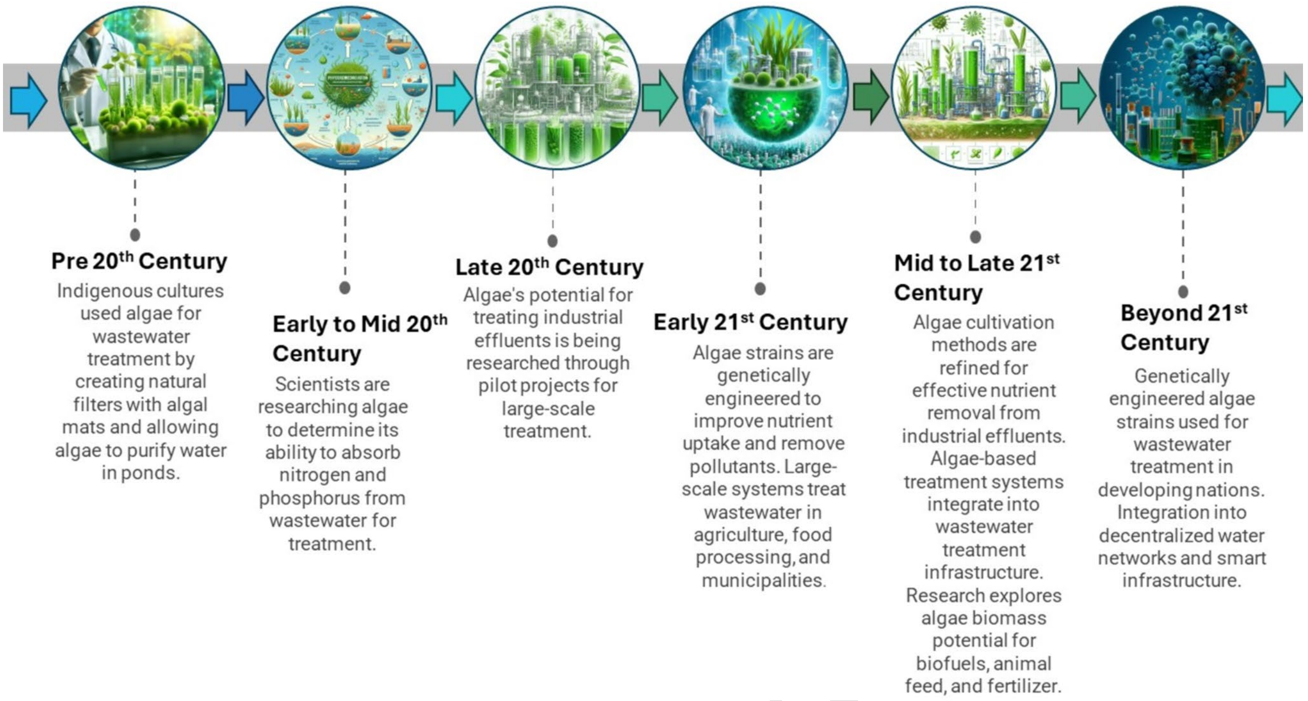

Fig. 2 Timeline of algae-based treatment of wastewater

biological physicochemical process whereby environmental pollutants (e.g., metal ions and dyes) can be absorbed or adsorbed (Brazesh et al. 2021). In contrast, bioaccumulation is an active treatment process that uses energy and involves the absorption of contaminants by living cells, which then accumulate or metabolize the contaminants. Furthermore, Mustafa et al. (2021) described bioaccumulation as an essential pathway for the removal of organic and inorganic pollutants from industrial wastewater. Biodegradation is one of the most effective processes to remove contaminants from effluents, and involves the breakdown of target pollutants either through 1) biotransformation which entails a series of enzymatic reactions to produce different metabolites, or 2) through complete mineralization of the parent compound to CO_2 and H_2O (Xiong et al. 2017). Through the processes outlined above, microalgae are able to remove nutrients, heavy metals, dyes, and xenobiotics. In addition to bioremediation capabilities, phycoremediation presents circular economy opportunities; microalgae biomass can be harvested and transformed into economically valuable products such as biofertilizers, biofuel, biogas, and health supplements.

Several processes inform microalgae's potential to remove hazardous compounds from wastewater. For instance, microalgae employ metabolic processes for pollutant removal from wastewater. (Fig. 4). Some of the key metabolic processes include photosynthesis (to convert carbon dioxide (CO_2) to oxygen (O_2), respiration (taking O_2 and releasing CO_2), nutrient uptake (microalgae require nutrients such as N and P, and assimilate these nutrients into their biomass, thereby reducing nutrient concentrations in the water), biodegradation (metabolizing organic pollutants into simpler, less toxic substances), and extracellular enzyme production (that facilitate the breakdown of organic pollutants in wastewater).

