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Review

Advancement in algal bioremediation for organic, inorganic, and emerging pollutants

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ABSTRACT

Rapidly changing bioremediation prospects are key drive to develop sustainable options that can offer extra benefits rather than only environmental remediation. Algal remediating is gaining utmost attention due to its mesmerising sustainable features, removing odour and toxicity, co-remediating numerous common and emerging inorganic and organic pollutants from gaseous and aqueous environments, and yielding biomass for a range of valuable products refining. Moreover, it also improves carbon footprint via carbon-capturing offers a better option than any other non-algal process for several high CO_2-emitting industries. Bio-uptake, bioadsorption, photodegradation, and biodegradation are the main mechanisms to remediate a range of common and emerging pollutants by various algae species. Bioadsorption was a dominant remediation mechanism among others implicating surface properties of pollutants and algal cell walls. Photodegradable pollutants were photodegraded by microalgae by adsorbing photons on the surface and intracellularly via stepwise photodissociation and breakdown. Biodegradation involves the transportation of selective pollutants intracellularly, and enzymes help to convert them into simpler non-toxic forms. Robust models are from the green microalgae group and are dominated by Chlorella species. This article compiles the advancements in microalgae-assisted pollutants remediation and value-addition under sustainable biorefinery prospects. Moreover, filling the knowledge gaps, and recommendations for developing an effective platform for emerging pollutants remediation and realization of commercial-scale algal bioremediation.

1. Introduction

Phycoremediation is becoming a key platform in the coming future for restoring the polluted system with added advantages which is a most beneficial platform than any other remediation platform can offer with such sustainable features. Microalgae are eukaryotic, unicellular photosynthetic microorganisms ubiquitously found in marine and freshwater, but their number is not adequate to perform the desired remediation level. Therefore, their adequate inclusion must be regulated with the proper lab-scale investigation to ensure their best remediation performance in polluted environments. Moreover, biomass recovery is an important step to gain added benefits once the treatment is mature enough to extract fuel and nonfuel products depending on the strain potential (Choi et al., 2019; Hong et al., 2019b; Patel et al., 2022d, 2022e). Fuel products can be extracted from biomass cultivated even in extremely polluted environments; however, edible products are not considered safe when derived from a highly polluted environment containing unknown hazardous chemicals and heavy metals (Patel et al., 2020a) but effluent from dairy, biomass processing, food and beverages industries could be safer streams (Hong et al., 2019a; Patel et al., 2020b,

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2022a). This biomass is the bioconversion of organic and inorganic nutrients available in polluted environments as well as CO_2 captured during photosynthesis in the presence of light. This way microalgae are efficient for the co-removal of organic and organic pollutants from wastewater and mitigate CO_2 simultaneously (Patel et al., 2020b). Moreover, microalgae do not discharge metabolic CO_2 like any other non-algal platforms and offer a long list of rewards that may attract industries to improve the carbon footprint of their existing process with an added advantage. Such advantages significantly offset the expenses subject to the installation and operation of the treatment facility (Patel et al., 2020a).

Advancement in microalgae research is remarkably marked during past decades and the major breakthrough was obtained when fast-growing microalgae were discovered with mixotrophic growth potential which could assimilate organic and inorganic fractions simultaneously via employing both pathways of respiration and photosynthesis together to offer increased biomass and product yields (Sim et al., 2019; Patel et al., 2019). Moreover, the selection of naturally occurring potential strains using high throughput technologies and mutation or gene editing approaches for improving their natural abilities were pioneering inventions to raise their efficiencies for treatment and product yields (Sung et al., 2019; Wang et al., 2016; Patel et al., 2022e). To reduce the harvesting cost, novel methods are now being developed using recyclable nanoparticles to bypass energy and cost-intensive processes (Patel et al., 2022h). However, other technologies such as nanobubble, and biochar are well-adopted in wastewater treatment for improving remediation efficiency however for microalgae systems these are emerging (Zhu and Wakisaka, 2019; Katiyar et al., 2022; Patel et al., 2022b, 2022f). Microalgae biomass is extremely useful for a wide range of high-value product refining such as carotenoids, proteins, omega fatty acids, dietary fibres, etc (Patel et al., 2021a, 2022g; 2022i). As whole biomass, it finds applications in functional food, and animal feed sectors, and also the extraction of pharmaceuticals and nutraceuticals (Patel et al., 2021c, 2022a). Besides, the algal remediation of organic and inorganic pollutants (Patel et al., 2022c), microalgae are also emerging for the biodesalination process at the primary stage to bring down the salt concentration low prior to the filtration. It greatly helps to offset the cost of reverse osmosis technology in the second stage to provide cost-effective drinking water from saline water resources (Patel et al., 2021b).

Microalgae growth is limited in a polluted environment hence it is important to acclimatize them adequately prior to exposing them to effective treatment. It is desirable to get adequate biomass before dilution in a polluted environment for effective treatment. The dilution is an important factor in prevailing adequate light deep in the polluted system for obtaining mixotrophic benefits. Microalgae are efficient in removing organic and inorganic pollutants once it reaches desirable growth and it employs several mechanisms for their removal. The most common mechanism is surface adsorption which is a spontaneous, reversible, and passive interaction. It may involve ion exchange and complexation processes with ionic pollutants. Bio-uptake is a slower and energy-dependent process that also employs quick adsorption at the beginning and subsequently leads to bioaccumulation by the algal cell. Once pollutants are taken up intracellularly, it undergoes biodegradation, an enzyme-mediated complex process. Photobiocatalysis is also carried out for certain pollutants intracellularly (Sutherland and Ralph, 2019).

Microalgae involve several mechanisms such as bioadsorption, bio-uptake, photodegradation, and biodegradation to remediate a range of general and emerging pollutants. Depending on the species, and cell wall structures, these mechanisms vary toward achieving bioremediation efficiency. Biodegradation involves the transportation of selective pollutants intracellularly, and enzymes help to convert them into simpler non-toxic forms (Tripathi and Poluri, 2021). Bioadsorption is a passive process and primary interaction which later facilitates the active bio-accumulation process. Photodegradation by microalgae is an indirect process to remove several organic pollutants mainly antibiotics (Wei et al., 2021). Biodegradation could be an extracellular or intracellular process to degrade organic and emerging pollutants into less or non-toxic and stable smaller molecules via microalgal enzymes. The ideal strains for bioremediation are mainly studied from the genus *Chlorella, Microsystis, Chlamydomonas, Isocychrysis* etc.

