Innovative Biosorption Techniques for Heavy Metal Removal Using Microalgae: A Comprehensive Review

Ali Akbar Ghotbi-Ravandi [1], Mahdi Pouresmaieli [2, 3], Negin Noorbakhsh [3, 4], Niloofar Khayati [5], Elena Ekrami [3, 6], Somayeh Zarezadeh [7*]

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Abstract

Water and soil pollution represents a fundamental human issue globally. Heavy metals are one of the basic pollutants of water and soil, which can be caused and intensified by anthropogenic activities, including mining, transportation, and various industries. Due to the toxic effects of these metals on the environment, organisms, and human health, the removal or recovery of these elements from polluted environments is of particular importance. Different methods and techniques have been applied to remove these pollutants, among which, bioremediation has received considerable attention due to its eco-friendly and cost-effectiveness. Bioremediation uses the ability of varoius organisms to decrease or remove pollutants. Algae are among the organisms that show significant capabilities in removing different types of contaminants, especially heavy metal ions. Phycoremediation is an application of algae as bio-remediate agents, and depends on factors such as light, temperature, pH, type of pollutant, and type of taxon. Various strains are known for their ability to remediation of heavy metals. The most basic methods in removing pollutants using algae are biosorption into the cell (absorption) and surface biosorption (adsorption), which uses the living or non-living mass of algae. New techniques, such as using transgenic microalgae, are among the effective detoxifying and rapidly growing methods. Genetic engineering for algae gene editing and gene silencing benefits various technologies and tools such as reporter genes, Cre-lox recombination, and CRISPR-Cas systems, modular cloning toolkits, regulatory elements, promoters, vectors, restriction enzymes, and post-transcriptional gene silencing technologies. Other novel techniques whose future on an industrial scale seems promising are the combined use of microalgae and bacteria, biochar addition, and biogenic nanomaterials generated from algae. These innovative methods offer sustainable and cost-effective solutions for environmental pollution, therefore boosting

1-Faculty of Life Sciences and Biotechnology, Shahid Beheshti University, Evin, Tehran, Iran
2-Faculty of Mining, Petroleum and Geophysics, Shahrood University of Technology, Shahrood, Iran
3-Department of Industrial and Environmental Biotechnology, National Institute of Genetic Engineering and Biotechnology (NIGEB), Tehran, Iran
4-Faculty of Medical Sciences and Technologies, Islamic Azad University Science and Research, Tehran, Iran
5-Department of Plant Physiology, Faculty of Science, University of Tehran, Tehran, Iran
6-Institute of Biochemistry, Biocenter, University Würzburg, Würzburg, Germany
7-Department of Applied Chemistry, Faculty of Chemistry, University of Tabriz, Tabriz, Iran
*The corresponding author's email address: s.zarezadeh@tabrizu.ac.ir
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public health. Studies on the development and implementation of these techniques are ongoing in the world. In this paper, the ability of 78 algae species to remove 18 heavy metals has been reviewed.

Keywords: Absorption, Bioremediation, Heavy metals, Phycoremediation, Transgenic microalgae

Introduction

Environmental pollution is considered one of the most critical issues around the world. Due to the rapid expansion of urbanization, industrialization, manufacturing, and production of hazardous by-products, this problem is getting worse by the day and ultimately endangers environmental sustainability and human health (Rahman et al., 2021). Heavy metals (HMs) are regarded as one of the most considerable pollutants in soil and aquatic ecosystems (Ahmad et al., 2021). The natural weathering of minerals, as well as recent industrial and anthropogenic activities, led to the discharge of significant levels of HMs into the environment (Malik and Kaur Sandhu, 2023). Mining, smelting, and refining processes produce enormous amounts of contaminants and HMs, which could be distributed through the air and negatively affect the nearby areas (Izydorczyk et al., 2021). Furthermore, industrial emissions and automotive industries, fossil fuels, sewage sludge, household activities, and excessive use of pesticides and insecticides significantly contribute to polluting the environment with HMs (Briffa et al., 2020) (Fig. 1). Contamination of the terrestrial and aquatic ecosystems with HMs poses a significant hazard to the environment and therefore human health as a result of direct toxic impacts on living organisms and further potential for increased exposure along the food chain (Huang et al., 2018). Numerous severe health conditions, including cancer, lung adenomas, kidney failure, neurological disorders, inhibition of enzyme activity, and infertility, are among the ailments caused by HM exposure (Alengebawy et al., 2021; Żukowska and Biziuk, 2008).

The rising content of HMs, their persistence in the environment, and potentially deleterious effects on ecological and human health demand effective remediation technologies. There are several methods for removing HMs from contaminated environments, including water and soil. Traditional methods such as ion exchange, chemical precipitation, coagulation, conventional and advanced oxidation, ultrafiltration, and electrochemical removal have some limitations like usability for limited metal ions, consuming higher energy and chemicals, and producing a considerable amount of sludge/solid waste (Razzak et al., 2022). Therefore, developing more effective and environmentally friendly solutions is very important. Today, the emergence of affordable methods in which no cutting-edge technology is required have attracted substantial attention as these methods are economically feasible for developed and developing countries. Among the new technologies used to reduce HMs is bioremediation, which has received greater attention from various communities because of its low-cost, simple technology, and availability.

Bioremediation is a process that applies organisms' potential to clean up environmental contamination, such as wastewater, ground or surface waters, sediments, and soils (Boopathy, 2000). The bioremediation technique uses bacteria, fungi, plants, and algae to break down, remove, change, immobilize, or detoxify different chemicals and physical pollutants from the ecosystem (Bala et al., 2022). When biological agents interact with pollutants, bioremediation occurs spontaneously without the aid of any chemical catalysts. To facilitate and speed up the bioremediation process, it is vital to generate the optimum environmental conditions (Verma and Jaiswal, 2016). The characteristics of the contaminated site have a great impact on the bioremediation process. The bioremediation process is influenced by various factors, including soil texture, permeability, pH, water-holding capacity, temperature, nutrients, and oxygen content (Boopathy, 2000).

Phycoremediation, the application of algae to remove contaminants from the environment, is recognized as an effective and affordable bioremediation technique. Microalgae are recognized as effective bioremediation agents in soil due to their rapid growth, large surface area, strong affinity

Fig. 1. Main sources of soil and water pollutants, including pesticides and insecticides, refining and smelting industries, automotive industries, mining, fossil fuels, sewage sludge, and household activities. Pictures used in this figure are adopted from (Di Capua, 2013; Khan, 2022), (https://commons.wikimedia.org/), (https://www.brainhealth.scot/), (https://iglobalpunjab.com/), and (https://truthout.org/).

for metal binding, high tolerance for various contaminants, and eco-friendly nature (Chugh et al., 2022; Yeheyo et al., 2024). They utilize natural metabolic processes through techniques such as bioconcentration and volatilization to detoxify and remediate polluted soils effectively. Their effectiveness lies in their ability to accumulate and degrade contaminants within their cellular structures. Furthermore, microalgae release exudates that support the growth of beneficial microorganisms in the soil, enhancing soil health and resilience (Yeheyo et al., 2024). Phycoremediation of water systems is primarily recognized for its ability to purify water contaminated with HMs and/ or other pollutants; however, it can be integrated into a broader bioremediation strategy that benefits both aquatic and terrestrial environments. Since the biomass produced by algae following the phycoremediation is used as feedstock to generate biofuel and other valuable products, algal-based bioremediation is strongly favored (Razaviarani et al., 2022)such as wastewater treatment and bioenergy industries. Microalgae are mixotrophic microorganisms that have potential to utilize nitrogen and phosphate (nutrients. Therefore, this review encompases the current research, advancements, and modern approaches in the phycoremediation of heavy-metal-polluted environments.

Phycoremediation of HMs

Algae are considered a new biological step that is a permanent, environmentally friendly, and affordable procedure for environmental protection (Touliabah et al., 2022). The merits of bioremediation based on algae are better production of biomass and higher aggregation ability, detoxification, and degrading xenobiotics and contaminants. Moreover, the produced biomass during bioremediation is cost-efficient in the field of clean energy.

Different species of algae, including macro- and micro-algae, diatoms, and cyanobacteria, can remove pollutants from soil and water. As an example, the ability of *Neochloris aquatica* in removing HMs including chromium (Cr) (88.7%), lead (Pb) (75.9%), nickel (Ni) (87.6%), cadmium (Cd) (60.4%), cobalt (Co) (52.9%), zinc (Zn) (84.9%), and copper (Cu) (54.4%) is considerable (Tamil Selvan et al., 2020). The study conducted by Ajayan et al. (2015) revealed the important effect of *Scenedesmus* sp. on reducing the HM pollution of Zn (65–98%), Pb (75–98%), Cu (73.2–98%), Cr (81.2–96%), and nutrients such as phosphate (>95%) and nitrate (>44.3%). Marine macroalgae such as *Caulerpa lentillifera* can also be used as inexpensive adsorbents to remove Cd, Cu, Zn, and Pb from aqueous solutions (Apiratikul and Pavasant, 2006). Table 1 lists 78 microalgae strains with the ability to bioremediate 18 HMs.

Diatoms, another group of microalgae, can bioremediate diverse forms of effluents due to their cellular structure and adaptive techniques. It may absorb and use different micro- and macro-elements (Marella et al., 2020). *Cylindrotheca closterium* be able to remove phthalate acid esters (PAEs) from surface sediments (Gao and Chi, 2015). Moreover, the herbicide mesotrione (an aromatic ketone) can be absorbed by *Halamphora* (*Amphora) coffeiformis* (Valiente Moro et al., 2012). *Nitzschia* sp., another diatom genus, causes fast decomposition of organic matter by enhancing aerobic bacterial activity (Yamamoto et al., 2008). Besides, *Nitzschia* sp. and *Skeletonema costatum* can degrade the highly toxic polyaromatic hydrocarbons (PAHs) from sediments (Hong et al., 2008).