Selection of algae species for treating industrial wastewater

Algae (macro- and micro-algae) are a diverse group of aquatic plants, with cellulose-based cell walls, lacking typical roots, and known to have high carbon mitigating and photosynthetic efficiencies (Priyadharshini et al. 2021). The selection of suitable microalgal species (or consortia thereof) is important depending upon the characteristics of wastewater for efficient wastewater treatment. As mentioned, a wide variety of algae are already applied to industrial wastewater treatment (Batista et al. 2015; Emparan et al. 2019). Table 1

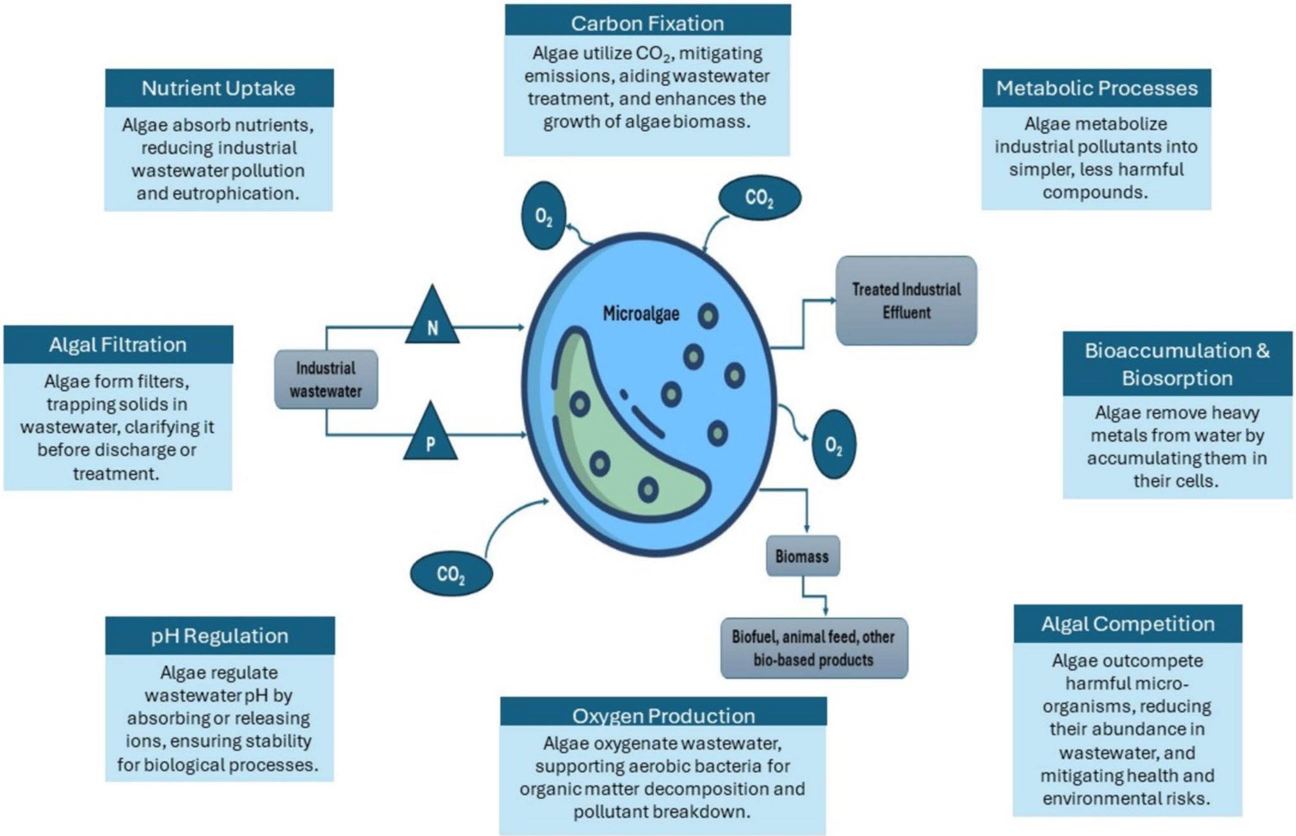

Fig. 3 Mechanisms used by algae cells to treat polluted water

provides a summary of laboratory-scale studies in the literature describing the various microalgal species used to effectively treat industrial wastewater.

Microalgae have the ability to remove heavy metals in wastewater due to the presence of proteins, lipids, and polysaccharides with heavy metal binding functional groups on their cell wall surface (Priatni et al. 2018). Reports on heavy metal affinity are numerous. Filamentous blue-green algae and freshwater filamentous diatoms have the potential to bind heavy metals effectively, while brown algae (e.g., *Ascophyllum sp*., *Sargassum sp*.) has a high affinity for divalent cations (Cd^{2+}, Zn^{2+}, Ca^{2+}, Pb^{2+}, Cu^{2+}). On the other hand, lead (Pb) is sorbed maximally by the majority of algal species when compared to other metals.

For organic substances, certain microalgae strains are known to successfully utilize the organic matter in effluents, reducing COD, BOD, and total organic carbon levels (TOC). For example, several studies reported that *Scenedesmus sp.* cultivation in pulp and paper mill waste efficiently removed > 75% COD, > 82% BOD, ~ 93% NH_4, > 65% NO_3, ~ 97% PO_4^3 and PO_4-P-71.29% (Table 1) (Usha et al. 2016; Pham et al. 2020), while *Planktochlorella Nurekis* and *Clamydomonas Reinhardtii* removed 92.8% COD, 95.6% N, 100% P, and 91.9% COD, 85.6% N, 87.5% P; respectively (Sasi et al. 2020). Lower removal efficiencies were reported for *Oocystis sp.* (71.1% COD, 70% P; Riano et al. (2011)), *C. zofingiensis* (82.70% TN, 68.96% COD; Zhu et al. (2013)), *Pithopora sp.* (87.23% COD, 87.75% BOD; Murugesan and Dhamotharan (2009)) and *Botryococcus sp.* (70.68% COD, 61.11% BOD, 76.66% TOC, 72.49% TN, 78.23% P, 86.62% N; Gani et al. (2015)).