Biorefinery is the latest trend worldwide to economize any bio-process by coextracting multiple products from one process (Singhania et al., 2021; Singh et al., 2022; Patel et al., 2021e). Bioremediation-supported biomass can be utilized for the extraction of more than one product for extended benefits, however cost-effective and easy extraction process has yet to be developed which can enable us to extract these products sequentially from the same biomass. Further advancement is much needed not only for treatment but also for further product refining from extractable biomass. Microalgae are recognized for inorganic nutrient removal therefore it is popular to adopt them in the tertiary municipal wastewater treatment process after organic treatment in primary and secondary treatment stages. Advancements in algal remediation for organic fraction have been realized much later and the recent focus is more towards emerging pollutants which include complex organic and inorganic pollutants such as siloxane, M-Xenes, pharmaceutical drugs, steroid hormones, etc (Sutherland and Ralph, 2019).

This article compiles the advancements in microalgae-assisted pollutants remediation of organic, inorganic, and emerging pollutants and value-addition under sustainable biorefinery prospects. The hypothesis of the bioremediation application of microalgae for inorganic and organic pollutants are based on adsorption on the surface via abundantly available anionic functional groups and bioaccumulating the selective pollutants via surface transporter intracellularly prior to biodegradation. Novelty aspect of this article is to cover recent advances in emerging organic pollutants under dedicated section and summary as well as analysis of those studies. Moreover, this article also filling the knowledge gaps, and providing recommendations for developing microalgae as a sustainable and effective platform, especially for emerging pollutants remediation and a way forward to the realization of commercial-scale algal bioremediation.

2. Microalgal remediation for a wide range of pollutants

2.1. Inorganic pollutants remediation by microalgae

Commonly, inorganic compounds include heavy metals, gases (CO_2, SO_X, NO_X, CO etc.) minerals (nitrates. nitrites, fluorides) etc. which are discharged from agroindustry, semiconductor, food processing, and chemical and metallurgic industries. Moreover, metals, salts, and minerals are also coming from household, farming, and industrial wastes. Other than above inorganic compounds, radioactive substances are also regarded as significant inorganic pollutants besides to HMs (Priya et al., 2014). Microalgae-based carbon capturing has widely been reported, where CO_2 from industrial flue gas is used along with various industrial and domestic wastewater. Nayak et al. (2018) cultivated microalgae by utilizing flue gas and wastewater as a nutrient source which has significant results in removing >90% COD and CO_2 sequestrations. It also 578.1 ± 23.1 mg L^{-1} biomass yield, it is containing approx. 34.6% of lipid. The CO_2 fixation from the flue gas has been reported up to 85% in an open system, whereas 42% in a closed system (Aslam and Mughal, 2016). Microalgae were also cultured using kitchen wastewater, sewage wastewater, and industrial CO_2. They had total average biomass of 0.6 g L^{-1}, which was further used for biofuel production (Kumar et al., 2019). Apart from treating industrial wastewater and CO_2 directly to microalgae, various mixed approaches have also been studied to meet the treatment goals more effectively, for example, microalgal-bacterial, and microalgal-fungal flocs (Nguyen et al., 2019; Xiong et al., 2019; Leng et al., 2021). Both viable and dried algal biomass exhibited impressive metal-absorbing potential. Importantly the metal-resistant microalgae species were efficient in remediating toxic medical and allied contaminants. Microalgae species such as *Chlamydomonas, Chlorella*, and *Scenedesmus* sp. exhibited the maximum pollutant removal efficiency in medicine-contaminated sites (Kandasamy et al., 2021).

Due to the toxicity of some heavy metal ions for living algal strains, optimization of metal ion concentrations is required for the effective development of algae. Algal cell death will lower metal ions absorption (Zeraatkar et al., 2016). Live photosynthetic microalgae are effective in removing metals from mine wastewater, according to field tests. A 99% of dissolved and particle metals could be eliminated by cyanobacteria in a system of manufactured pools and meanders. According to research, *Coelastrum proboscideum* 100% absorbs lead from a 1.0 ppm solution after 20 h at 23 °C (Gilbert and Ashraf, 2017). It has been documented in many literatures that the microalgae can acquire heavy metal ions. In addition to ion exchange and chemisorption, covalent bonding, and surface precipitation are some of the methods they employ. It has been reported that from synthetic wastewater, *Sinus incrassatulus* eliminates 52.7, 31.7, and 24.1% of Cr, Cu, and Cd (Jais et al., 2016). In removal of heavy metal process, microalgae are used for the uptake of HMs and is the main mechanism for sequestration of HMs reported that *Scenedesmus* sp. under controlled condition has immense potential to remove Hg (II) up to 64% in 20 days (Singh et al., 2021). *Spirulina platensis* is effectively removing Copper and iron 79.2% and 100% respectively from Tannery effluent. And there are many microalgae that effectively help in the removal of heavy metals as shown in Table 1.

2.2. Organic pollutants remediation by microalgae

Microalgae are elegant in bioremediating wastewater that is generated from domestic and industrial processes. Wastewater is generally classified into municipal, industrial, and agricultural wastewater (Goswami et al., 2020b). The main objective of using wastewater is to reduce water and nutrient cost. It has been estimated the consumption of nutrients to produce 1 kg of dry microalgae biomass is approx. 7–23 and 10–150 g phosphate, and nitrogen sources respectively along with a massive amount of freshwater are required (Mayers et al., 2016). Industrial, municipal, and agricultural effluents are introduced as organic pollutants that contains mainly pesticides, petroleum hydrocarbons, and tributyltin (TBT) into aquatic ecosystems.

The use of algae to remove, decompose, or reduce other common harmful organic contaminants in aquatic systems has recently become more and more popular. The breakdown of organic contaminants has been accomplished by a variety of algae species in recent studies such as *Chlorella, Scenedesmus, Phormidium, Botryococcus, Chlamydomonas, Arthrospira, Spirulina, Oscillatoria, Desmodesmus, Nodularia, Cyanothece,* etc. are some of the microalgal species used in bioremediation (Baghour, 2019a,b; Bayazit et al., 2019; Patel et al., 2020a, 2022c). There are two main processes, (i) metabolism-dependent process (enzyme-mediated degradation) and (ii) physiochemical interaction, such as absorption and electrostatic contact, which are involved in dye degradation by microalgae (Singh et al., 2022). Degradation of dye is relatively less challenging for microalgae. Rhodamine B was removed by *Celastrella* sp. to an amount of 80% (Baldev et al., 2013). The best Remazol Black B (RBB) removal conditions for dried microalgal biosorbent (4 g L^{-1}) were at initial RBB conc. 93.16 mg L^{-1} at 45 °C, for 24 days. The RBB removal efficiency reported by this study from dried *P. animale* was 99.66% which looks absurd considering 24 days to reach equilibrium by dried microalgal biomass (Bayazit et al., 2019). The *Chlorella pyrenoidosa* has been cultivated using secondary effluent of domestic wastewater, and the biomass obtained was 1.71 ± 0.04 g L^{-1} and obtained biomass has >20% lipids (Dahmani et al., 2016). Based on wastewater types, and degree of pollution, various microalgae models have yielded different results in terms of treatment efficiency, pollution reduction, biomass, and products. *Chlorella vulgaris* was cultured using the dairy wastewater effluent with dry biomass of 1.2 g L^{-1} containing 77.35% of unsaturated fatty acids and 22.65% of saturated fatty acids Choi (2016). Similarly, dairy wastewater was used to cultivate *Tetraselmis suecica* and *Scenedesmus quadricauda*, that produced 470–560 mg L^{-1} biomass, however, *Chlorella protothecoides* yielded 4.54 and 1.8 g L^{-1} of biomass and total lipid respectively (Daneshvar et al., 2018; Patel et al., 2020b). *Chlorella protothecoides* were very efficient in removing >99% organic and 91–100% inorganic fractions from pretreated dairy wastewater. On Culturing the *Chlamydomonas* sp. In swine wastewater, it has been

Table 1
Removal of heavy metals and minerals from various industrial wastewater by microalgae.