Some reports on the biodegradation of pesticides by algae can be found in the literature (Megharaj et al., 2000, 1994, 1987). El-Bestawy et al. (2007) illustrated the ability of the strains *Synechococcus*, *Oscillatoria*, *Nostoc*, *Cyanothece,* and *Nodularia* in degrading of the pesticide Lindane (chlorinated aliphatic pesticide). Kuritz and Wolk (1995) also reported the ability of *Nostoc ellipsosporum* and *Anabaena* sp. to degrade Lindane. Moreover, soil isolates of *Chlorella vulgaris, Synechococcus elongatus, Tetradesmus obliquus* (*Scenedesmus bijugatus*), *Leptolyngbya tenuis* (*Phormidium tenue*), *Leptolyngbya* (*Phormidium*) *foveolarum, Kamptonema animale* (*Oscillatoria animalis*), *Desmonostoc* (*Nostoc*) *muscorum,* and *Nostoc linckia* can detoxify and break down the organophosphate insecticides (Megharaj et al., 1994, 1987).

Acid mine drainage bioremediation using algae

Acid Mine Drainage (AMD) is considered an important source of HM pollution around the world that endangers species of plants, animals, and human life (Samal et al., 2020). Different strains of algae, especially microalgae, are used as a cost-efficient way of removing HMs these days. Some genera and species, such as *Spirulina*, *Scenedesmus*, *Chlorella*, *Cladophora*, *Anabaena*, *Oscillatoria*, *Stigeoclonium*, *Phaeodactylum tricornutum,* non-living *Caulerpa lentillifera*, *Ulothrix zonata*, and *Turbinaria ornate*, are among the hyper-accumulator and hyper-adsorbent microalgae from AMD. They also produce a lot of alkalinities, which is important during HM precipitation treatment (Apiratikul and Pavasant, 2006; Bwapwa et al., 2017; Kandasamy et al., 2021). The lifeless biomass of *Spirulina* sp. can absorb Zn (86–98%), iron (Fe) (100%), Cu (38–76%), and Pb (40–78%) and decrease the acidity of AMD by enhancing the pH, as AMD has the acidic nature (Bwapwa et al., 2017). *Stigeoclonium* spp. are freshwater algae that can thrive in mine water containing high levels of HMs, particularly Zn, and are recognized for their effectiveness in removing Zn from the environment (Pawlik-Skowrońska, 2001).

The bioremediation mechanism of algae

Algae from various species can be used to break down organic contaminants. HM removal from the environment can also be accomplished through bioremediation. It is worth mentioning that the terms bioremediation and biodegradation are increasingly interchangeable (Singh, 2019). However, biodegradation is considered a natural process in nature, while bioremediation is commonly controlled to optimize the conditions for microorganisms. This process can take a few to several months to finish and is carried out in situ or ex-situ. In-situ bioremediation includes the remediation of pollutants at the site, while ex-situ involves the removal of the pollutants in another site (Gavrilescu, 2010). Ex-situ bioremediation can be employed if the environmental conditions are unfavorable for the growth of microorgan-

Table 1. List of micro- and macroalgae used for phycoremediation of HMs

Number	Algae species	Family	Metal	References
1	*Halamphora (Amphora) subtropica* (Wachnicka & E.E.Gaiser) Rimet & R.Jahn	Amphipleuraceae	Ni	(Dahmen-Ben Moussa et al., 2018)
2	*Dolichospermum affine (Anabaena affinis)* (Lemmermann) Wacklin, L.Hoffmann & Komárek	Aphanizomenonaceae	As	(Huang et al., 2014)
3	*Anabaena cylindrica (subcylindrica)* Lemmermann	Aphanizomenonaceae	Cu, Co, Pb, Mn	(El-Sheekh et al., 2005)
4	*Trichormus (Anabaena) variabilis* (Kützing ex Bornet & Flahault) Komárek & Anagnostidis	Aphanizomenonaceae	Pb, Zn, Ca, Mn, Cr	(Abd El-Hameed et al., 2018; Ahammed et al., 2023)
5	*Ascophyllum nodosum* (Linnaeus) Le Jolis	Fucaceae	Cu, Cd, Zn, Ni, Pb	(Leusch et al., 1995; Medeiros et al., 2017)
6	*Chlamydomonas reinhardtii* P.A.Dangeard	Chlamydomonadaceae	Pb, Cd, Cu, Hg	(Bayramoğlu et al., 2006; Flouty and Estephane, 2012; Li et al., 2021; Tüzün et al., 2005)
7	*Chlorella sorokiniana* Shihira & R.W.Krauss	Chlorellaceae	Cu, Ni, Cd, Pb, Cr	(Akhtar, 2004; Akhtar et al., 2008; Husien et al., 2019; Liang et al., 2017; Petrovič and Simonič, 2016)
8	*Mychonastes homosphaera (Chlorella minutissima)*	Mychonastaceae	As, Cd, Cu, Zn, Mn, Cr	(Arora et al., 2017; Singh et al., 2012; Yang et al., 2015)

	(Skuja) Kalina & Puncochárová			
9	*Auxenochlorella (Chlorella) pyrenoidosa* (H.Chick) Molinari & Calvo-Pérez	Chlorellaceae	Mn, Cu, Zn, Pb, Cd, Cr, Ni	(Kothari et al., 2022; P.S et al., 2021; Purushanahalli Shivagangaiah et al., 2021; Zhou et al., 2012)
10	*Chlorella miniata (Kützing)* Oltmanns	Chlorellaceae	Ni, Cr	(Han et al., 2014, 2007; Wong et al., 2000)
11	*Chlorella* sp. Beyerinck [Beijerinck]	Chlorellaceae	Cr	(Shukla et al., 2012)
12	*Chlorella vulgaris* Beijerinck	Chlorellaceae	Ca, Mn, Pb, Cu, Cd, Ni, Zn, Cr, Fe	(Ahammed et al., 2023; Atoku et al., 2021; Manzoor et al., 2020)
13	*Pleurastrum (Chlorococcum) aquaticum* (P.A.Archibald) Sciuto, M.A.Wolf, Mistri & Moro	Pleurastraceae	Pb	(Liyanage et al., 2020)
14	*Chlorococcum infusionum* (Schrank) Meneghini	Chlorococcaceae	Fe, Mn	(Gomes et al., 2021)
15	*Chlorococcum* sp. Meneghini	Chlorococcaceae	Cu, Cd, As	(Qiu et al., 2006; Upadhyay et al., 2022)
16	*Cladophora vagabunda (fascicularis)* (Linnaeus) C.Hoek	Cladophoraceae	Cu, Pb, Cd	(Deng et al., 2008, 2007b, 2007a, 2006)
17	*Cladophora fracta* (O.F.Müller ex Vahl) Kützing	Cladophoraceae	Cu, Cd, Zn, Hg	(Ji et al., 2012)

18	*Cladophora glomerata* (Linnaeus) Kützing	Cladophoraceae	Cr, Zn, Cu, Pb, Cd, Co, Ni, Fe, Mn	(Çeleklı and Bulut, 2020; Khan et al., 2023; Vymazal, 1990, 1984)
19	*Cladophora parriaudii* C.Hoek	Cladophoraceae	Cu, Al, Pb, Mn	(Ross et al., 2021)
20	*Cladophora rivularis* (Linnaeus) Kuntze	Cladophoraceae	Pb	(Jafari and Senobari, 2012)
21	*Cladophora* sp. Kützing	Cladophoraceae	Pb, Cu, Cr, Cd, Zn, Ni, As	(Abioye et al., 2020; Sargın et al., 2016)
22	*Closterium lunula* Ehrenberg & Hemprich ex Ralfs	Closteriaceae	Cu	(Yan and Pan, 2002)
23	*Dunaliella salina* (bardawil) (Dunal) Teodoresco	Dunaliellaceae	Al, Cd, Cu, Cr, Fe, Zn, Mn, Ni, Pb	(Akbarzadeh and Shariati, 2014)
24	*Dunaliella* sp. Teodoresco	Dunaliellaceae	Zn, Ni	(Dahmen-Ben Moussa et al., 2018; Elleuch et al., 2021)
25	*Ecklonia radiata* (C.Agardh) J.Agardh	Lessoniaceae	Zn, Pb	(Matheickal and Yu, 1996; Zhang et al., 2022)
26	*Euglena gracilis G.A.Klebs*	Euglenaceae	Cu, Ni, As	(Tahira et al., 2019; Winters et al., 2017)
27	*Fucus distichus* ssp. Evanescens (C.Agardh) H.T.Powell	Fucaceae	Cu, Cd, Pb, Zn	(Medeiros et al., 2017)
28	*Fucus vesiculosus* Linnaeus	Fucaceae	Cu, Cd, Ni, Pb, Hg, Zn	(Brinza et al., 2020, 2009; El-Naggar et al., 2021; Henriques et al., 2017; Mata et al., 2008; V.R. et al., 2019)

29	*Gloeocapsa* sp. Kützing	Aliterellaceae	Pb	(Raungsomboon et al., 2008)
30	*Hydrodictyon reticulatum* (Linnaeus) Bory	Hydrodictyaceae	U	(Zhang and Luo, 2022)
31	*Laminaria digitata* (Hudson) J.V.Lamouroux	Laminariaceae	Cd, Cu	(Anacleto et al., 2017; Papageorgiou et al., 2008)
32	*Saccharina (Laminaria) japonica* (J.E.Areschoug) C.E.Lane, C.Mayes, Druehl & G.W.Saunders	Laminariaceae	Cd, Pb, Zn, Fe	(Ghimire et al., 2008; Luo et al., 2006; Xiao et al., 2012; Yin et al., 2001)
33	*Limnoraphis (Lyngbya) hieronymusii* (Lemmermann) J.Komárek, E.Zapomelová, J.Smarda, J.Kopecký, E.Rejmánková, J.Woodhouse, B.A.Neilan & Komárková	Microcoleaceae	Cd, Pb, Hg	(Inthorn et al., 2002)
34	*Phormidium (Lyngbya) taylorii* (Drouet & Strickland) Anagnostidis	Oscillatoriaceae	Cd, Pb, Ni, Zn	(Klimmek et al., 2001)
35	*Micrasterias denticulata* Brébisson ex Ralfs	Desmidiaceae	Cr	(Volland et al., 2012)
36	*Microcystis aeruginosa* (Kützing) Kützing	Microcystaceae	Pb, Cu, Zn, Cd, Ni, Hg, As	(Chen et al., 2005; Deng et al., 2020; Huang et al., 2014; Pradhan and Rai, 2001; Rzymski et al., 2014; Zeng et al., 2022)
37	*Nostoc commune* Vaucher ex Bornet & Flahault	Nostocaceae	Cu, Cd, Fe, Ni, Pb, Zn	(Atoku et al., 2021; Morsy et al., 2011)