Phycoremediation treatment techniques

Conventional treatment of industrial wastewater includes various chemical and physical treatment techniques. These techniques typically include chlorination, coagulation/flocculation, ultraviolet light, and ozonation (Al-Tohamy et al. 2022; Yusuf et al. 2020). These techniques, however, have

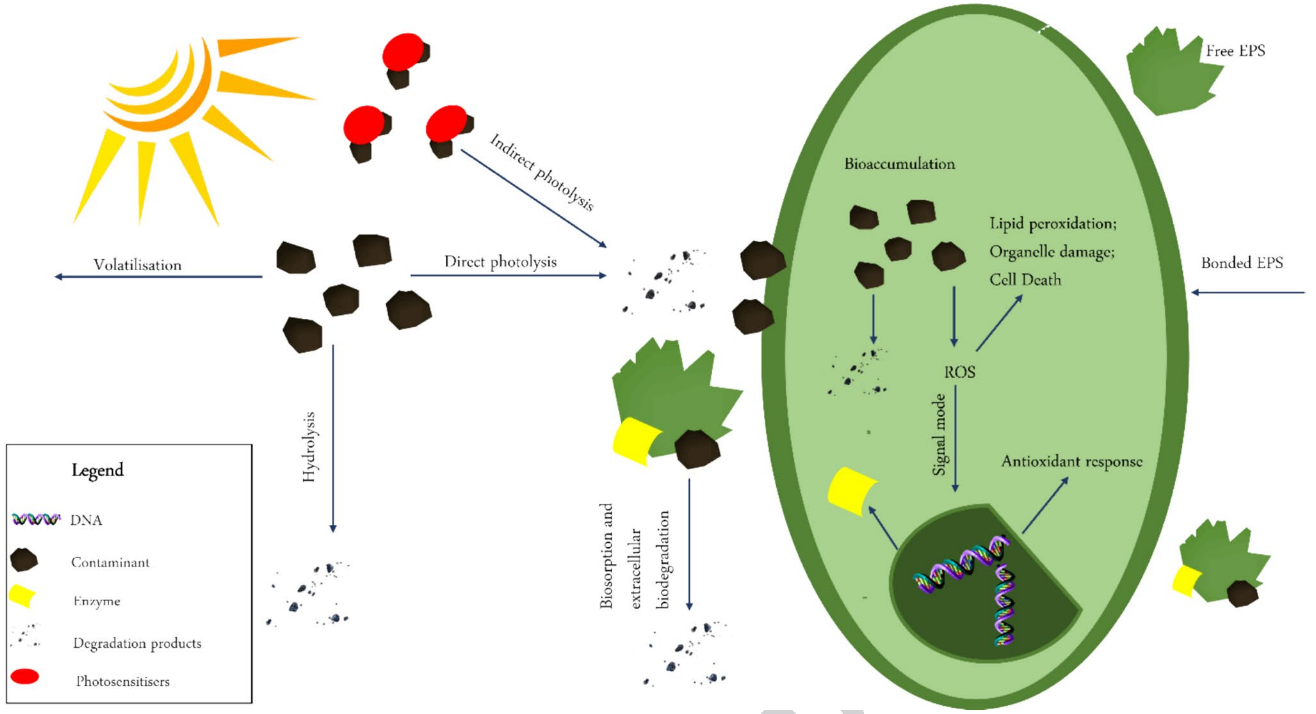

Fig. 4 An overview of metabolic processes that microalgae employ for pollutant removal (adapted from Zhou et al. 2022)

several drawbacks including high operating costs, generation of wastes and by-products, and removal inefficiencies.

Biological treatment of industrial wastewater using microalgae has gained significant attention as a potential treatment option. Microalgae can metabolize hazardous materials into non-toxic substances, which makes it one of the most promising and sustainable alternatives to conventional treatment methods. Microalgal treatments for wastewater are mostly implemented using pond systems or high-rate algal ponds in domestic wastewater in commercialized treatment approaches (Wollmann et al. 2019). These are largely grouped as open systems. A major advantage of algal-mediated wastewater treatment is that it targets emerging contaminants with efficiency with low operating costs. This has increased their appeal for industrial, domestic, and agricultural wastewater treatment.

Treatments applying algal consortia are typically applied in outdoor conditions however, some industrial effluents require monitored conditions for treatment due to extreme parameters such as acidity, temperature, and nutrient loads of raw effluent. These systems are classified as closed systems. In these cases, implementation of algal treatment has been reported at laboratory and pilot scale, with effluent volumes treated ranging from a few liters to just under 1 KL.

In high-rate algal ponds (HRAPs), the system consists of symbiotic algae and bacterial growth, within raceway ponds. The benefit of this system is the ability to recover algal biomass as well as the ability of the system to remove emerging contaminants such as antibiotics. Other contaminants such as hydrocarbons and surfactants have also been efficiently removed in HRAPs (Matamoros et al. 2015). Quite often the use of the recovered biomass is applied in biofuel production or other commercially valuable products, with biomass yields often being a key factor in the viability of this treatment (Sutherland et al. 2020).

A comparison of differently sized HRAPs found that although nutrient removal occurred at large, pilot and mesocosm size, optimal conditions, and yield were observed at smaller scales. In a similar study, the modification of the retention times of full-scale algal treatments led to an improvement in the final effluent quality as well as the overall efficiency of the HRAP performance (Sutherland et al. 2020).