Microalgae	Pollutants	Efficiency (%)	Initial conc. mg L^{-1}	Time (h)	Source of wastewater	References
Wild-type C. reinhardtii	Cd (II)	90.2	1	6	–	Piña-Olavide et al. (2020)
Ascophyllum nodosum	Ni (II)	43.3	50	2	–	Romera et al. (2007)
Spirulina platensis	Cu	79.2	–	–	Tannery effluent	Subashchandrabose et al. (2011a)
Ascophyllum nodosum	Fe	100	50			
	Zn (II)	42				Romera et al. (2007)
Chlorella vulgaris, Phormidium teneu	Co(II)	94	50			Abdel-Raouf et al. (2022)
S. incrassatulus	Cr	52.7	–	–	Artificial wastewater	Jais et al. (2016)
	Cu	31.7				
	Cd	24.1				
Chlorella sp.	Cu	69.9	56.8	245	Oil polluted wastewater	Camacho et al., 2019
Scenedesmus obliquus	Ni	62	30	48		
	Zn	90	20			
Chlorella vulgaris (free)	Cr (III)	61.7	20	–	Synthetic water & tannery wastewater	Ardila et al. (2017)
	Cr (VI)					
Scenedesmus sp.	P	100		168	Palm oil mill effluent	Srinuanpan et al. (2019)
Aphanothess sp	Pb (II)	93	18.6	30[a]	–	Keryanti and Mulyono, (2021)
Scenedesmus sp.	Hg (II)	64	0.007	480	Gold mine wastewater	Vela-García et al. (2019)
Chlorella pyrenoidosa	Cr, Cu, Pb & Cd	>80	–	–	Tannery wastewater	Saavedra et al., 2018
Chlorella sp. MOW 12	Pb	93	60	192	Municipal wastewater	Oyebamiji et al. (2021)
Cladophora hutchinsiae	Se (IV)	74.9	–	1	–	
Scenedesmus quadricauda.	N	100		288	Dairy wastewater	Daneshvar et al. (2019)
Ascophyllum nodosum	Cd (II)	87.7[b]	50	2		Romera et al. (2007)
Scenedesmus quadricauda.	S	100	–	288	Dairy wastewater	Daneshvar et al. (2019)
Coelastrum proboscideum	Pb	100	1.0	20	Artificial pools	Gilbert & Ashraf, (2017)
Ulothrix cylindricum	As (III)	67.2	10	1	–	Tian et al., 2019

Note: [a]min; [b]mg g^{-1}.

observed that it helps to reduce 81% COD, 96% TN, and approx. 100% TP (Qu et al., 2020). Likewise, with non-suspended system and cell absorption mechanism, microalgae were able to remove COD (91.6%), TN (78.2%), TP (87.5%) NH_4 (93.21%), and NO_3^- (81.7%) from the wastewater (Zhuang et al., 2020). Microalgae have also been reported to remove heavy metals from industrial wastewater via bioabsorption. *C. colonies* showed higher removal efficiency of different heavy metals such as cadmium (97.05%), chromium (97.8%), iron (98.6%), cobalt (95.15%), and arsenic (96.5%) Jaafari and Yaghmaeian, (2019).

2.3. Microalgal remediation of emerging pollutants or contaminants (Eps or ECs)

Nowadays, one of the global environmental problems greatly attracts attention is raised emerging pollutants (EPs) concentration in wastewater. Emerging contaminants are primarily organic chemicals found in aquatic systems major sources of EC are pharmaceuticals, personal care products, pesticides, and flame retardants. Microalgae have demonstrated the potential for detoxifying organic and inorganic pollutants from wastewater. Three major pathways include bioabsorption, bio uptake, and biodegradation by which microalgae can be bioremediated ECs (Sutherland and Ralph, 2019). They are mainly originating from municipal and pharmaceutical plants and are basically discovered in landfills and effluent commonly home products, cosmetics, medications, PCPs, nanomaterials, and perfluorinated chemicals are a few examples. Because of its high polarity, the bioaccumulation, and biodegradation resistance are greatly enhanced. As a result, they have antibacterial effectiveness against a variety of microbes (viruses, bacteria, and fungi). The most common ECs are endocrine disrupting substances (EDS), gasoline additives, perfluorinated substances (PFCs), surfactants, by-products of disinfection, cyanobacterial and algae toxins, brominated, organometallic, plasticizers, and nanoparticles are a few examples. Currently, roughly 10,000 tons of pharmaceutical and personal care items are consumed annually worldwide. Some of the unfavorable characteristics of ECs that substantially jeopardize aquatic resources and human health are high polarity, bioaccumulation, and persistence to biodegradation. Numerous steroid drugs and chemicals that act as endocrine disruptors can cause the feminization and disruption of fish reproductive (Maryjoseph and Ketheesan, 2020).

Most of the organic wastes produced by chemical industries and fertilizer wastes are persistent hazardous compounds known as persistent organic pollutants (POPs), while household wastes such as kitchen or domestic wastes, and garden wastes are biodegradable. POPs are the pollutants of global concern as their persistence is prolonged in the environment due to low biodegradability and complex structure. Major ECs are primarily covering several POPs or micropollutants (MPs) which are overlapping terms. They are often bioaccumulated in the ecosystem and elicit significant negative effects on environment and human health. POPs are mainly consisting of pesticides, pharmaceuticals, steroids hormones, polyaromatic hydrocarbons (PAHs), personal care products (PCPs), endocrine disrupting compounds (EDCs), and polychlorinated biphenyls (PCBs) are examples of persistent compounds or pollutants (Gupta and Pandey, 2019; Nguyen et al., 2021). The above POPs are significantly removed from various microalgae with different treatment condition and efficiencies. During biodegradation, microalgae have a complex enzyme system that allows them to oxidize, hydrogenate, demethylate and cleave POPs (Ding et al., 2017). The maximum removal efficiency of 91% by *Nostoc muscorum* was achieved in 24 days against malathion contaminant (up to 20 ppm), however >20 ppm conc, was challenging for microalgal growth (Ibrahim et al., 2014). Some of these POPs removal by microalgae is summarized in Table 2 with their and involved removal mechanisms.