38	*Desmonostoc (Nostoc) muscorum* (Bornet & Flahault) Hrouzek & S.Ventura	Nostocaceae	Pb, Cu, Co, Mn, Zn, Cd	(Abd El-Hameed et al., 2018; Dixit and Singh, 2014; El-Hameed et al., 2021; El-Sheekh et al., 2005; Hazarika et al., 2015; Roy et al., 2015)
39	*Nostoc* sp. Vaucher ex Bornet & Flahault	Nostocaceae	Pb, Cu, Cd, Zn, Ni	(Ahad et al., 2021; Rakic et al., 2023)
40	*Oedogonium hatei* N.D.Kamat	Oedogoniaceae	Cr, Ni	(Gupta et al., 2010; Gupta and Rastogi, 2009)
41	*Oedogonium rivulare* A.Braun ex Hirn	Oedogoniaceae	Cu, Cr, Pb, Cd, Co , Ni, Zn, Fe, Mn	(Vymazal, 1984)
42	*Oedogonium* sp. Link ex Hirn	Oedogoniaceae	Cr, Cu, Co, Fe, Hg, Ni, Zn, U	(Bakatula et al., 2014; Rai et al., 2008)
43	*Oocystis* sp. Nägeli ex A.Braun	Oocystaceae	Cd, Ni, Pb	(Karaca, 2008)
44	*Jaaginema angustissimum (Oscillatoria angustissima)* (West & G.S.West) Anagnostidis & Komárek	Synechococcales familia incertae sedis	Zn	(Ahuja et al., 1999)
45	*Jaaginema quadripunctulatum (Oscillatoria quadripunctulata)* (Brühl & Biswas) Anagnostidis & Komárek	Synechococcales familia incertae sedis	Cu, Pb, Co, Zn	(Ajayan et al., 2011)
46	*Oscillatoria limosa* C.Agardh ex Gomont	Oscillatoriaceae	Cu, Cd, Fe, Zn, Ni, Pb	(Atoku et al., 2021)

47	*Phormidium nigrum (Oscillatoria nigra)* (Vaucher ex Gomont) Anagnostidis & Komárek	Oscillatoriaceae	Cr, Fe, Ni	(Rai et al., 2008)
48	*Oscillatoria* sp. Vaucher ex Gomont	Oscillatoriaceae	Cd, Cr, Ca	(Bon et al., 2021; Jayashree et al., 2012; Mathimani et al., 2024; Shukla et al., 2012)
49	*Oscillatoria tenuis* C.Agardh ex Gomont	Oscillatoriaceae	As	(Huang et al., 2014)
50	*Padina* sp. Adanson	Dictyotaceae	U	(Khani, 2011)
51	*Parachlorella kessleri* (Fott & Nováková) Krienitz, E.H.Hegewald, Hepperle, V.Huss, T.Rohr & M.Wolf	Chlorellaceae	Cd, Cr	(Bauenova et al., 2021)
52	*Phormidium bohneri* Schmidle	Oscillatoriaceae	Cr, Fe, Ni	(Rai et al., 2008)
53	*Phormidium* sp. Kützing ex Gomont	Oscillatoriaceae	Cr, Ca	(Mathimani et al., 2024; Shukla et al., 2012)
54	*Pylaiella littoralis* (Linnaeus) Kjellman	Acinetosporaceae	Fe, Cu, Co, Cd, Cr, Zn, Al	(Carrilho and Gilbert, 2000)
55	*Tetraselmis (Platymonas) subcordiformis* (Wille) Butcher	Chlorodendraceae	Sr	(Mei et al., 2006)
56	*Porphyridium purpureum (cruentum)* (Bory) K.M.Drew & R.Ross	Porphyridiaceae	Cu, Cd, Cr, Pb, Hg, Ni	(Karaca, 2008; Soeprobowati and Hariyati, 2013; Zaib et al., 2016)
57	*Sargassum filipendula* C.Agardh	Sargassaceae	Cu, Cr, Cd, Ni, Pb, Zn, Ag, Fe, Mn	(Cardoso et al., 2016; Davis et al., 2000; Seepersaud et

				al., 2018; Verma et al., 2018, 2016)
58	*Sargassum fluitans* (Børgesen) Børgesen	Sargassaceae	Cd, Pb, Cu, Zn, Ni	(Fourest and Volesky, 1996; Kratochvil et al., 1995; Leusch et al., 1995; López-Miranda et al., 2020)
59	*Sargassum natans* (Linnaeus) Gaillon	Sargassaceae	Pb	(López-Miranda et al., 2020)
60	*Sargassum* sp. C.Agardh	Sargassaceae	Cd, Zn	(Esteves et al., 2000; Mahmood et al., 2017)
61	*Sargassum vulgare* C.Agardh	Sargassaceae	Cu, Cd, Zn, Pb, Ni, Mn, Fe	(Seepersaud et al., 2018)
62	*Tetradesmus obliquus (Scenedesmus acutus)* (Turpin) M.J.Wynne	Scenedesmaceae	Cd, Cu, Zn, Cr, Pb	(Alayi et al., 2021; Monteiro et al., 2011, 2009; Omar, 2002; P.S et al., 2021; Purushanahalli Shivagangaiah et al., 2021; Zhang et al., 2016; Zhou et al., 2012)
63	*Desmodesmus (Scenedesmus) protuberans* (F.E.Fritsch & M.F.Rich) E.Hegewald	Scenedesmaceae	Cd, Pb, Ni	(Karaca, 2008)
64	*Desmodesmus communis (Scenedesmus quadricauda)* (E.Hegewald) E.Hegewald	Scenedesmaceae	Zn, Cr, Cu, Pb	(Kafil et al., 2022; Omar, 2002)

65	*Scenedesmus* sp. Meyen	Scenedesmaceae	As, Fe, Zn	(Ajayan et al., 2015; Arora et al., 2017; Bte Jais et al., 2015)
66	*Spirogyra hyalina* Cleve	Spirogyraceae	Cd, Hg, Pb, As, Co	(Kumar and Oommen, 2012)
67	*Spirogyra* sp. Link	Spirogyraceae	Fe, Cr, Cu, Ni, As, Cd, Pb, Mn, Se, Zn	(Abioye et al., 2020; Mane and Bhosle, 2012; Rai et al., 2008)
68	*Limnospira (Spirulina) platensis* (Gomont) K.R.S.Santos & Hentschke	Microcoleaceae	Cd, Cr, Cu, Co, Ni, Pb, Al, Fe, Zn, Sr, Ba	(Balaji et al., 2015, 2014; Diaconu et al., 2023; Kumar et al., 2020; Rangsayatorn et al., 2002; Zinicovscaia et al., 2018)
69	*Limnospira (Arthrospira) indica* (Desikachary & Jeeji-bai) Nowicka- Krawczyk, Mühlsteinová & Hauer	Microcoleaceae	Pb, Cr, Cd	(Balaji et al., 2014)
70	*Limnospira (Arthrospira) maxima* (Setchell & N.L.Gardner) Nowicka-Krawczyk, Mühlsteinová & Hauer	Microcoleaceae	Pb, Cr, Cd	(Balaji et al., 2014)
71	*Spirulina* sp. Turpin ex Gomont	Spirulinaceae	Cr, Cd, Pb,Mn, Se, Fe, Cu, Zn	(Hernández and Olguín, 2002; Mane and Bhosle, 2012)
72	*Synechococcus elongatus* (Nägeli) Nägeli	Synechococcaceae	Fe, Mn	(Gomes et al., 2021)
73	*Tetradesmus (Scenedesmus) incrassatulus* (Bohlin) M.J.Wynne	Scenedesmaceae	Cr, Cd, Cu	(Alayi et al., 2021; Peña-Castro et al., 2004)

74	*Tetraselmis indica* Arora & Anil	Chlorodendraceae	Mn, Pb, Al, Ca, Cd, Cu	(Amit et al., 2017)
75	*Trichormus variabilis* (Kützing ex Bornet & Flahault) Komárek & Anagnostidis	Aphanizomenonaceae	Cd	(El-Hameed et al., 2021)
76	*Ulothrix* sp. Kützing	Ulotrichaceae	Ni	(Rai et al., 2008)
77	*Ulva lactuca* Linnaeus	Ulvaceae	Cd, Cu, Cr, Fe, Zn, Mn, Ni, Pb	(Mofeed, 2017)
78	*Vaucheria cruciata (debaryana)* (Vaucher) De Candolle	Vaucheriaceae	Cd, Pb	(Khan et al., 2023)

isms (Alori et al., 2022). It usually included biological augmentation (bioaugmentation), during which some selected strains of microorganisms are added to the process to accelerate the breakdown of a pollutant (Herrero and Stuckey, 2015).

Algae species take the HMs by biosorption and bioaccumulation (Singhal et al., 2021). During biosorption, certain living/non-living microorganisms or biomass can passively concentrate and bind pollutants onto their cellular structure through the physiochemical process and immobilize them (Volesky and Holan, 1995). In other words, biosorption is the term used to describe the capacity of biological materials to ingest HMs physically or chemically from wastewater (Fard et al., 2011). While bioaccumulation is carried out in the following stages of biosorption and involves living organisms (Hlihor et al., 2017). Bioaccumulation and biosorption are subcategories of bioremediation. During biosorption, metals are retained through interactions with functional groups on the cell surface (*e.g.*, adsorption, ion exchange). This process can be affected by variables, including ionic strength, environmental acidity, biomass concentration, temperature, particle size, and other ions (Pagnanelli et al., 2003; Vilar et al., 2005). It can occur with both living and non-living biomass, as it does not depend on cell metabolism. In contrast, bioaccumulation involves both intra- and extracellular processes. Therefore, only live biomass can perform bioaccumulation (Coelho et al., 2015). Algae species often filter nutrients, heavy metals (depending on the species), and other minerals from wastewater through a combination of biosorption and their ability to absorb, adsorb, and bioaccumulate. Since these species need nutrients to grow, algae growth occurs as these elements are removed from wastewater. Some are absorbed by outer cells, while others are absorbed by inner cells (Bwapwa et al., 2017) (Fig. 2).

Most algae species (*e.g.*, *Euglena* sp., *Scenedesmus* sp., *Oscillatoria* sp., *Chlorel-*

la sp.) absorb contaminants and immobilize them within their cell structure; these microalgae biomass can later be used as energy-enriched biomass for biofuel generation (Kandasamy et al., 2021).