Among the open systems, stabilization ponds are also a common solution, driven by similar factors; the response to emerging contaminants and a need for feasible treatment solutions. Waste stabilization ponds are non-aerated/mixed systems, unlike HRAPs. The system depends on sunlight

Table 1 Studies on industrial wastewater treatment efficiencies of various microalgal species

Algal species	Industry type	Removal efficiencies	Type of WW treatment	Reference(s)
Scenedesmus sp.	Fertilizer wastewater plant effluent	COD–93%; BOD–84%; NH_4–93%; NO_3–84%, PO_4^{3}–97%	Flask Bioreactors, under laboratory conditions	Pham et al. (2020)
Scenedesmus sp.	Pulp and paper mill effluent	COD–75%; BOD–82%; NO3N–65%; PO4–P–71.29%	Outdoor open ponds	Usha et al. (2016)
Planktochlorella Nurekis	Pulp and paper mill effluent	Cr–100%; Co–97%; Ni—71%; Zn–74%; As–98%; N–95.6%; P–100%; S–80%; COD–92.8%	Flask Bioreactors, under laboratory conditions	Sasi et al. (2020)
Chlamydomonas reinhardtii	Pulp and paper mill effluent	Cr–100%; Co–47%; Ni–49%; Zn–68%; As–57%; N–85.6%; P–87.5%; S–60%; COD–91.9%	Flask Bioreactors, under laboratory conditions	Sasi et al. (2020)
Oocystis sp.	Fish processing wastewater	COD- 71.1%; P-70%	Flask Bioreactors, under laboratory conditions	Riano et al. (2011)
Chlorella zofingiensis	Piggery wastewater collected from the private farm	TN–82.70%; COD–68.96%	Flask Bioreactors, under laboratory conditions	Zhu et al. (2013)
Pithopora sp.	Thermal wastewater	COD–87.23%; BOD–87.75%	Flask Bioreactors, under laboratory conditions	Murugesan and Dhamotharan (2009)
Botryococcus sp	Laundry effluent	COD–70.68%; BOD–61.11%; TOC–76.66%; TN–72.49%; P–78.23%; N–86.62%	Flask Bioreactors, under laboratory conditions	Gani et al. (2015)
Chlorella pyrenoidosa	Textile effluent	Cr–80%; Cu–85%; Pb—80%; Cd–91%	Flask Bioreactors, under laboratory conditions	Soeprobowati and Hariyati (2017)
Chlorella sp. and *Scenedesmus* sp.	Textile effluent	TDS–89.1%; BOD–91.5%; COD–91.9%	Flask Bioreactors, under laboratory conditions	Aragaw and Asmare (2018)
Scenedesmus sp.	Tannery effluent	Cr–57%; Cu–79%; Pb—48%; Zn–65%	Flask Bioreactors, under laboratory conditions	Ajayan et al. (2015)
Scenedesmus sp.	Tannery effluent	N–90%;.1 P–99.85; % S–92.68%; BOD–88%	Flask Bioreactors, under laboratory conditions	Ballen-Segura et al. (2016)
Oscillatoria sp. and *Westiellopsis* sp.	Dye effluent	Colour removal–75%; COD–95%; Cl–50%; Mg- 90%	Flask Bioreactors, under laboratory conditions	Vijayakumar (2005)
Chlorella conglomerate	Soft drink industrial effluent	BOD–77.0%; COD–77.7%; Mg–66.7%; P–50%	Outdoor open ponds	Sivasubramanian et al. (2012)
Chlorococcum humicola	Soft drink industrial effluent	BOD–86.1%; COD–85.9%; Mg–62%; P–50%	Outdoor open ponds	Sivasubramanian et al. (2012)
Chlorella vulgaris	Brewery effluent	BOD–91.43%; COD–83.11%; TN–83.74%; TP–54.69%	Flask Bioreactors, under laboratory conditions	Choi et al. (2016)
Scenedesmus obliqus	Brewery effluent	COD–57.5%; TN–20.8%	Flask Bioreactors, under laboratory conditions	Mata et al. (2012)
Chlorococcum humicola	Oil drilling industrial effluent	BOD–96.17%; COD–52.19%; Cr–92.57%; Cu–88.17%; NO_3–78.04%	Flask Bioreactors, under laboratory conditions	Sivasubramanian and Muthukumaran (2012)

and microalgae-driven nutrient removal. These systems can be decentralized and are often applied as secondary or tertiary water treatment. The low operating costs (e.g., no need for electricity as these are systems are gravity-fed) of such systems have led to their suitability in low-income or developing countries, especially in tropical and subtropical regions (Kaloudas et al. 2021). Challenges in biomass recovery, hydraulic retention times, temperature, sunlight, as well as contamination (e.g., protozoa) are however factors that affect the optimal functioning of this open system (Arora et al. 2021; Mahapatra et al. 2022).

Closed systems comprise examples of photobioreactors, where biomass recovery, volumes, and effluent quality can be closely monitored and optimized. The usage of these systems is beneficial where effluent is industrial or contains high nutrient loads. Floating bioreactors or immobilized algae, either through alginate beads or biofilms, are examples of smaller-scale treatments where algal biomass can be recovered more easily. A few of these technologies have been commercialized globally, such as the revolving algal biofilm for example, as well as a suspended photobioreactor that treats up to 50 000 gallons of wastewater per day (Wollmann et al. 2019). The operational and maintenance costs however, of these closed systems are substantially more, and although improved, the challenge in enhancing the recovery of biomass due to size and the usage of flocculation and/or other immobilizing techniques remains immanent.

According to Amin et al. (2022), the main objective of wastewater treatment is to reduce nutrient levels and loads to concentrations that are acceptable to the regulating bodies with respect to the final effluent discharged. To achieve this, the application of co-culture methods has also proven effective in the successful treatment of industrial effluent (Qi et al. 2018; Perera et al. 2022). This involves the co-culturing of algal isolates with fungal or bacterial isolates for enhanced treatment.