Emerging research is now focused on utilizing microalgae to bioremediate emerging organic pollutants mainly from pharma or medical compounds that are well summarized in Table 3. With the recent research advances in this direction, it can be shown that *Chlorella, Chlamydomonas, Chlamydomonas reinhardtii, Haematococcus pluvialis, Picocystis* sp., *Scenedesmus Sp*. among other model strains are the most commonly reported and in-depth examined for the removal of ECs (Maryjoseph and Ketheesan, 2020). Strain of *Chlorella* sp. L38 shows good results in removing the Sulfadimethoxine up to 88% and the concentration initially used was 0.5 mg L^{-1} (Li et al., 2022). Where the 7-amino cephalosporin acid was completely (100%) removed by microalgal strain *Chlamydomonas* sp., *Chlorella* sp., *Mychonastes* sp by the process of Photodegradation and bioadsorption (Gojkovic et al., 2019). Likewise, Bioadsorption as the main pathways by *Chlorella sorokiniana, Chlorella vulgaris, Chlorella saccharophila* and *Coelastrella* sp. were used to remove the bupropion by the algal system in a batch process (Gojkovic et al., 2019). There are different pharmaceutical effluents comprising paracetamol, diclofenac, ibuprofen, and other drugs that are efficiently removed by various microalgae with a remarkable removal efficiency shown in Table 3.

3. Mechanisms involved in pollutant remediation by microalgae

Algal cells are largely composed of polysaccharides, lipids, and natural proteins that are responsible for binding hazardous chemicals, in addition to polymeric cell components such proteins and exopolysaccharides that include uronic groups (hydroxylic, sulfonate, thiol, imidazole, amino, carboxylic, phosphate and others (Manikandan et al., 2022). Microalgae are possessing several functional groups on its cell surface and act as active binding sites for heavy metal contaminants to help in their removal and sewage treatment. This binding results in flocculation; hence, the total dissolved solids (TDS) material is

Table 2
Bioremediation of important organic pollutants from wastewaters by microalgae.

Microalgae	Pollutants	**Removal efficiency**	Initial conc. mg L^{-1}	**Time (h)**	Mechanism	References
Nostoc muscorum	Malathion	75%	20	24	Biodegradation	Ibrahim et al. (2014)
Coelastrella sp.	Rhodamine B	80%	100	120		Baldev et al. (2013)
Nannochloropsis oculata	Acenaphthylene	95%	–	336	Bioaccumulation	Marques et al. (2021)
Rhodomonas baltica	Fluoranthene	56%	–	216	Bioaccumulate	Arias et al. (2017)
Spirulina platensis	Acid black 210	98.55%	125	1	Adsorption	Al Hamadi et al. (2017)
S. quadricuda	Malathion	90%	100	480	Biodegradation	Ibrahim et al. (2014)
Selenastrum capricornutum	Benzo[a]pyrene	99%	–	15	Biodegradation	García de Llasera et al. (2016)
C. vulgaris	Congo red	81%	–	96	Biosorption and Biodegradation	Hernández-Zamora et al. (2015)
Desmodesmus sp.	Bisphenol A	78%	50	–	Biodegradation	Wang et al. (2017)
Cymbella sp. Scenedesmus quadricauda	Naproxen	100%	100	24	Biodegradation	Ding et al. (2017)
Selenastrum capricornutum Anabaena catenula	Salicylate	100%	500		Biodegradation	Subashchandrabose et al., 2011a
Phormidium animale	Remazol black B	99.66	93.16	576	Bioadsorption	Bayazit et al. (2019)

Table 3
Bioremediation of some emergent organic pollutants by microalgae in recent studies.

Microalgae	Pollutants	Efficiency (%)	Initial conc. (mg L^{-1})	Mechanism	Operation	References
Chlorella sp. L38	Sulfadimethoxine	88	0.5	Biodegradation	Batch culture	Li et al. (2022)
Chlamydomonas sp. Mychonastes sp	7-amino cephalosporanie acid	100 100	–	Photodegradation and bioadsorption	Batch culture	Gojkovic et al., 2019
H. pluvialis,	Sulfamerazine, sulfamethoxazole sulfamonomethoxine	84 74 75	–	Bioaccumulation	Batch reactors	Kiki et al. (2020)
N. oculata	Lindane	68.2	0.5	Biodegradation	Batch	Pérez-Legaspi et al. (2016)
Chlamydomonas reinhardtii	Chlortetracycline	>99	24	Biodegradation, photolysis Bioaccumulation	Batch	Zhao et al. (2020)
Chlorella sp. L38	Thiamphenicol	95	46.2	Biodegradation Bioaccumulation	–	Singh et al., 2021
Scenedesmus dimorphus	Estriol	85	–	Biodegradation	Batch culture	Zhang et al. (2014)
Chlorella vulgaris C. sorokiniana, Coelastrella sp.	Bupropion	82 60 89	–	Bioadsorption	Batch culture	Gojkovic et al. (2019)
Chaetoceros muelleri	Diethyl phthalate	95.5	0.1	Biodegradation	Batch culture	Choi et al., 2019
Chlamydomonas sp. Tai-03	Bisphenol A	100	10	Photolysis Biodegradation	Batch culture	Xiong et al., 2019
Chlorella sorokiniana	Salicylic acid	73	–	Biodegradation	Batch culture	Escapa et al. (2015)
Chlorella sorokiniana	Paracetamol	41–69		Biodegradation	Batch culture	Escapa et al. (2015)
Picocystis sp.	Diclofenac	73	25	Biodegradation	–	Banu et al., 2020
Navicula sp	Ibuprofen	60	1	Biodegradation Bioaccumulation	–	Ding et al. (2017)
Chlamydomonas sp.	Ciprofloxacin	100	–	–	Batch	Xie et al. (2020)
Microcystis aeruginosa	Tetracycline	99	10	Biodegradation, and Biosorption	Batch culture	Patel et al., 2021b
Spirulina platensis	Chlortetracycline	99.83	5	Biosorption, Biodegradation & Bioaccumulation	–	Zhao et al., 2020
Scenedesmus obliquus	Sulfamethazine	62.3	–	–	Batch	Xiong et al. (2019)
Scenedesmus sp. LX1	Methylisothiazolinone	100	–	–	Batch	Wang et al. (2020)

subsequently decreased. There are different methods that are used by various microalgae, such as exclusion and chelation, heavy metal immobilization, phytonutrients, or chemical reactions to lessen the unsafe heavy metals. These pathways are used to minimize systemic toxicity. Even cyanobacteria can produce microbial protein molecules without altering their method of action. Microalgae are used in a three-way system to remove inorganic pollutants (Priatni et al., 2018). The initial process involves passive outer membrane adsorption (biosorption), followed by delayed positive diffusion and intracellular material aggregation (bioaccumulation), and finally, biotransformation by diverse reactions such redox potential, ROS, and methylation.