In some strains, HMs or other nutrients with positive charges are clasped negatively charged groups (*e.g.*, —OH/ hydroxyl, —COOH/ carboxyl, —SH/ sulphydryl, —NH_2/ amino, —PO_3H_2/ phosphoryl) on the surface layer of the cell wall (adsorption) (Spain et al., 2021). While in several microalgae, these pollutants are taken into the algae cell (absorption) (Gündoğdu and Türk Çulha, 2023). These algae accumulate HMs in their intercellular regions or their vacuoles (Torres, 2016). *Spirogyra* algal species had a removal efficiency of 20 mg/L Cu (II) (58-85%) at 30 minutes (Bishnoi et al., 2004). *Cladophora glomerata* and *Oedogonium rivulare* are among the species with the ability to remove Co, Pb, Ni, Mn, Cd, Cr, Cu, and Fe from contaminated water (Vymazal, 1984). *Ulothrix zonata* and *Turbinaria ornata* are also considered great adsorbents of HMs (Nuhoglu et al., 2002; Vijayaraghavan et al., 2005).

Factors affecting phycoremediation

Algae can remove HMs in a variety of ways. This process depends on the metal type, taxon, pH, light, and temperature (Mehta and Gaur, 2005; Novis and Harding, 2007). As algae are sensitive to light and temperature, the efficiency of phycoremediation can also be affected through different seasons. For example, the best time to remove HM sand contamination by algae is variable depending on the season (Brake et al., 2004; Elbaz-Poulichet, 2000). The strain of algae is also important in the process of phycoremediation. Some strains are more resistant to pollutants and have a higher ability to detoxify the HMs. An ecological study of soil in polluted sites with insecticides shows the replacement of sensitive species with resistant species (Megharaj et al., 1999). As previously mentioned, the non-living biomass of microalgae has the ability to adsorb pol-

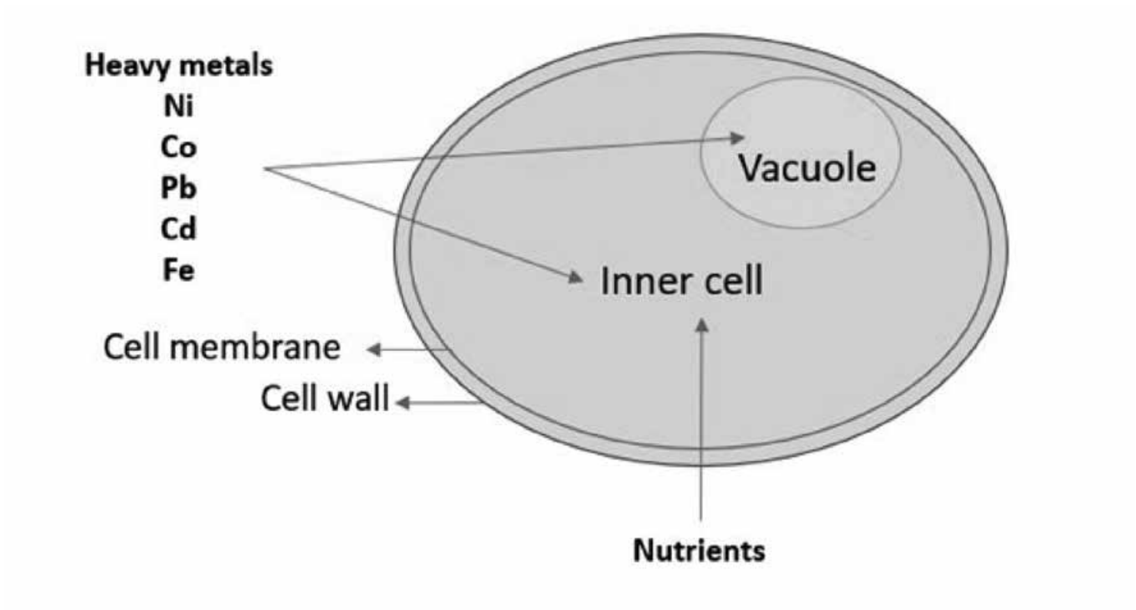

Fig. 2. A microalgae cell's absorption and adsorption scheme (modified from Kaplan, 2013)

lutants. It was revealed that the biomass of non-living algae adsorbs a higher amount of metals than that of living algae (Mehta and Gaur, 2005).

Methods to increase the efficiency of HM remediation by algae

To increase the efficiency of phycoremediation, some modern technologies have been developed in recent years. Chemical and molecular techniques are among the methods being used in this regard to manage algae to boost their productivity.

Transgenic algae to improve bioremediation

Genetic engineering for algae gene editing and gene silencing benefits various technologies and tools such as reporter genes, Cre-lox recombination, and CRISPR-Cas systems, modular cloning toolkits, regulatory elements, promoters, and vectors, restriction enzymes, and post-transcriptional gene silencing (PTGS) technologies (Fajardo et al., 2020). Data required for finding the appropriate genes to manipulate genetically is supplied by multi-omics approaches, including data of proteomics, transcriptomics, genomics, interactomics, and metabolomics, for various strains of algae, and is freely accessible on different online platforms (Ranjbar and Malcata, 2022)due to accelerated anthropogenic activities, and is nowadays, a matter of serious global concern. Removal of such inorganic pollutants from aquatic environments via biological processes has earned great popularity, for its cost-effectiveness and high efficiency, compared to conventional physicochemical methods. Among candidate organisms, microalgae offer several competitive advantages; phycoremediation has even been claimed as the next generation of wastewater treatment technologies. Furthermore, integration of microalgae-mediated wastewater treatment and bioenergy production adds favorably to the economic feasibility of the former process—with energy security coming along with environmental sustainability. However, poor biomass productivity under abiotic stress conditions has hindered the large-scale deployment of microalgae. Recent advances encompassing molecular tools for genome editing, together with the advent of multiomics technologies and computational approaches, have permitted the design of tailor-made microalgal cell factories, which encompass multiple beneficial traits, while circumventing those associated with the bioaccumulation of unfavorable chemicals. Previous studies unfolded several routes through which genetic engineering-mediated improvements appear feasible (encompassing sequestration/uptake capacity and specificity for heavy metals.

Transporters of HMs in algae cell membranes are important options in genetic engineering. These membrane proteins, which are responsible for the transportation and tolerance of metals, basically Co, Cd, Fe, Ni, Mn, and Zn, are known as metal-tolerance proteins (MTP) (Ram et al., 2019). Some species of microalgae, including *Microcystis aeruginosa*, *Spirulina* sp., *Synechococcus* sp., *Nostoc* sp., *Anabaena flos-aquae*, and *Fischerella,* carry MTP genes. These genes, which are involved in the regulation of metal ion storage, are expressed in response to higher concentrations of HMs like Cu (Kandasamy et al., 2021). Different families of MTP genes are known in *Chlamydomonas*. More than eleven gene families are responsible for encoding the metal ion transporters (Rajamani et al., 2007). Upregulation of *CRMTP4*, which encodes the metal transporter, enhances the tolerance of *Chlamydomonas reinhardtii* to the toxicity of Cd; these microalgae strains with upregulated *CRMTP4* had 2.81-3.06 times higher ability in bioaccumulation of Cd in comparison to wild *Chlamydomonas reinhardtii* (Ibuot et al., 2017).

However, the authors indicated that wastewater-adapted strains, *Parachlorella kessleri*, *Parachlorella hussii*, and *Jaagichlorella* (*Chlorella*) *luteoviridis*, had also higher tolerance to Cd, Zn, Al, and Cu than the wild strain of *Chlamydomonas reinhardtii*. These three microalgae also revealed higher tolerance and bioaccumulation of Cd than the upregulated *CRMTP4 Chlamydomonas reinhardtii*. This indicated clearly that the mechanisms of adapted strains, which can be attributed to their oxidative stress tolerance and upregulation of several genes, overcome the upregulation of a single MTP gene (Ibuot et al., 2017), and therefore, producing transgenic microalgae with multi-metal tolerance and absorption should be prioritized in genetic engineering of algae.

In *Auxenochlorella protothecoides*, high expression of metal transporter genes, the Nramp family, has been shown under Cd stress (Lu et al., 2019). These genes also play a role in Cd tolerance of *Chlamydomonas acidophila* (Puente-Sánchez et al., 2018). In *Chlamydomonas reinhardtii*, a member of the Nramp family, *DMT1*, is responsible for the transportation of Cd, Cu, Fe, and Mn (Rosakis and Köster, 2005). Moreover, it seems that *MTP1* in *Chlamydomonas reinhardtii* encodes the vacuolar membrane protein which plays a critical role in detoxification of Cd and homeostasis of Zn (Blaby-Haas and Merchant, 2012). Phosphate transporters in *Microcystis aeruginosa* play a role in accumulation of arsenate (As) due to similar chemical structure of organic phosphate and As, lead to indiscrimination between these two elements (Wang et al., 2019).

Expression of *acr3* gene, which encodes protein ACR3 present in vacuole membrane of *Pteris vittata* and involved in bioaccumulation of As, in *Chlamydomonas reinhardtii* resulted in 1.5-3 times enhancement of As accumulation; the ability of this recombinant strain in bioaccumulation of As was even higher in environment with reduced phosphate (Ramírez-Rodríguez et al., 2019). Microalga *Euglena gracilis* exposed to Cd, Hg, and Pb revealed an enhancement in membrane transporter Major Facilitator Superfamily, P(1B)-type ATPases, Cd/Zn-transporting ATPase, as well as proteins participating in microalgae stress response and thiol-rich proteins which play an important role in metal chelation, at proteome level (Khatiwada et al., 2020). Cell surface engineering can also be employed to enhance the algae-based bioremediation of HMs. Transgenic *Chlamydomonas reinhardtii* due to plasma membrane-anchored metallothionein polymer expression revealed enhanced capacityfor Hg (II) binding compared to wild strains (He et al., 2011).