The natural processes associated with microalgae-driven treatment are advantageous from an environmental, potential cost, and infrastructure perspective, as well as a robust response to emerging contaminants. Moreover, the ability to decentralize treatments and modify retention times provides a responsive, efficient solution that services the specific needs of a community or area. However, these benefits are realized when applied on a larger scale open system, as the costs linked to closed, smaller scale treatment on harsh effluent may be at a higher operating cost. In addition, the impacts of climate, temperature, and the need to optimize biomass recovery due to cell size are some of the continued challenges, especially in coupling this with any by-product generation from algae.

Algae-assisted industrial wastewater treatment

The industrial sector is an important consumer of freshwater resources and a significant contributor to waste. In South Africa, industry is one of the largest consumers of water for development (DWS 2017), and globally consumes 22% of water (UN Water 2018). Similarly, the sector represents one of the largest contributors to wastewater generation (van der Merwe et al. 2009; Cloete et al. 2010), with an estimated 11.5 million tons of brine per year. Nationally, water consumption and effluent production volumes are highest in the petroleum and paper and pulp industries (Cloete et al. 2010). Treated wastewater from various industry types has different properties, such as colour, pH, TDS, TSS, BOD, COD, total solids (TS), electric conductivity (EC), and heavy metals which are often above the permissible limits.

The composition of industry wastewater is highly diverse and generally includes pesticides, dioxins, heavy metals, poly-aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), phenolic compounds, petrochemicals and microorganisms (Kanu and Achi 2011). These contaminants overall have negative effects on human life and aquatic life. Phosphate nutrients in wastewater are used in algae for the synthesis of nucleic acids, phospholipids, and phosphate esters (Benitez-Nelson 2000). Like phosphorous, nitrogen-based contaminants in wastewater are assimilated for algal growth and development (Kumar et al. 2013; Singh et al. 2021).

The bioremediation of the most common industrial effluent using algae is discussed in the sections below.

Effluents from the paper and pulp industry

The pulp and paper industry generates significant amounts of waste from its various processes (Patel et al. 2021; Esmaeeli et al. 2023). According to Chaudhry and Paliwal (2018), besides lignin and naturally occurring polymers, the xenobiotic compounds generated by the industry include chlorinated lignin, chlorinated phenol, chlorinated resin acid, dioxins, chlorophenols, phenols, adsorbable organic halogens (AOX), and extractable organic acids, halogens, and metal ions. Several algal species have been reported for their ability to remove contaminants from the wastewater of paper industries. For example, paper and pulp effluent was treated using *Planktochlorella nurekis* and *Chlamydomonas reinhardtii*, and the results reported a nitrate reduction (96% and 86%), phosphate (100% and 88%), COD (92% and 93%) and heavy metals (100% Cr, 97% Co, 77% Ni, 71% Cu, 72%

Zn and 88% Cd). Sasi et al. (2020) reported similar results for the same algal species. Another study reported on the benefits of mixed algal strains of *Chlorella*, *Chlorococcum*, *Chlamydomonas*, *Pandorina*, and *Eudorina*, in removing 75% COD, 84% colour, and 80% AOX (Tarlan et al. 2002).

Effluents from the petrochemical industry

Effluent from the petrochemical industry contains an array of contaminants including organic solvents, phenolic compounds, aniline, nitrobenzene, and sulfides (Tian et al. 2020; Cechinel et al. 2016). Microalgae have been reported to be promising for the treatment of wastewater from the petrochemical industry (Madadi et al. 2016; Madadi et al. 2021). Specifically, the algae strain *Chlorella vulgaris* was found to be the most effective for the removal of hydrocarbon with 98% efficiency (Al-Hussieny 2020).

Phycoremediation has also been reported to be a promising technique for the tertiary treatment of phenol-polluted petrochemical effluents through the degradation process (El-Gendy and Nassan 2021). Eukaryotic microalgae were reported to degrade phenol to less toxic β-ketoadipate (Das et al. 2015), while *Ochromonas Danica* was reported to degrade phenol to cis-2-hydroxypenta-2.4-dienoate (Semple and Cain 1996).

A combination of bacteria and algae has been reported to be effective in the treatment of phenol-polluted wastewater (Nassar and El-Gendy 2021). Bacteria provide algae with carbon dioxide needed for photosynthesis while algae provide the bacteria with oxygen for their growth (Liang et al. 2013). Light was reported to be essential for the biodegradation of high concentrations of phenol in algae and bacteria combinations. A combination of the algal strain *Chlorella sp* with bacteria resulted in a complete removal of 1200 mg/L of phenol (Nassar and El-Gendy 2021). A recent study by Madadi et al. (2021) reported promising results for lipid production at the same time as treating petrochemical wastewater using *Chlorella vulgaris*.

Effluents from acid mine drainage

The high acidic effluent from acid mine drainage (AMD) can be harmful to wastewater treatment plants and the ecosystem. Acidic effluent contains high levels of heavy metals, and hence, there is a need for an economically and eco-friendly method for removing heavy metals in the effluent. Algae can absorb or bond with metals based on the heavy metal biosorption properties, a process that results in a higher pH that eliminates metals from wastewater. At high pH, heavy metals are not soluble in water (Monteiro et al. 2012). Algal strains including *Spirulina, Chlorella, Anabaena,* and *Oscillatoria* have been reported for the effective treatment of AMD wastewater (Shinde et al. 2018). A recent laboratory-scale study by Santos et al. (2020) reported the use of *Scenedesmus sp* for successful treatment and removal of metals from coal mining AMD, while also producing algal biomass.