Microalgae synthesize organic matters (OMs) which helps in the photodegradation pathways. OMs are categorized as extracellular and intracellular organic matter based on secretion location. The extracellular organic matter or EOM (proteins, carbohydrates, humic substances) in a polluted aquatic environment plays a dominant role in the indirect photodegradation of organic pollutants under irradiance (Wei et al., 2021). EOM is involved in the active oxygen species generation prior to the photodegradation of organic pollutants (Tian et al., 2019). On the other hand, intracellular organic matter (IOM) which is 80% of the OM is involved in intracellular degradation reactions. EOM with a high number of carbonyl compounds is likely to produce more triplet excited-state EOM^{3*} and accounts for over 90% photolysis process. It may vary from species to species (Tian et al., 2019; Wei et al., 2021).

The ability to determine the heavy metal ion binding affinity of biosorbents is achieved by a knowledge of their molecular structure. Determining the heavy metal ion binding affinity of bio-sorbents is made much easier by knowing their chemical structure. On the other hand, the process of heavy metal ion aggregation within the cell appears to be significantly slower. Heavy metal ions are actively transported into the cytosol and outer layer, followed by the spreading and connected to the development of protein and peptide internals, including metal transporters, oxidation-reduction agents, and phytochelatins.

3.1. Specific pathways of inorganic, organic and ECs remediation by microalgae

Microalgae play a crucial role in the bioremediation of inorganic, organic and emerging pollutants. There are various kinds of reaction mechanisms that have been involved during the remediation of toxic pollutants such as bio uptake, bioaccumulation, biosorption, biodegradation, and photodegradation (Gondi et al., 2022; J. Nie et al., 2020).

3.1.1. Biosorption

Biosorption is a process of rapid and reversible binding of pollutants on the surface of microorganisms. It is the most convenient technique for the removal of heavy metals from wastewater (Yan et al., 2022). Algae has great potential to be used as a biosorbent because, on the algal surface, several functional groups such as proteins, lipids, and polysaccharides serve as adsorption sites (El-Naggar et al., 2018). Basically, there are two types of biosorption: chemisorption (chemical adsorption) and physisorption (physical adsorption). During chemical adsorption formation of chemical bonds takes place, while in physical adsorption interactions occur between pollutant molecules and sorbent surface binding sites (Gondi et al., 2022). The mechanisms of organic pollutants adsorption up on microalgae cell surface are collective results of several physicochemical interactions. They are dependent on the surface chemistry of microalgae, properties of pollutants, and important affecting factors such as temperature and pH of the solution (Ho et al., 2019). These interactions mainly include electrostatic interaction, ion exchange, π-π interactions, co-precipitation, cationic and anionic attraction, etc. Moreover, this adsorption subsequently led to biochemical and enzymatic oxidation, or degradation of organic pollutants (Wei et al., 2018; Inyang et al., 2016).

Bioadsoption is also a dominant interaction for inorganic pollutants removal by microalgae. Basically, anionic and cationic attraction, precipitation, physisorption or chemisorption plays main role in toxic heavy metals adsorption into the microalgal cell surface. For these interactions, pH is the most affecting factors among others. The algal strain *Chlorella vulgaris* was used to remove mercury from aqueous solutions and it showed the maximum adsorption capacity of mercury at pH 6 (Kumar et al., 2020). Some algae, including *Scenedesmus* sp., and *Chlamydomonas* sp. have been used as bio sorbents to remove chromium Cr(Vl) (Pradhan et al., 2019; Ayele et al., 2021). Recently, the algal strain *chlorella sorokiniana* used is used for the biosorption of uranium and it shows a maximum adsorption capacity of 188.7 mg g^{-1} (Embaby et al., 2022). Therefore, this method is an effective option for the remediation of toxic pollutants and possesses several benefits such as being easy to operate, cost-effective, no production of sludge, and a great ability to treat large amounts of wastewater with low contaminant concentration (Lo et al., 2014).

3.1.2. Bioaccumulation and/or bio-uptake

The gradual accumulation of substances, such as toxic pollutants, pesticides, or other chemicals inside the cell's cytoplasm is termed bioaccumulation. The bioaccumulation and bio-adsorption pathways of pollutants are completely separate, and their quantification is somehow challenging because both actions occur simultaneously in the most cases. It is like bio-adsorption is the primary stage of bioaccumulation (Gondi et al., 2022). Microalgae is one of the natural sources that effectively absorb different pollutants and gather inside cells, where they are then utilized for their growth (Bhatt et al., 2022). Sometimes, accumulation of harmful pollutants also benefits the host with certain responsive ability. For instance, Sulfamethoxazole acclimation enhanced the resistance of *Chlorella vulgaris* to its toxicity and enhanced biodegradability capacity (Zhang et al., 2022). According to reports, the green microalga *Chlamydomonas Mexicana* can bioaccumulate atrazine and then decompose up to 14–36% of it (10–100 μg L^{-1}) afterwards (Bhatt et al., 2022). *Desmodesmus subspicatus* shows a 23% bioaccumulation rate of 17α-ethinylestradiol (Maes et al., 2014) and *Nannochloris species* shows 42% for triclosan (Bai and Acharya, 2016). While sometimes microalgal cells bioaccumulate chemicals (triclosan and Sulfamethoxazole) in extreme amounts, which causes excess reactive oxygen species and at last cell death (Bai and Acharya, 2019). Although the benefits of algae bioaccumulation, some studies do not take emerging pollutants' fate into account (Gojkovic et al., 2019) and are concerned to dispose of the used algal biomass.

Bio uptake is described as the various toxic pollutants penetrating through the algal cell wall and binding to the intracellular proteins of microorganism cells. Bio uptake of pollutants can happen only in living cells, and it is the major difference between bioaccumulation and bio uptake (Mulla et al., 2019). One of the parts of this environment that exhibits the highest rate of uptake of various harmful pollutants is algae. Due to the presence of negatively charged functional groups on the microalgae cell wall, they show high metal binding capacities. Consequently, when those pollutants are present at low levels, microalgal cells are especially effective at absorbing them while at higher concentrations microalgal cells developed self-defense mechanisms to survive (Monteiro et al., 2012). In some studies, *C. kesslerii* algal strain is used for the uptake of Cd(II) and Pb(II) from wastewater treatment plant effluents and results show Pb(II) uptake was much greater compared to Cd(II) (Worms et al., 2010). Even though microalgae may be used to remediate emerging pollutants, bio-uptake does not offer a long-term solution because it aids in the conversion of pollutants from one form to another. Because of this, it is not possible to use harmful algal biomass to make biofuels or other high-value products, which might make the entire process unprofitable (Maryjoseph and Ketheesan, 2020).