It has also been shown that microalgae under HM stress upregulate particular HM-binding organic molecules in order to reduce the HM toxicity through the formation of chelated forms (Balzano et al., 2020). Transformed *Chlamydomonas reinhardtii* with increased synthesis of cysteine (*HAL2* gene) revealed 5-times enhancement in metal binding capacity (Rajamani et al., 2007; Ranjbar and Malcata, 2022)due to accelerated anthropogenic activities, and is nowadays, a matter of serious global concern. Removal of such inorganic pollutants from aquatic environments via biological processes has earned great popularity, for its cost-effectiveness and high efficiency, compared to conventional physicochemical methods. Among candidate organisms, microalgae offer several competitive advantages; phycoremediation has even been claimed as the next generation of wastewater treatment technologies. Furthermore, integration of microalgae-mediated wastewater treatment and bioenergy production adds favorably to the economic feasibility of the former process—with energy security coming along with environmental sustainability. However, poor biomass productivity under abiotic stress conditions has hindered the large-scale deployment of microalgae. Recent advances encompassing molecular tools for genome editing, together with the advent of multiomics technologies and computational approaches, have permitted the design of tailor-made microalgal cell factories, which encompass multiple beneficial traits, while circumventing those associated with the bioaccumulation of unfavorable chemicals. Previous studies unfolded several routes through which genetic engineering-mediated improvements appear feasible (encompassing sequestration/uptake capacity and specificity for heavy metals. Moreover, the engineering of microalgae to enhance the activity of particular enzymes to tolerate HM can be effective. For example, in *Chlorella vulgaris* chromate reductase play a role in the reducing toxic of Cr (VI) to the less dangerous trivalent chromium (Cr (III)). Therefore, it enhances the tolerance of microalgae cells against Cr toxicity (Yen et al., 2017).

Biochar addition for optimizing the phycoremediation

As biochar is enriched with nutritional components, a combination of biochar made from plant biomass with microalgae could aid in the cleanup of HMs and other hazardous materials. Microalgae may use biochar nutrients to boost their biomass. The bioremediation process is carried out simultaneously by biochar and metal-tolerant algae. This promising and long-term technique could result in more efficient phycoremediation with energy-containing biomass of microalgae. With the appropriate energy conversion method, this energy-enriched biomass of microalgae is able to generate a greater volume of ethanol (Anae et al., 2021).

Biogenic nanomaterials generated from algae

Biogenic nanoparticles are those that are produced using biological organisms. Biologically produced nanoparticles have emerged as a viable substitute for chemically synthesized nanoparticles due to their nontoxicity. Several biogenic nanoparticles have been produced in recent years with possible applications in medicine and environmental cleanup. Biogenic nanoparticles like palladium nanocrystals, nano-magnets, biogenic manganese oxide (BioMnOx), and biogenic iron species have been shown to be successful at removing a variety of micropollutants, HMs, refractory pollutants, and halogenated chemicals. Nano-bioremediation has the potential to be a more effective, safer, environmentally friendly, and cost-efficient technology, with a significant long-term impact on the field of environmental remediation (Kumari et al., 2019).

Algal nanocomposites reveal novel materials that mix algae-based polymers with nanoparticles. One of the main applications of these nanocomposites is in the remediation of wastewater. The application of alginate, derived from algae, as the base material in wastewater treatment is a green alternative to conventional fossil-fuel-based treatment methods (Lakshmi et al., 2023). Researchers have developed a *Fucus vesiculosus*-based sorbent for the effective removal of HMs, including Pb (II), Cd (II), Cu (II), and Zn (II) from polluted waters (Demey et al., 2018). Moreover, the ability of algal-made nanocomposites for the removal of Cr (VI) and iron compounds has been approved (Wu et al., 2018). In another research, a higher ability of *Sargassum glaucescens* and chitosan/polyvinyl alcohol (PVA) nano-fiber membrane at pH 6 for biosorption of Ni in a continuous system has been shown (Esmaeili and Aghababai Beni, 2018). The world nanomaterials market, including algal nanocomposites, reached 10.88 billion US dollars in 2022 and is projected to show a 14.8% growth by 2030 (Yuan et al., 2023).

Algae and bacterial consortia

Microalgae combine with other aerobic or anaerobic microorganisms to form a microbial community. Compared with a single microorganism, a combination of algae and bacteria can work together to eliminate organic and inorganic pollutants. The combined use of microalgae and bacteria can be complementary and synergistic to obtain better pollutant degradation efficiency (Fu and Secundo, 2016). For instance, consortia of algae and bacteria mix revealed a significant removal rate of 92.6% for 1,2-dichloroethane from the petroleum industry (Alhajeri et al., 2024). On the one hand, algae photosynthesis produces oxygen, which is a key electron acceptor for heterotrophic bacteria to break down pollutants into organic matter. On the other side, bacteria provide carbon dioxide and other stimulating media to support the photosynthetic autotrophic growth of their partners (Subashchandrabose et al., 2011). The mixing of different strains, *i.e.*, algae-bacteria, can produce a synergistic effect, and the microbial population usually acts more effectively than a single strain or species. Some advantages of co-cultivation are the robustness to environmental fluctuations, the stability of the limbs, the ability to survive periods of nutrient limitation, to share metabolites, and resistance against other species. The self-oxidation of these natural systems that have been tested is beneficially used to remediate many pollutants (Muñoz and Guieysse, 2006). Compared with traditional engineering technology, it is more economically and technologically superior (Subashchandrabose et al., 2013). Contemporary molecular technology, combined with the careful selection of specific members of the microbial community, will enable the creation of autonomous systems that serve the dual purpose of contaminant removal and metabolite production.

The bacteria-algae complex is effective in dealing with harmful pollutants, and their efficiency in the bioremediation of HMs has been established (Boivin et al., 2007). The normal growth and metabolism of algae require small amounts of various metals, but higher levels of the same metals are toxic. In this way, algae communities in symbiotic interactions can absorb and detoxify the metals. The process of detoxification involves physical or chemical adsorption, active absorption into the cell for a small amount, covalent bonding, ion exchange, surface precipitation, redox reaction, or cell surface crystallization (Muñoz and Guieysse, 2006; Subashchandrabose et al., 2013). Besides the HMs, the mentioned methods can be used by microalgae to degrade organic contaminants such as black oil, naphthalene, acetonitrile, phenol, thiocyanate, benzopyrene, azo compounds (Mahdavi et al., 2015; Muñoz and Guieysse, 2006; Ryu et al., 2015; Subashchandrabose et al., 2013), and toxic pesticides including methion, quinophos, methyl parathion, DDT, atrazine, and α-endosulfan (Subashchandrabose et al., 2013, 2011).

Compared with individual microorganisms, microalgae and bacterial consortia can effectively detoxify inorganic and organic contaminants and remove nutrients from wastewater. The resource competition and pollutant reduction cooperation between the two microbial associations will determine the success of the consortium project while harnessing the biotechnology potential of the partners (Subashchandrabose et al., 2011).

Conclusion and perspectives

Bioremediation of polluted environments has attracted much attention during the last decades. As it is considered an eco-friendly and cost-effective method of treating contaminated water and soil, it has some advantages over other known existing techniques. Microalgae with an excessive tolerance to HMs and a high capacity for metal ion binding are the best accumulators of metals. Algae species such as Chlorella, Spirulina, Spirogyra, Scenedesmus, and many others are applied for the disposal of Cr, Cu, Ni, Cd, Hg, Sp, Pb, and other HM ions. Although using algae for bioremediation of HMs could encounter some problems, such as poor adaptability of exogenous microalgae with contaminated sites, and is affected by the intensity of light, operation time, and temperature, yet using various techniques, including ex-situ bioremediation and bioaugmentation, can help to manage these limitations. Moreover, some new methods and technologies have been employed to enhance the efficiency of phycoremediation. Biochar addition, applying genetically engineered and transgenic microalgae with MTP genes, and consortia of microalgae together or with other microorganisms, are among the new techniques that are rapidly growing to provide a greener world.

In spite of numerous advantages, some novel techniques encounter challenges, including scaling up. Most phycoremediation processes employing genetically engineered algae are still confined to laboratory settings (Pradhan et al., 2022). The main limitations include low product yields and high cultivation costs (Wang et al., 2024). In order to address these challenges, it is necessary for future studies to focus on the expansion and development of universal cloning toolkits and rapid expression kits, which enable gene editing tools to be applicable to a broad range of microalgae (Webster et al., 2024).

Algae-bacteria consortia have a notable advantage over other monoculture techniques in resistance to contamination (Naseema Rasheed et al., 2023). This feature makes them suitable for application in open ponds (Su et al., 2022). Moreover, the partnership offers practical benefits in harvesting the biomass due to enhanced flocculation efficiency when certain strains of bacteria are co-cultured with algae (Ravindran et al., 2016). Recent developments have focused on creating optimized consortia through careful selection of species and engineering. It has been shown that identification of the most effective combination, with some engineered consortia, achieves over 90% removal for various pollutants (Cai et al., 2024). These systems not only perform better in terms of pollutant removal but also generate valuable biomass that can be used for various applications (Navarro and Caipang, 2024; Torres et al., 2024).

The implementation of advanced algal bioremediation techniques remains primarily in developmental stages, with most successful applications in controlled conditions. A key challenge in scaling up these technologies is a requirement for a better understanding of how microalgae-microalgae or microalgae-bacteria co-culture perform in open systems over a long time (Al-Jabri et al., 2020). The future success of these applications will depend on continued research to optimize performance and validate long-term effectiveness, particularly in outdoor conditions where environmental factors can significantly impact system performance (Al-Jabri et al., 2020). Natural symbiotic relationships between algae and native microorganisms show promise, particularly for water treatment applications, as these partnerships can effectively utilize carbon dioxide and minerals while producing oxygen without generating waste products (Touliabah et al., 2022). In Iran, there is inadequate information about the implementation of these methods. However, these approaches could be applicable in local environments.

References

Abd El-Hameed, M.M., Abuarab, M.E., Mottaleb, S.A., El-Bahbohy, R.M. and Bakeer, G.A., 2018. Comparative studies on growth and Pb (II) removal from aqueous solution by *Nostoc muscorum* and *Anabaena variabilis*. *Ecotoxicology and Environmental Safety*, *165*, pp.637-644. DOI: https://doi.org/10.1016/j.ecoenv.2018.08.103

Abioye, O.P., Ezugwu, B.U., Aransiola, S.A. and Ojeba, M.I., 2020. Phycoremediation of water contaminated with arsenic (As), cadmium (Cd) and lead (Pb) from a mining site in Minna, Nigeria. *European Journal of Biological Research*, *10*(1), pp.35-44.