Effluents from the pharmaceutical industry

Pharmaceuticals and personal care products are of emerging concern due to their substantial usage and persistent nature. The growth of the pharmaceutical industry poses a threat to wastewater treatment processes as many wastewater treatment plants are not fully equipped to remove all pharmaceutical contaminants in wastewater (Goswami et al. 2022). Wastes generated by the pharmaceutical industry are as diverse as their processes and operations, however generally contain antibiotics, antiepileptics, psychiatric drugs, anti-inflammatories, diuretics, analgesics, and β blockers (Mustafa et al. 2021). Biosorption, bioaccumulation, and biodegradation have been reported as the main processes to remove pharmaceutical contaminants in wastewater (Gentili and Fick 2017; Gojkovic et al. 2019; Sun et al. 2023). Microalgal remediation of the effluents from the industry has been reported. For example, Gentili and Fick (2017) reported 70% N and 89% P removal by *C. sorokiniana*, whereas Escapa et al. (2015) reported only 67.8% N and 55.6% P removal by *Dictyosphaerium*. Similarly, Prathiba et al. (2020) reported high removal efficiencies in reducing BOD, COD, TSS, and TDS by *Chlorella* and *Scenedesmus sp.*

Effluents from the food and beverage industry

The food and beverage industry is generally a large consumer of water and a large producer of wastewater effluent with high levels of nutrients and organic compounds; and hence has high levels of COD, volatile acid, total nitrogen, total phosphorous, and heavy metals. Several food processing companies are unable to meet the regulations imposed by municipalities for the disposal of effluent to wastewater treatment plants. Furthermore, the current methods used to reduce the level of contaminants in effluent from the industry are often costly, and hence, there is a need for less expensive wastewater purification methods. Microalgae-based methods of wastewater treatment from the food and beverage industry have been reported. Daneshvar (2019) observed 76.7% organic carbon, 92% total N, and 100% P removal by *S.*

quadricauda from dairy wastewater. Song (2020) reported 90% ammonia, 76% total nitrogen, 95% total phosphate, and 74% chemical oxygen demand removal by *Scenedesmus sp.* from brewery waste. Mawi et al. (2020) reported nitrate removal of up to 58.8% and ammonia removal of 72.5% from wastewater from a shrimp industry by using *Gracilaria edulis* and *G. changii* in a biofilter. The microalgae *Scenedesmus dimorphus* was able to remove more than 99% of both N and P from brewery wastewater within one week (Lutzu et al. 2016).

Future prospects of phycoremediation

The future prospects of algae treatment and the need for improvements in phycoremediation to allow for scalability and sustainable wastewater treatment for industry are summarised in Fig. 5. As technology continues to advance, there is increasing potential for the development of more efficient and cost-effective algae cultivation and wastewater treatment systems. These advancements encompass improvements in photobioreactors, cultivation techniques, and genetic engineering of algae strains to bolster their pollutant removal capabilities (Razzak et al. 2023). Industries are exploring the integration of algal bioremediation into their sustainability initiatives, cultivating algae either on-site or nearby to treat wastewater before release. This strategic approach minimizes the environmental footprint and reduces expenses associated with regulatory compliance (Sousa et al. 2022; Razzak et al. 2023).

Research efforts are anticipated to concentrate on identifying and engineering novel algal strains with enhanced pollutant removal capabilities. This may involve selecting strains that thrive in specific industrial effluents or utilizing genetic modification to optimize nutrient uptake and pollutant degradation (Abdelfattah et al. 2022; Hassanien et al. 2023). Furthermore, scaling up algal bioremediation systems to meet the demands of large industrial facilities is a key focus. This could entail the development of modular systems that can be easily expanded or replicated to accommodate varying wastewater volumes and pollutant loads (Goh et al. 2023).

Algae-based wastewater treatment also offers integration with circular economy concepts, where treated wastewater and algal biomass can be reused or repurposed within industrial processes. For instance, algal biomass can be converted into biofuels, biofertilizers, or high-value products, generating additional revenue streams and reducing waste (Zabochnicka et al. 2022). Collaboration among research institutions, industries, government agencies, and environmental organizations is essential for driving innovation and knowledge sharing in the field of algal bioremediation (Mellor et al. 2022).

Moreover, regulatory support and incentives play a crucial role in driving the implementation of sustainable wastewater treatment practices, including algal bioremediation, in industries (Abdel-Raouf et al. 2012). Increasing public awareness of the benefits of algal bioremediation can lead to greater acceptance and demand for these solutions. Education campaigns and outreach efforts can help foster support for algae-based wastewater treatment initiatives (Mellor et al. 2022).

While phycoremediation presents promising technology for industrial wastewater treatment, further research is necessary to identify suitable algae for maximum pollutant removal while maximizing biomass production (Ahmad et al. 2022). Optimizing growth conditions for microalgae on a large scale is imperative for successful industrial wastewater treatment. Additionally, advancements in microalgal engineering and genetic modification hold promise for enhancing bioremediation efficiencies and increasing the utility of phycoremediation technology (Cabanelas et al. 2016; Fajardo et al. 2020; Kumar et al., 2020). By capitalizing on these advancements and promoting collaborative efforts, phycoremediation can emerge as a vital tool for achieving environmental sustainability in wastewater treatment practices.