3.1.3. Biodegradation

The metabolic degradation or transformation of chemical compounds or pollutants by the biological action of living organisms is termed biodegradation (Patel et al., 2022e). Basically, microalgae convert complicated parent compounds into simpler forms during biodegradation. There are various types of enzymatic processes that are involved, like hydrolysis, hydrogenation, hydroxylation, and glycosylation (Gondi et al., 2022). Three major steps occur during biodegradation. In the first step detoxification of pollutants occur by using cytochrome P450 enzyme which involves oxidation, reduction, and hydrolysis. Also, the conversion of lipophilic molecules to hydrophilic molecules takes place by using the addition of a hydroxyl group. In the second step, cells protect themselves from oxidative damage by the formation of conjugate bonds between compounds containing electrophilic groups and glutathione. And during the third step, different enzymes are used such as decarboxylase, carboxylase, dehydrogenase, and laccases. The biodegradability of compounds mostly depends on the complexity of the structure. When compared to complicated compounds with cyclic structures, those with linear, unsaturated structures and electron-donating groups biodegrade more quickly, e.g., *S. obliquus, Navicula* sp., and *C. pyrenoidosa* showed 95% biodegradability (Gondi et al., 2022; Xiong et al., 2016; Ding et al., 2020). The study conducted on *Scenedesmus* sp. shows effective biodegradation of carbamazepine. On the basis of the results, a high-level concentration of carbamazepine (100 mg L^{-1}) only inhibits 30% growth of microalgae (Xiong et al., 2016). Some studies are conducted for pesticide removal by using the algae-based system and results found that 97% chlorpyrifos, 88% oxadizon, and 74% cypermethrin were removed from the liquid phase (Avila et al., 2021). But still more research in algal biodegradation is necessary due to the fate of emerging pollutants and the end application of algal biomass.

3.2. Photobiocatalysis and photodegradation

A long-standing goal of synthetic chemistry is to harness biocatalysts for new biochemical transformations. Algal platform is the best platform to provide the solution for such goals. Past investigations were largely focused on independent photocatalytic and biocatalytic processes, however recent years several works combined both the process together for investigating the photoremediation efficiency of numerous photodegradable pollutants and photobiocatalysis emerge as new avenue (Harrison et al., 2022). This combination offers numerous benefits such as more efficiency, novel photoreactivity, higher enantioselectivity etc. Photoenzymes are required for continuous flow of photons to catalyse the reaction (Okeke et al., 2022). Antibiotics were photocatalysed using low-cost designed g-C3N4 material for better photocatalytic response and photodegraded by microalgae *Scenedesmus obliquus* and *Chlorella pyrenoidosa* effectively. The g-C3N4 formed $^*O_2$, H^+ and $^*OH$ to enhance antibiotic breakdown such as norfloxacin (NOR), sulfamethoxazole degradation which was further biodegraded by both microalgae (Li et al., 2022). A photocatalytic degradation pathway for NOR has been proposed as an oxidation reaction, hydroxylation reaction, and a decarboxylation reaction. Because of many unmineralized products of NOR were formed, NOR photocatalytic reaction solution has an increased acute toxicity which was effectively reduced by microalgae via biodegradation (Li et al., 2022). Due to low tolerance of *Chlorella vulgaris* against enrofloxacin, two stage treatment was designed by combining photocatalysis and algae degradation to achieve $>55\%$ enrofloxacin remediation (Lu et al., 2022). Photobiocatalysis process were explained to be very effective for valorisation of organic wastes and its conversion into value added bioproducts using whole-cell biotransformation (Magri and Cannella, (2022).

4. Supporting technologies for algal remediation

4.1. Nanoparticle

Nanoparticle (NP) plays an important role in enhancing the bioremediation performance of microalgae by inducing enzyme synthesis involved in pollutant degradation. NP has also been used solely or in combination for enhancing the yield of biomass and products such as carotenoids, proteins, and lipids. Apart from these, several nanoparticles are also used for improving surface bonding and flocs formation for microalgae harvesting. Especially Fe_3O_4 nanoparticle has been often used for the efficient harvesting of microalgae as biocompatible and recyclable magnetic adsorbents and have received tremendous attention in recent years (Patel et al., 2022h).

Several studies have reported the beneficial role of nanoparticles produced by algae to help in the bioremediation of numerous organic pollutants. In some studies, algae-synthesized nanoparticles are also supported by a catalytic agent to accomplish photo remediation of emerging pollutant. Several studies targeted dye and nitro compounds treatment by these NPs. Both organic dyes and nitro compounds are common contaminants in several industrial wastewater. The reduction kinetics of synthesized nanoparticles exhibited decent catalytic efficiency in the degradation of organic dyes (Rhodamine B and Sulforhodamine 101) in presence of a sodium borohydride-reducing agent. It also reduced harmful aromatic compounds (4-nitrophenol and p-nitroaniline) into harmless amino aromatic compounds. Numerous types of nanoparticles have been synthesized from algal extracts in past studies. For instance, Ramakrishna et al. (2016) have successfully synthesized the gold nanoparticle from the extract of the macroalgae Turbinaria conoides and Sargassum tenerrimum. Green synthesis of silver nanoparticles (AgNPs) has also been reported from Ulva lactuca and Chlorella ellipsoidea and has been used for the photo-biocatalytic degradation of methyl blue and orange blue (Ramakrishna et al., 2016; Borah et al., 2020). Another study synthesized AgNPs from the freshwater microalgae Chlorella vulgaris that was able to degrade >96% of methylene blue within 3 h of treatment (Rajkumar et al., 2021). Zinc oxide nanoparticle was synthesized from microalgae Chlorella sp. extract as well as brown macroalgae Sargassum muticum (Azizi et al., 2014; Khalafi et al., 2019). Nanoparticles synthesized from *Chlorella* sp. exhibited an efficiency of 97% for the photo-desulfurization of dibenzothiophene contaminant (Khalafi et al., 2019). It has also been reported that zinc oxide nanoparticle plays an essential role in the photobiocatalytic degradation of selective cationic dye (Prasad et al., 2019).

The iron oxide was synthesized from several algae species like brown seaweed macroalgae, Sargassum muticum, a soil microalga, Chlorococcum sp., and the microalgae Spirulina platensis. Iron nanoparticles are essential in detoxifying chromium ions by converting Cr(VI) to nontoxic form Cr(III) (Shalaby et al., 2021). Iron nanoparticles derived from Spirulina platensis helped to remove crystal violet (256.4 mg g^{-1}) and methyl orange (270 mg g^{-1}) from the aqueous solution (Madhavi et al., 2013). Nanoparticles synthesized from Spirulina platensis also helped to remove food dyes (azo dye, triphenylmethane dye), maximum absorption capacity was seen at pH 4 and 298 K azo dye absorbed 468.7 mg g^{-1} and triphenylmethane dye were absorbed 1619.4 mg g^{-1}(Dotto et al., 2012).