Ahad, R.I.A., Ahad, R.I.A., Syiem, M.B. and Rai, A.N., 2021. Cd (II) sorption by *Nostoc* sp. JRD1: Kinetic, thermodynamic, and isotherm studies. *Environmental Technology & Innovation*, *21*, p.101283.

Ahammed, M.S., Baten, M.A., Ali, M.A., Mahmud, S., Islam, M.S., Thapa, B. Sen, Islam, M.A., Miah, M.A. and Tusher, T.R., 2023. Comparative evaluation of *Chlorella vulgaris* and *Anabaena variabilis* for phycoremediation of polluted river water: Spotlighting heavy metals detoxification. *Biology (Basel), 12,* p. 675. DOI: https://doi.org/10.3390/biology12050675

Ahmad, W., Alharthy, R.D., Zubair, M., Ahmed, M., Hameed, A. and Rafique, S., 2021. Toxic and heavy metals contamination assessment in soil and water to evaluate human health risk. *Scientific Reports*, *11*(1), p.17006. DOI: https://doi.org/10.1038/s41598-021-94616-4

Ahuja, P., Gupta, R. and Saxena, R.K., 1999. Zn^{2+} biosorption by Oscillatoria anguistissima. *Process Biochemistry*, *34*(1), pp.77-85. DOI: https://doi.org/10.1016/S0032-9592(98)00072-7

Ajayan, K.V., Selvaraju, M. and Thirugnanamoorthy, K., 2011. Growth and heavy metals accumulation potential of microalgae grown in sewage wastewater and petrochemical effluents. *Pakistan Journal of Biological Sciences*, *14*(16), p.805. DOI: https://doi.org/10.3923/pjbs.2011.805.811

Ajayan, K.V., Selvaraju, M., Unnikannan, P. and Sruthi, P., 2015. Phycoremediation of tannery wastewater using microalgae Scenedesmus species. *International Journal of Phytoremediation*, *17*(10), pp.907-916. DOI: https://doi.org/10.1080/15226514.2014.989313

Akbarzadeh, N. and Shariati, M., 2014. Aluminum remediation from medium by *Dunaliella*. *Ecological Engineering*, *67*, pp.76-79. DOI: https://doi.org/10.1016/j.ecoleng.2014.03.014

Akhtar, N., 2004. Removal and recovery of nickel(II) from aqueous solution by loofa sponge-immobilized biomass of *Chlorella sorokiniana*: characterization studies. *Journal of Hazardous Materials, 108,* pp.85-94. DOI: https://doi.org/10.1016/j.jhazmat.2004.01.002

Akhtar, N., Iqbal, J. and Iqbal, M., 2004. Removal and recovery of nickel (II) from aqueous solution by loofa sponge-immobilized biomass of *Chlorella sorokiniana*: characterization studies. *Journal of hazardous materials*, *108*(1-2), pp.85-94. DOI: https://doi.org/10.1016/S1001-0742(08)60036-4

Al-Jabri, H., Das, P., Khan, S., Thaher, M. and AbdulQuadir, M., 2020. Treatment of wastewaters by microalgae and the potential applications of the produced biomass—a review. *Water*, *13*(1), p.27. DOI: https://doi.org/10.3390/w13010027

Alayi, M., Mohammadi, A., Mashhadi, H. and Mahmoudnia, F., 2021. Investigating the capability of chromium heavy metal removal and biodiesel production by three species of algae: *Scenedesmus acutus*, *Scenedesmus incrass atulus*, *Scenedesmus obliquus*. *Annals of the Romanian Society for Cell Biology, 25,* pp.21127-21138.

Alengebawy, A., Abdelkhalek, S.T., Qureshi, S.R. and Wang, M.-Q., 2021. Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics, 9,* p.42. DOI: https://doi.org/10.3390/toxics9030042

Alhajeri, N.S., Tawfik, A., Elsamadony, M., Al-Fadhli, F.M. and Meng, F., 2024. Synergistic algal/bacterial interaction in membrane bioreactor for detoxification of 1,2-dichloroethane-rich petroleum wastewater. *Journal of Hazardous Materials, 470,* p.134125. DOI: https://doi.org/10.1016/j.jhazmat.2024.134125

Alori, E.T., Gabasawa, A.I., Elenwo, C.E. and Agbeyegbe, O.O., 2022. Bioremediation techniques as affected by limiting factors in soil environment. *Frontiers in Soil Science, 2*. DOI: https://doi.org/10.3389/fsoil.2022.937186

Amit, Chandra, R., Ghosh, U.K. and Nayak, J.K., 2017. Phycoremediation potential of marine microalga *Tetraselmis indica* on secondary treated domestic sewage for nutrient removal and biodiesel production. *Environmental Science and Pollution Research, 24,* pp.20868-20875. DOI: https://doi.org/10.1007/s11356-017-9734-6

Anacleto, P., van den Heuvel, F.H.M., Oliveira, C., Rasmussen, R.R., Fernandes, J.O., Sloth, J.J., Barbosa, V., Alves, R.N., Marques, A. and Cunha, S.C., 2017. Exploration of the phycoremediation potential of *Laminaria digitata* towards diflubenzuron, lindane, copper and cadmium in a multitrophic pilot-scale experiment. *Food and Chemical Toxicology, 104,* pp.95-108. DOI: https://doi.org/10.1016/j.fct.2017.01.030

Anae, J., Ahmad, N., Kumar, V., Thakur, V.K., Gutierrez, T., Yang, X.J., Cai, C., Yang, Z. and Coulon, F., 2021. Recent advances in biochar engineering for soil contaminated with complex chemical mixtures: Remediation strategies and future perspectives. *Science of the Total Environment, 767,* p.144351. DOI: https://doi.org/10.1016/j.scitotenv.2020.144351

Apiratikul, R. and Pavasant, P., 2006. Sorption isotherm model for binary component sorption of copper, cadmium, and lead ions using dried green macroalga, *Caulerpa lentillifera*. *Chemical Engineering Journal, 119,* pp.135-145. DOI: https://doi.org/10.1016/j.cej.2006.02.010

Arora, N., Gulati, K., Patel, A., Pruthi, P.A., Poluri, K.M. and Pruthi, V., 2017. A hybrid approach integrating arsenic detoxification with biodiesel production using oleaginous microalgae. *Algal Research, 24,* pp.29-39. DOI: https://doi.org/10.1016/j.algal.2017.03.012

Atoku, D.I., Ojekunle, O.Z., Taiwo, A.M. and Shittu, O.B., 2021. Evaluating the efficiency of *Nostoc commune*, *Oscillatoria limosa* and *Chlorella vulgaris* in a phycoremediation of heavy metals contaminated industrial wastewater. *Scientific African, 12,* p.e00817. DOI: https://doi.org/10.1016/j.sciaf.2021.e00817

Bakatula, E.N., Cukrowska, E.M., Weiersbye, I.M., Mihaly-Cozmuta, L., Peter, A. and Tutu, H., 2014. Biosorption of trace elements from aqueous systems in gold mining sites by the filamentous green algae (*Oedogonium* sp.). *Journal of Geochemical Exploration, 144,* pp.492-503. DOI: https://doi.org/10.1016/j.gexplo.2014.02.017

Bala, S., Garg, D., Thirumalesh, B.V., Sharma, M., Sridhar, K., Inbaraj, B.S. and Tripathi, M., 2022. Recent strategies for bioremediation of emerging pollutants: A review for a green and sustainable environment. *Toxics, 10,* p.484. DOI: https://doi.org/10.3390/toxics10080484

Balaji, S., Kalaivani, T., Rajasekaran, C., Shalini, M., Siva, R., Singh, R.K. and Akthar, M.A., 2014. *Arthrospira* (*Spirulina*) species as bioadsorbents for lead, chromium, and cadmium – a comparative study. *CLEAN – Soil, Air, Water, 42,* pp.1790-1797. DOI: https://doi.org/10.1002/clen.201300478

Balaji, S., Kalaivani, T., Rajasekaran, C., Siva, R., Shalini, M., Das, R., Madnokar, V. and Dhamorikar, P., 2015. Bioremediation potential of *Arthrospira platensis* (*Spirulina*) against chromium(VI). *CLEAN – Soil, Air, Water, 43,* pp.1018-1024. DOI: https://doi.org/10.1002/clen.201400133

Balzano, S., Sardo, A., Blasio, M., Chahine, T.B., Dell'Anno, F., Sansone, C. and Brunet, C., 2020. Microalgal metallothioneins and phytochelatins and their potential use in bioremediation. *Frontiers in Microbiology*, *11*, p.517. DOI: https://doi.org/10.3389/fmicb.2020.00517

Bauenova, M.O., Sadvakasova, A.K., Mustapayeva, Z.O., Kokociński, M., Zayadan, B.K., Wojciechowicz, M.K., Balouch, H., Akmukhanova, N.R., Alwasel, S. and Allakhverdiev, S.I., 2021. Potential of microalgae *Parachlorella kessleri* Bh-2 as bioremediation agent of heavy metals cadmium and chromium. *Algal Research, 59,* p.102463. DOI: https://doi.org/10.1016/j.algal.2021.102463

Bayramoğlu, G., Tuzun, I., Celik, G., Yilmaz, M. and Arica, M.Y., 2006. Biosorption of mercury(II), cadmium(II) and lead(II) ions from aqueous system by microalgae *Chlamydomonas reinhardtii* immobilized in alginate beads. *International Journal of Mineral Processing, 81,* pp.35-43. DOI: https://doi.org/10.1016/j.minpro.2006.06.002

Bishnoi, N.R., Pant, A. and Nagpal, G., 2004. Biosorption of copper from aqueous solution using algal biomass. *Journal of Scientific & Industrial Research (India), 63,* pp.813-816.