Challenges involved in phycoremediation

Phycoremediation is undoubtedly a beneficial strategy for remediating the environment and improving the quality of industrial wastewater. It has been proven to be an eco-friendly and sustainable bioremediation solution. However, like any innovation, this technology has some challenges that may hinder its optimal operation and efficiency.

Since phycoremediation uses microalgae to remove pollutants from industrial wastewater, the selection of microalgae is therefore important to ensure maximum efficiency. As mentioned in the previous sections, species such as *Scenedesmus sp.*, *Chlorella vulgaris*, and *Oscillatoria limos*, have been used successfully to remediate industrial wastewater effluent. However, the data also shows that the efficiency of microalgae in phycoremediation may be species-specific as well as industry wastewater-specific. For instance, the use of *Scenedesmus sp.* was effective for nutrient removal in tannery wastewater (Ajayan et al.

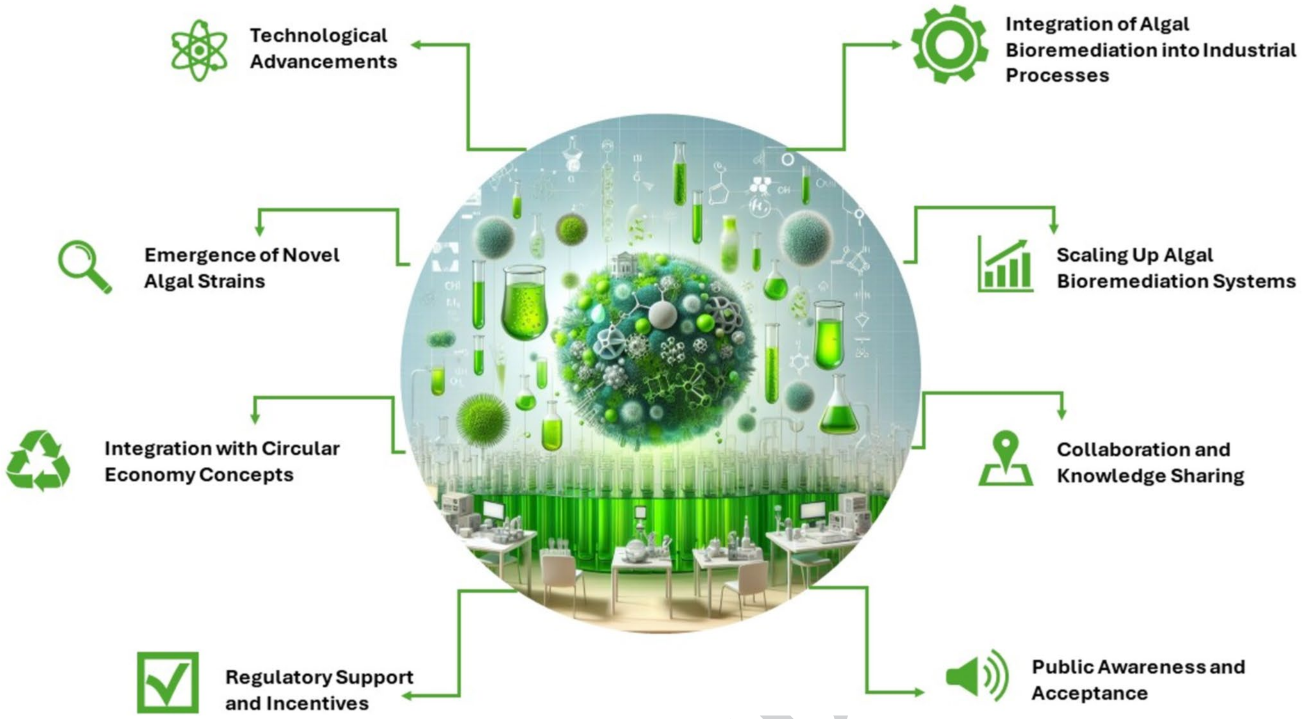

Fig. 5 Key aspects impacting algae-based wastewater treatment in future

2015), but not as efficient for pulp and paper mill industrial wastewater (Amit and Ghosh 2018). However, species such as *Chlorella sp.* are generalists; their efficiency was reported to be high in textile wastewater (*Chlorella pyrenoidosa*), rolling mill wastewater, and tannery wastewater (*Chlorella vulgaris*) (Atoku et al. 2021; Nagabalaji et al. 2019; Pathak et al. 2014), with the efficiency dependent of target pollutants. Therefore, microalgal culturing should be undertaken in different wastewater types to determine the most efficient species to utilize. To this end, the use of consortia has been recommended to ensure phycoremediation efficiency. This is due to multiple species complementing each other's metabolic processes thus leading to successful bioremediation (Rambabu et al. 2023). Moreover, the inefficiencies of one species due to effluent type are supplemented by the species active in that particular media. The microalgae consortia can be further supplemented by incorporating specific species of bacteria. Algae-bacteria consortia have been shown to increase the growth rate of microalgae and improve their efficiency in pollutant removal (Mujtaba et al. 2016). For the success of this consortia, adequate concentrations of CO_2, light intensity, and nutrients need to be optimized to ensure the successful growth of both the microalgae and bacteria (Chia et al. 2021).

In addition to species selection, microalgal cultures must be successfully reared. Climatic conditions have been reported to affect algal growth and efficiency. For instance, low temperatures have been shown to prohibit biological processes and reduce the removal of contaminants (Kumar et al. 2021). As a result, there is little evidence of successful phycoremediation in colder climates. Algae rearing presents additional challenges in addition to climatic conditions. For example, algae reared in open systems has been reported to be vulnerable to contamination (Hejna et al. 2022; Kumar et al. 2021). This leads to negative effects on the successful cultivation of microalgae. In closed systems such as bioreactors, microalgal biofilms form on the inner walls of photobioreactors limiting light penetration and reducing the supply of CO_2 to the culture medium and the build-up of O_2 generated during photosynthesis (Rambabu et al. 2023).