Many studies were also carried out where nanoparticles were supplemented in microalgae systems to improve the algal remediation for emerging, organic, and inorganic pollutants from wastewater. Removal of heavy metals from wastewater with the help of nanoparticles supplemented microalgae has been greatly studied. Shen et al. (2020) reported that Fe_2O_3 in combination with microalgae helps to remove a number of heavy metals from sewage, mainly Cr(VI) (69.77 mg g^{-1}), Pb (II) (62.63 mg g^{-1}), Cd(II) (42.12 mg g^{-1}), Cu(II) (38.68 mg g^{-1}). Nanoparticles synthesized from Spirulina platensis were used for the removal of Cr(VI) from the wastewater. The condition was also monitored and the nanoparticle dose of 250 mg L^{-1} for chromium removal at pH 4 maximum efficiency obtained was >99%.

4.2. Nanobubble

Nanobubble (NBs) of size less than 1 μm has gained tremendous popularity because it doubles the mass transfer efficiency compared to the traditional aeration method by prolonged retention in the aqueous phase before rising on the surface and burst. It helps to obtain maximum energy utilization and saves power consumption (Zimmerman et al., 2011b). It also provides a comprehensive stirring motion that helps in the appropriate mixing of microalgae biomass in the culture medium. Due to its uniform non-porous membrane has various applications in the diverse field (Kukizak and Goto, 2006). Microalgae platforms have been used for nanobubble application in past studies for the enhancement of biomass and several high-value products such as carotenoids and lipids, moreover, it is also used for removing pollutants or degrading toxic compounds from wastewater (Patel et al., 2021d). A recent study revealed that using nanobubble in the microalgae culture improves the CO_2 dissolution for better growth, reducing the active O_2 inhibitors to biomass loss and thus significantly helping to reduce COD, ammonia, and total nitrogen (TN), and removal efficiency improved with respect to culture lacking nanobubble application (control) by 3.3, 5.9, and 10.58% respectively. It was further noted that the nanobubble-treated culture consumed extra 30.12 mg L^{-1} oxygen as compared to the control, which resulted in the extra removal of the pollutant from wastewater (Xiao et al., 2021). As a rule, nitrate removal was based on denitrification, which was closely related to the structural properties of microbial aggregates and the internal oxygen consumption process, including the composition of EPS, the internal mass transfer resistance of activated sludge, and biofilm thickness (Ning et al., 2012; Yan et al., 2022). NB addition enlarged the size and thickness of activated sludge and biofilm, which further helped to remove TN from the culture. Direct application of bulk nanobubbles has been widely used in wastewater treatment for removing organic and inorganic pollutants however its application on the algal system for wastewater treatment is undergoing and yet to understand properly what dosing and which nanobubble-sources (CO_2, O_2, air, O_3 etc.) are more effective for the treatment of specific composition of wastewater.

4.3. Gene alterations/mutation

Microalgae have evolved with several anti-toxic mechanisms both intracellular and extracellular for the mitigation of heavy metal toxicity. The outer layer of the microalgae cell wall and extracellular polymeric substance allow the binding of positively charged heavy metals onto the surface via a mechanism called bio adsorption (Worms et al., 2010). The cell wall of microalgae consists of mostly negatively charged multinational groups like amino, hydroxyl, carboxyl, sulfhydryl, sulfate, phosphate carbonyl, imidazole, thioether, phenol, and a few positively charged groups of amides (Saavedra et al., 2018; Singh et al., 2021). These groups bind with opposite charged pollutants via ion exchange, chelation and complexation, hydroxide condensation, covalent binding, redox interaction, biomineralization, and precipitation. In this natural mechanism, limiting steps are ionic imbalance, and the quantitative supply of active transporters, and detoxifying or degrading enzymes obtain higher bioremediation ability. Hence research advancements have been focused to improve the inherent ability of microbes through genetic interventions.

The identification and characterization of these targeted molecules in attempts to develop transgenic microalgae can help to improve the overall bioremediation potential. The overexpression of NRAMP1 in *Auxenochlorella protothecoides* helped in the utilization of a higher concentration of cadmium from the solution (Lu et al., 2019). Similarly, the upregulation of gene encoding NRAMP1, Zrt-Irt-like proteins, and Cu-transporter in *Dunaliella acidophila* to have higher uptake of Cd. Puente-SÃ¡nchez et al. (2018) increased the uptake of As in

Chlamydomonas eustigma and *Microcystis aeruginosa* with increased overexpression of phosphate transporters and aquaglyceroporin. An additional study examined the Cd uptake by transformants of *Chlamydomonas* sp. was five-fold higher than wild type after expression of MT-II polymer and a fusion protein that was composed of low CO-induced plasma membranes protein (Rajamani et al., 2007). The *C. reinhardtii* has the capacity to remove cadmium was greatly enhanced and the removal rate increased from 69.8% to 90.2% in 6 h as a result of the integration of the gene gshA encoding γ-glutamylcysteine into the microalgae. This was done by increasing the activity of intracellular glutathione S-transferase and the synthetic concentration of GSH (Yan et al., 2022).

Microalgae have great potential for detoxifying organic and inorganic pollutants however, uptake of ECs is limited due to the complex chemical structure of the EC. Through electrostatic interactions, hydrophobic, cationic ECs are attracted to microalgal cell surfaces, whereas hydrophilic ECs are repelled (Xiong et al., 2017). Without modification (wild type) a very smaller number of ECs removal was detected. For example,>20% adsorption of ECs on microalgae *Chlorella sorokiniana* was reported by de Wilt et al. (2016). Similarly, Priya et al. (2014) reported that *Scenedesmus obliquus* and *Chlorella pyrenoidosa* adsorb progesterone and norgestrel approximately by 10%. By modifying the microalgae uptake of ECs can be enhanced. By chemically modifying the microalgae biomass 70% higher bioabsorption of EC was improved (Azizi et al., 2014). Radionuclide cesium uptake by the green alga Haematococcus pluvialis was enhanced when the cell was in the cyst stage and was further enhanced by changing the number of cellular potassium transporter at different lifecycle stages (Lee et al., 2019). Microalgal biodegradation of ECs can also be enhanced by the introduction and overexpression of Phase I and Phase II enzyme families present in the microalgae. The main role of these enzymes in biodegradation is to make contaminants more hydrophilic by either adding or unmasking hydroxyl groups through hydrolysis, oxidation, or reduction (Xiong et al., 2018).