Blaby-Haas, C.E. and Merchant, S.S., 2012. The ins and outs of algal metal transport. *Biochimica et Biophysica Acta - Molecular Cell Research, 1823,* pp.1531-1552. DOI: https://doi.org/10.1016/j.bbamcr.2012.04.010

Boivin, M.E.Y., Greve, G.D., García-Meza, J.V., Massieux, B., Sprenger, W., Kraak, M.H.S., Breure, A.M., Rutgers, M. and Admiraal, W., 2007. Algal–bacterial interactions in metal contaminated floodplain sediments. *Environmental Pollution, 145,* pp.884-894. DOI: https://doi.org/10.1016/j.envpol.2006.05.003

Bon, I.C., Salvatierra, L.M., Lario, L.D., Morató, J. and Pérez, L.M., 2021. Prospects in cadmium-contaminated water management using free-living cyanobacteria (*Oscillatoria* sp.). *Water, 13,* p.542. DOI: https://doi.org/10.3390/w13040542

Boopathy, R., 2000. Factors limiting bioremediation technologies. *Bioresource Technology, 74,* pp.63-67. DOI: https://doi.org/10.1016/S0960-8524(99)00144-3

Brake, S.S., Hasiotis, S.T. and Dannelly, H.K., 2004. Diatoms in acid mine drainage and their role in the formation of iron-rich stromatolites. *Geomicrobiology Journal, 21,* pp.331-340. DOI: https://doi.org/10.1080/01490450490454074

Briffa, J., Sinagra, E. and Blundell, R., 2020. Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon, 6,* p.e04691. DOI: https://doi.org/10.1016/j.heliyon.2020.e04691

Brinza, L., Geraki, K., Cojocaru, C., Holdt, S.L. and Neamtu, M., 2020. Baltic *Fucus vesiculosus* as potential bio-sorbent for Zn removal: Mechanism insight. *Chemosphere, 238,* p.124652. DOI: https://doi.org/10.1016/j.chemosphere.2019.124652

Brinza, L., Nygård, C.A., Dring, M.J., Gavrilescu, M. and Benning, L.G., 2009. Cadmium tolerance and adsorption by the marine brown alga *Fucus vesiculosus* from the Irish Sea and the Bothnian Sea. *Bioresource Technology, 100,* pp.1727-1733. DOI: https://doi.org/10.1016/j.biortech.2008.09.041

Bte Jais, N.M., Bte Radin Mohamed, R.M.S., Wan Mohamad Apandi, W.A. and Matias Peralta, H.M., 2015. Removal of nutrients and selected heavy metals in wet market wastewater by using microalgae *Scenedesmus* sp. *Applied Mechanics & Materials,* pp.773-774, 1210-1214. DOI: https://doi.org/10.4028/www.scientific.net/AMM.773-774.1210

Bwapwa, J.K., Jaiyeola, A.T. and Chetty, R., 2017. Bioremediation of acid mine drainage using algae strains: A review. *South African Journal of Chemical Engineering, 24,* pp.62-70. DOI: https://doi.org/10.1016/j.sajce.2017.06.005

Cai, Z., Karunakaran, E. and Pandhal, J., 2024. Bottom-up construction and screening of algae-bacteria consortia for pollutant biodegradation. *Frontiers in Microbiology, 15*. DOI: https://doi.org/10.3389/fmicb.2024.1349016

Cardoso, S.L., Moino, B.P., Costa, C.S., da Silva, M.G. and Vieira, M.G., 2016. Evaluation of metal affinity of Ag^{+}, Cd^{2+}, Cr^{3+}, Cu^{2+}, Ni^{2+}, Zn^{2+} and Pb^{2+} in residue of double alginate extraction from Sargassum filipendula seaweed. *Chemical Engineering Transactions, 52,* pp.1027-1032.

Carrilho, E.N.V.M. and Gilbert, T.R., 2000. Assessing metal sorption on the marine alga *Pilayella littoralis*. *Journal of Environmental Monitoring, 2,* pp.410-415. DOI: https://doi.org/10.1039/b004128i

Çeleklı, A. and Bulut, H., 2020. Biochemical and morphological responses to cadmium-induced oxidative stress in *Cladophora glomerata*. *Turkish Journal of Botany, 44,* pp.222-231. DOI: https://doi.org/10.3906/bot-2001-12

Chen, J.-Z., Tao, X.-C., Xu, J., Zhang, T. and Liu, Z.-L., 2005. Biosorption of lead, cadmium and mercury by immobilized *Microcystis aeruginosa* in a column. *Process Biochemistry, 40,* pp.3675-3679. DOI: https://doi.org/10.1016/j.procbio.2005.03.066

Chugh, M., Kumar, L., Shah, M.P. and Bharadvaja, N., 2022. Algal bioremediation of heavy metals: An insight into removal mechanisms, recovery of by-products, challenges, and future opportunities. *En-*

ergy Nexus, 7, p.100129. DOI: https://doi.org/10.1016/j.nexus.2022.100129

Ciarkowska, K., 2018. Assessment of heavy metal pollution risks and enzyme activity of meadow soils in urban area under tourism load: a case study from Zakopane (Poland). *Environmental Science and Pollution Research, 25,* pp.13709-13718. DOI: https://doi.org/10.1007/s11356-018-1589-y

Coelho, Luciene M., Rezende, H.C., Coelho, Luciana M., de Sousa, P.A.R., Melo, D.F.O. and Coelho, N.M.M., 2015. Bioremediation of polluted waters using microorganisms, in: Advances in Bioremediation of Wastewater and Polluted Soil. *InTech.* DOI: https://doi.org/10.5772/60770

Dahmen-Ben Moussa, I., Athmouni, K., Chtourou, H., Ayadi, H., Sayadi, S. and Dhouib, A., 2018. Phycoremediation potential, physiological, and biochemical response of *Amphora subtropica* and *Dunaliella* sp. to nickel pollution. *Journal of Applied Phycology, 30,* pp.931-941. DOI: https://doi.org/10.1007/s10811-017-1315-z

Davis, T.., Volesky, B. and Vieira, R.H.S.., 2000. *Sargassum seaweed* as biosorbent for heavy metals. *Water Research, 34,* pp.4270-4278. DOI: https://doi.org/10.1016/S0043-1354(00)00177-9

Demey, H., Vincent, T. and Guibal, E., 2018. A novel algal-based sorbent for heavy metal removal. *Chemical Engineering Journal, 332,* pp.582-595. DOI: https://doi.org/10.1016/j.cej.2017.09.083

Deng, J., Fu, D., Hu, W., Lu, X., Wu, Y. and Bryan, H., 2020. Physiological responses and accumulation ability of *Microcystis aeruginosa* to zinc and cadmium: Implications for bioremediation of heavy metal pollution. *Bioresource Technology, 303,* p.122963. DOI: https://doi.org/10.1016/j.biortech.2020.122963

Deng, L., Su, Y., Su, H., Wang, X. and Zhu, X., 2007a. Sorption and desorption of lead (II) from wastewater by green algae *Cladophora fascicularis*. *Journal of Hazardous Materials, 143,* pp.220-225. DOI: https://doi.org/10.1016/j.jhazmat.2006.09.009

Deng, L., Su, Y., Su, H., Wang, X. and Zhu, X., 2006. Biosorption of copper (II) and lead (II) from aqueous solutions by nonliving green algae *Cladophora fascicularis*: Equilibrium, kinetics and environmental effects. *Adsorption, 12,* pp.267-277. DOI: https://doi.org/10.1007/s10450-006-0503-y

Deng, L., Zhu, X., Su, Y., Su, H. and Wang, X., 2008. Biosorption and desorption of Cd^{2+} from wastewater by dehydrated shreds of *Cladophora fascicularis*. *Chinese Journal of Oceanology and Limnology, 26,* pp.45-49. DOI: https://doi.org/10.1007/s00343-008-0045-0

Deng, L., Zhu, X., Wang, X., Su, Y. and Su, H., 2007b. Biosorption of copper(II) from aqueous solutions by green alga *Cladophora fascicularis*. *Biodegradation, 18,* pp.393-402. DOI: https://doi.org/10.1007/s10532-006-9074-6

Di Capua, F., 2013. Nitrogen removal from low pH and heavy metal contaminated mine wastewater.

Diaconu, M., Soreanu, G., Balan, C.D., Buciscanu, I.I., Maier, V. and Cretescu, I.,

2023. Study of *Spirulina platensis* (*Arthrospira*) development under the heavy metals influence, as a potential promoter of wastewater remediation. *Water, 15,* p.3962. DOI: https://doi.org/10.3390/w15223962

Dixit, S. and Singh, D.P., 2014. An evaluation of phycoremediation potential of cyanobacterium *Nostoc muscorum*: characterization of heavy metal removal efficiency. *Journal of Applied Phycology, 26,* pp.1331-1342. DOI: https://doi.org/10.1007/s10811-013-0145-x

El-Bestawy, E.A., El-Salam, A.Z.A. and Mansy, A.E.-R.H., 2007. Potential use of environmental cyanobacterial species in bioremediation of lindane-contaminated effluents. Int. *Biodeterioration & Biodegradation, 59,* pp.180-192. DOI: https://doi.org/10.1016/j.ibiod.2006.12.005

El-Hameed, M.M.A., Abuarab, M.E., Al-Ansari, N., Mottaleb, S.A., Bakeer, G.A., Gyasi-Agyei, Y. and Mokhtar, A., 2021. Phycoremediation of contaminated water by cadmium (Cd) using two cyanobacterial strains (*Trichormus variabilis* and *Nostoc muscorum*). *Environmental Sciences Europe, 33,* p.135. DOI: https://doi.org/10.1186/s12302-021-00573-0

El-Naggar, N.E.-A., Hamouda, R.A., Saddiq, A.A. and Alkinani, M.H., 2021. Simultaneous bioremediation of cationic copper ions and anionic methyl orange azo dye by brown marine alga *Fucus vesiculosus*. *Scientific Reports, 11,* p.3555. DOI: https://doi.org/10.1038/s41598-021-82827-8

El-Sheekh, M.M., El-Shouny, W.A., Osman, M.E.H. and El-Gammal, E.W.E., 2005. Growth and heavy metals removal efficiency of *Nostoc muscorum* and *Anabaena subcylindrica* in sewage and industrial wastewater effluents. *Environmental Toxicology and Pharmacology, 19,* pp.357-365. DOI: https://doi.org/10.1016/j.etap.2004.09.005

Elbaz-Poulichet, F., 2000. Influence of sorption processes by iron oxides and algae fixation on arsenic and phosphate cycle in an acidic estuary (Tinto river, Spain). *Water Research, 34,* pp.3222-3230. DOI: https://doi.org/10.1016/S0043-1354(00)00073-7

Elleuch, J., Ben Amor, F., Chaaben, Z., Frikha, F., Michaud, P., Fendri, I. and Abdelkafi, S., 2021. Zinc biosorption by Dunaliella sp. AL-1: Mechanism and effects on cell metabolism. *Science of the Total Environment, 773,* p.145024. DOI: https://doi.org/10.1016/j.scitotenv.2021.145024