Another major constraint is that some pollutants have been reported to inhibit the growth of microalgae. For instance, Atoku et al. (2021) utilized *Nostoc commune*, *Oscillatoria limos,* and *Chlorella vulgaris* to remove heavy metals (Cu, Fe, Ni, Pb, Cd, Zn) from raw wastewater from the rolling mill industry. The phycoremediation process was able to address the physiochemical parameters such as pH, DO, and BOD. Chloride, nitrates, and sulphates were reduced by 59–63%, 93–99%, and 60–70%, respectively (Atoku et al. 2021). Although there was a significant removal of Pb (71–90%), Cd (49–54%), Cu (9–10%), Fe (27–30%), Ni (31–38%), and Zn (24–27%), the average concentrations of heavy metals in the final effluent did not meet the required local standard for the final effluent (Atoku et al. 2021). The removal efficiency of heavy metals from raw wet market wastewater produced similar results. The use of *Scedenemus spp*. had low removal of Cd (47.2%), Zn (51.75%), and Fe (62.57%) (Apandi et al. 2018). Only Cr had a significant removal of 89.2% (Apandi et al. 2018). In contrast, there was a higher removal efficiency of heavy metals in the diluted (50%) wet market wastewater (Apandi et al. 2018). This is due to the toxic nature of the industrial wastewater to microalgae resulting from high pollutant load (Saranya and Shanthakumar 2019). The authors reported that textile wastewater- inhibited the growth of microalgae biomass to below control levels. Thus, pollutants' toxicity affects the optimal growth of the algae and their efficiency. To this end, phycoremediation can only be used as a supplementary tertiary treatment, and pre-treatment of the wastewater is required to ensure maximum efficiency.

The scale-up challenge has also been reported. Phycoremediation on a smaller scale (laboratory setting and small domestic ponds) has been piloted successfully (Angelaalincy et al. 2023; Cavieres et al. 2021; Sivasubramanian et al. 2009; Oberholster et al., 2019). However, the scale-up has been shown to reduce the efficiency of the process of pollutant removal (Kumar et al. 2021).

Perhaps the biggest challenge in the use of phycoremediation at a large scale is the harvesting of algae biomass (Hejna et al. 2022). Microalgae cells are small and have a density close to that of water (1.08–1.13 g/cm^3), have a strong surface charge, and are highly mobile (Leong et al. 2021). The harvesting process is costly; 30% of total production expenses are incurred for harvesting algae biomass (Kumar et al. 2021; Pacheco et al. 2015). To this end, several methods have been investigated in an attempt to recover the microalgae biomass. Such methods include centrifugation, flocculation, filtration, flotation, sedimentation, and electrocoagulation (Grima et al. 2003; Morais Junior et al. 2020). Centrifugation is effective, especially for the recovery of high-nutrient biomass useful in resource recovery (Najjar & Abu-Shamleh 2020). However, centrifugal harvesting only works well for cells with high settleability (e.g. *Scenedesmus spp.*) and with a high rotation rate of the centrifuge (a low rate has been reported to reduce harvest efficiency by up to 55% (Dassey and Theegala 2013)). Furthermore, centrifugation is economically unviable since the process is energy-intensive and the financial cost is too high (Vandamme et al. 2013). On the other hand, while the sedimentation process is efficient, the recovered biomass is generally too dilute and compromises resource recovery (Mathimani & Mallick 2018). Due to the use of membrane technology in the filtration process, this recovery method is only viable on a small scale (Salim et al. 2011; Zhu et al. 2018). In the flocculation process, large concentrations of inorganic flocculants are required which leads to high production of sludge, is only effective for some algal species, and the final product is highly contaminated due to the addition of inorganic salts (Chen et al. 2011; Christenson & Sims 2011; Singh & Patidar 2018). Overall, the harvesting method used must be able to process large volumes of algal biomass, at a large scale, while keeping the cost at a minimum. Once the harvesting has been optimized, the successful and sustainable recovery of resources (by-products) can be honed.

Conclusion

Phycoremediation presents a viable alternative to conventional wastewater treatment processes. The technology has been primarily recommended due to its resource recovery capabilities and has the potential to produce biodiesel, biogas, and biofertilizer (De Mendonça et al. 2021). At the laboratory scale, the production of biofuel has already been evidenced. However, without successful and optimal biomass harvesting, this remains a challenge. So far, the production of biodiesel and biogas is energy-intensive. **AQ1** This is in addition to challenges related to biomass recovery. Furthermore, the sustainable and economically viable recovery of primary and secondary metabolites needs further research. Moreover, the low biomass yield and complicated contaminants removal (targeting fit-for-purpose utilization) compromise the full circular economy implementation of the phycoremediation process. The benefits of phycoremediation have been highlighted in this review. Phycoremediation presents a green approach for contaminant removal to support environmental protection and a long-term remediation option. As evident, removal efficiencies are not only dependent on the algae use but also on the type of wastewater. However, much more investigation is needed to support the current research. Future research should therefore focus on the selection of effective algal species, cultivation methods, and a combination of other physicochemical variations.

Acknowledgements The authors gratefully acknowledge financial support from the Parliamentary Grant number P1EWG01 which facilitated the conduct of this study.

Declarations

Conflict of 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.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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