5. Microalgae bioremediation towards sustainability and circular bioeconomy

There has been an upsurge in the development of products produced from renewable sources that use the end products, such as CO2 and other gases released from industries, and wastewater effluent from various small- and large-scale enterprises. Microalgae have been identified as one of the most promising microorganisms to utilize as the end product of industries. Microalgae biomass obtained from waste remediation is also a valuable resource for value-added fuel and non-fuel products. However edible products must be safe for consumers and certain effluent from food industries and defined flue gas composition from biofuel industries are acceptable upon safety check. Various literature suggests that microalgae-derived several molecules have numerous health benefits, such as anti-inflammatory, antioxidant, anti-aging, antimicrobial, anti-obesity, and anticancer properties. In addition to nutraceuticals, pharmaceuticals, and cosmetics, they can also be used to manufacture next-generation products (Camacho et al., 2019). A microalgae-based cultivation system can help reduce environmental pollution by mitigating CO_2 emissions and removing wastewater. Moreover, in a circular bioeconomy, biomass can be converted to biofuels and co-products to offset treatment costs or generate revenues (Herrera et al., 2021; Banu et al., 2020). However, the final product produced by microalgae from the circular bioeconomy cannot be used to produce functional food sources (Goswami et al., 2021a). Overall, microalgae are a most sustainable platform which able to fulfill treatment goals with several benefits. In brief account, it makes environments clean, provides a hygienic society, and satisfies localized or centralized energy needs, improves carbon footprint by capturing greenhouse gases. Moreover, several algal products are applied in cosmeceuticals, therapeuticals, nutraceuticals and other health applications and providing a widening circular economy platform. These benefits make a full circular loop by covering three important aspects to fulfill the economic, environmental, and social goals and thus it strongly claims as the most sustainable platform for the sustainable treatment opportunity of several polluted resources.

6. Challenges, limitations, and strategies to improve algal remediation

The recently added knowledge of algae-based pollutant remediation establishes a promising alternative to conventional wastewater remediation as a profitable and sustainable option. Still, marked limitations must be overcome prior to implementing microalgae as a sustainable remediation platform for municipal or industrial wastewater treatment goals for co-culture or mixed culture system. First, the harvesting of microalgae biomass is known as the major problem to become viable wastewater bioremediation, including in aquaculture. The majority of recently studied harvesting methods have their limitations related to viable scale-up usage and cost-effective downstream processing. As far as cheaper harvesting is concerned, the desired microbial configuration for wastewater treatment is one of the best alternatives to existing harvesting methods due to its sustainable performance and low energy consumption under optimal conditions (Lavrinovičs and Juhna, 2017). Another strategy for testing potential microbial species in open systems to facilitate the natural swing of dominant algal species that are likely to grow. Consequently, the biofiltration stage of the microalgal system may lose its effectiveness due to grazers' preferences for food. Biofiltration uses valuable substances produced by algae for filter feeder metabolism. As a cost-effective and profit-maximizing mode to offset treatment costs, the naturally occurring food web is well suited for high-valued organism aquaculture. Although algae-based wastewater treatment reduces coliforms efficiently, its mechanism and drivers are yet to be fully understood which affects its proper implementation. It is also imperative to note that microalgae do not reduce all metal ions and emerging contaminants sufficiently, which demands further research advancement into treatment (Lavrinovičs and Juhna, 2017).

The microalgae-bacterial consortia-based bioremediation method is emerging and found more effective in high organics-loaded wastewaters in which both groups of microbes are complementary in the degradation of organic fractions simultaneously or sequentially (X. Nie et al., 2020). However, major challenges exist in the selection of effective consortia is a selection of compatible strains each other. Moreover, the lab condition is the most favorable and controlled environment for bioremediation performance with precise ratio but the outdoor environment is non-controllable that greatly affects the remediation efficiency depending on the naturally occurring microbial composition. High pollutant loading also negatively affects the bioremediation performance, hence the selection of robust strain which can tolerate and exhibit better remediation performance must be selected for bioremediation (Abdel-fattah et al., 2022).

The latest trend of microalgae-based remediation is also focused on retrieving the value from harvested biomass to offset the treatment cost and sustainability. Since microalgae are efficient in lipid accumulation and a polluted environment favors biofuel production rather than edible and bioactive products. Except for effluents from dairy, beverages, and food industries which are acceptable for nonfuel product harvesting. But the commercialization of microalgae-based biofuels still faces many challenges. Algal biodiesel is two times more expensive than fossil fuel with current technologies. Among algal biodiesel production processes, the price of the dewatering stage should be reduced intensively, as it represents 20–30% of the overall cost. Therefore, the research should also focus on the mass production of microalgae utilizing urban and livestock wastewater to reduce the costs of biomass production and product extraction (Romera et al., 2007).

Utilizing recycling technologies may also result in cost savings when the solvent is recovered after extraction. It is imperative to prioritize downstream production that uses low energy and yields high amounts of algae oil for commercialization. A high selling price for protein is a viable reason to use microalgae as a protein source, but lipids are lost during protein recovery. This is also the case for carbohydrate fractions. It is, therefore, necessary to further investigate efficient co-extraction and sequential extraction of products from the same microalgal biomass (Binda et al., 2020).

7. Conclusions and prospects

Microalgal remediation with value-added products extraction is determined as the most sustainable option exhibiting more energy-efficient, cost-effective, and environmentally friendly treatment technology for a wide range of pollutants. Especially, this technology is fascinating for wide pollutant range especially emerging pollutants with sustainable features for several industries facing stringent regulatory challenges by national legislation to maintain a positive carbon footprint and zero emission goals. However, it is still in its infancy and requires significant research advancements to adopt at a greater scale. Bioadsorption, bioaccumulation photodegradation, and biodegradation are the main mechanisms for the effective remediation of organic and inorganic pollutants by microalgae. However, bioadsorption is a dominant interaction among others that can be strategically enhanced by altering abiotic factors for attaining desirable bioremediation efficiency. The desired breakthrough in algae-mediated bioremediation research can be realized by utilizing robust, potential vigour mixotrophic and fast-growing strains which can generate greater biomass to avail bioadsorption as the dominant interaction for effective treatment. Moreover, bioadsorption can further be enhanced before harvesting via regulation of pH, temperature, and ionic species for encouraging interactions. Nanoparticles and nanocomposites were impressive in enhancing bioadsorption. Nanobubble, gene editing, mutation and biochar technologies could be pioneering to enhance removal, biodegradation and detoxification of emerging pollutants remediation using microalgae platforms shortly as a sustainable solution. The microalgal platform is fascinating for carbon mitigation and to improve the overall carbon footprint of the process as well as for value-added product recovery to make the bioprocess more sustainable. However, further advancement is required to co-extraction or sequential extraction of more than one product for sustainability.

Credit author statement

Siddhant Dubey: Data collection, Writing – original draft. Chiu-Wen Chen: Validation, writing, Supervision. Dibyajyoti Haldar: Writing – original draft. Vaibhav Sunil Tambhat: Writing – original draft. Prashant Kumar: Writing – original draft. Ashutosh Tiwari: Writing – original draft, Reeta Rani Singhania: Conceptualization, Data curation, Supervision, Cheng-Di Dong: Validation, Data curation, Visualization, Supervision, Anil Kumar Patel: Conceptualization, Data curation, Writing – original draft,Writing – review & editing, Visualization, Supervision.

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.

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