Esmaeili, A. and Aghababai Beni, A., 2018. Optimization and design of a continuous biosorption process using brown algae and chitosan/PVA nano-fiber membrane for removal of nickel by a new biosorbent. *International Journal of Environmental Science and Technology, 15,* pp.765-778. DOI: https://doi.org/10.1007/s13762-017-1409-9

Esteves, A.J.P., Valdman, E. and Leite, S.G.F., 2000. Repeated removal of cadmium and zinc from an industrial effluent by waste biomass *Sargassum* sp. *Biotechnology Letters, 22,* pp.499-502. DOI: https://doi.org/10.1023/A:1005608701510

Fajardo, C., De Donato, M., Carrasco, R., Martínez-Rodríguez, G., Mancera, J.M.

and Fernández-Acero, F.J., 2020. Advances and challenges in genetic engineering of microalgae. *Reviews in Aquaculture, 12,* pp.365-381. DOI: https://doi.org/10.1111/raq.12322

Fard, R.F., Azimi, A.A. and Bidhendi, G.R.N., 2011. Batch kinetics and isotherms for biosorption of cadmium onto biosolids. *Desalination and Water Treatment, 28,* pp.69-74. DOI: https://doi.org/10.5004/dwt.2011.2203

Flouty, R. and Estephane, G., 2012. Bioaccumulation and biosorption of copper and lead by a unicellular algae *Chlamydomonas reinhardtii* in single and binary metal systems: A comparative study. *Journal of Environmental Management, 111,* pp.106-114. DOI: https://doi.org/10.1016/j.jenvman.2012.06.042

Fourest, E. and Volesky, B., 1996. Contribution of sulfonate groups and alginate to heavy metal biosorption by the dry biomass of *Sargassum fluitans*. *Environmental Science & Technology, 30,* pp.277-282. DOI: https://doi.org/10.1021/es950315s

Fu, P. and Secundo, F., 2016. Algae and their bacterial consortia for soil bioremediation. *Chemical Engineering Transaction, 49,* pp.427-432.

Gao, J. and Chi, J., 2015. Biodegradation of phthalate acid esters by different marine microalgal species. *Marine Pollution Bulletin, 99,* pp.70-75. DOI: https://doi.org/10.1016/j.marpolbul.2015.07.061

Gavrilescu, M., 2010. Environmental biotechnology: Achievements, opportunities and challenges. Dyn. Biochem. Process Biotechnol. *Molecular Biology, 4,* pp.1-36.

Ghimire, K.N., Inoue, K., Ohto, K. and Hayashida, T., 2008. Adsorption study of metal ions onto crosslinked seaweed *Laminaria japonica*. *Bioresource Technology, 99,* pp.32-37. DOI: https://doi.org/10.1016/j.biortech.2006.11.057

Gomes, M.P., Kochi, L.Y., Freitas, P.L., Figueredo, C.C. and Juneau, P., 2021. Periphytic algae and cyanobacteria from the Rio Doce Basin respond differently to metals and salinity, showing different potential for bioremediation. *Plants, 10,* p.2349. DOI: https://doi.org/10.3390/plants10112349

Gündoğdu, A. and Türk Çulha, S., 2023. The use of algae in removal of heavy metal ions from wastewater, in: Pioneer and Contemporary Studies in Agriculture, Forest and Water Issues. *Duvar Publishing*. DOI: https://doi.org/10.59287/pcsafwi.50

Gupta, V.K. and Rastogi, A., 2009. Biosorption of hexavalent chromium by raw and acid-treated green alga *Oedogonium hatei* from aqueous solutions. *Journal of Hazardous Materials, 163,* pp.396-402. DOI: https://doi.org/10.1016/j.jhazmat.2008.06.104

Gupta, V.K., Rastogi, A. and Nayak, A., 2010. Biosorption of nickel onto treated alga (*Oedogonium hatei*): Application of isotherm and kinetic models. *Journal of Colloid and Interface Science, 342,* pp.533-539. DOI: https://doi.org/10.1016/j.jcis.2009.10.074

Han, X., Gong, Y.-F., Wong, Y.-S. and Tam, N.F.Y., 2014. Cr(III) removal by a microalgal isolate, *Chlorella miniata*: effects of nitrate, chloride and sulfate. *Ecotoxicology, 23,* pp.742-748. DOI: https://doi.org/10.1007/s10646-014-1178-x

Han, X., Wong, Y.S., Wong, M.H. and Tam, N.F.Y., 2007. Biosorption and bioreduction of Cr(VI) by a microalgal isolate, *Chlorella miniata*. *Journal of Hazardous Materials, 146,* pp.65-72. DOI: https://doi.org/10.1016/j.jhazmat.2006.11.053

Hazarika, J., Pakshirajan, K., Sinharoy, A. and Syiem, M.B., 2015. Bioremoval of Cu(II), Zn(II), Pb(II) and Cd(II) by *Nostoc muscorum* isolated from a coal mining site. *Journal of Applied Phycology 27,* pp.1525-1534. DOI: https://doi.org/10.1007/s10811-014-0475-3

He, Z., Siripornadulsil, S., Sayre, R.T., Traina, S.J. and Weavers, L.K., 2011. Removal of mercury from sediment by ultrasound combined with biomass (transgenic *Chlamydomonas reinhardtii*). *Chemosphere, 83,* pp.1249-1254. DOI: https://doi.org/10.1016/j.chemosphere.2011.03.004

Henriques, B., Lopes, C.B., Figueira, P., Rocha, L.S., Duarte, A.C., Vale, C., Pardal, M.A. and Pereira, E., 2017. Bioaccumulation of Hg, Cd and Pb by Fucus vesiculosus in single and multi-metal contamination scenarios and its effect on growth rate. *Chemosphere, 171,* pp.208-222. DOI: https://doi.org/10.1016/j.chemosphere.2016.12.086

Hernández, E. and Olguín, E.J., 2002. Biosorption of heavy metals influenced by the chemical composition of *Spirulina* sp. (*Arthrospira*) biomass. *Environmental Technology, 23,* pp.1369-1377. DOI: https://doi.org/10.1080/09593332508618442

Herrero, M. and Stuckey, D.C., 2015. Bioaugmentation and its application in wastewater treatment: A review. *Chemosphere, 140,* pp.119-128. DOI: https://doi.org/10.1016/j.chemosphere.2014.10.033

Hlihor, R.-M., Apostol, L.-C. and Gavrilescu, M., 2017. Environmental bioremediation by biosorption and bioaccumulation: Principles and applications, in: Enhancing Cleanup of Environmental Pollutants. *Springer International Publishing, Cham,* pp.289-315. DOI: https://doi.org/10.1007/978-3-319-55426-6_14

Hong, Y.-W., Yuan, D.-X., Lin, Q.-M. and Yang, T.-L., 2008. Accumulation and biodegradation of phenanthrene and fluoranthene by the algae enriched from a mangrove aquatic ecosystem. *Marine Pollution Bulletin, 56,* pp.1400-1405. DOI: https://doi.org/10.1016/j.marpolbul.2008.05.003

Huang, W.-J., Wu, C.-C. and Chang, W.-C., 2014. Bioaccumulation and toxicity of arsenic in cyanobacteria cultures separated from a eutrophic reservoir. *Environmental Monitoring and Assessment, 186,* pp.805-814. DOI: https://doi.org/10.1007/s10661-013-3418-6

Huang, Y., Chen, Q., Deng, M., Japenga, J., Li, T., Yang, X. and He, Z., 2018. Heavy metal pollution and health risk assessment of agricultural soils in a typical peri-urban area in southeast China. *Journal of Environmental Management, 207,* pp.159-168. DOI: https://doi.org/10.1016/j.jenvman.2017.10.072

Husien, S., Labena, A., El-Belely, E.F., Mahmoud, H.M. and Hamouda, A.S., 2019. Absorption of hexavalent chromium by green micro algae *Chlorella sorokiniana*: live planktonic cells. *Water Practice & Technology, 14,* pp.515-529. DOI: https://doi.org/10.2166/wpt.2019.034

Ibuot, A., Dean, A.P., McIntosh, O.A. and Pittman, J.K., 2017. Metal bioremediation by CrMTP4 over-expressing *Chlamydomonas reinhardtii* in comparison to natural wastewater-tolerant microalgae strains. *Algal Research, 24,* pp.89-96. DOI: https://doi.org/10.1016/j.algal.2017.03.002

Inthorn, D., Sidtitoon, N., Silapanuntakul, S. and Incharoensakdi, A., 2002. Sorption of mercury, cadmium and lead by microalgae. *ScienceAsia, 28,* pp.253-261. DOI: https://doi.org/10.2306/scienceasia1513-1874.2002.28.253

Izydorczyk, G., Mikula, K., Skrzypczak, D., Moustakas, K., Witek-Krowiak, A. and Chojnacka, K., 2021. Potential environmental pollution from copper metallurgy and methods of management. *Environmental Research 197,* p.111050. DOI: https://doi.org/10.1016/j.envres.2021.111050

Jafari, N. and Senobari, Z., 2012. Removal of Pb (II) ions from aqueous solutions by *Cladophora rivularis* (Linnaeus) Hoek. *Science World Journal, 2012,* pp.1-6. DOI: https://doi.org/10.1100/2012/793606

Jayashree, S., Thangaraju, N. and Gnanadoss, J.J., 2012. Toxic effects of chromium on the aquatic cyanobacterium *Oscillatoria* sp and removal of chromium by biosorption. *Journal of Experimental Sciences, 3,* pp.28-34.

Ji, L., Xie, S., Feng, J., Li, Y. and Chen, L., 2012. Heavy metal uptake capacities by the common freshwater green alga *Cladophora fracta*. *Journal of Applied Phycology, 24,* pp.979-983. DOI: https://doi.org/10.1007/s10811-011-9721-0

Kafil, M., Berninger, F., Koutra, E. and Kornaros, M., 2022. Utilization of the microalga *Scenedesmus quadricauda* for hexavalent chromium bioremediation and biodiesel production. *Bioresource Technology, 346,* p.126665. DOI: https://doi.org/10.1016/j.biortech.2021.126665

Kandasamy, S., Narayanan, M., He, Z., Liu, G., Ramakrishnan, M., Thangavel, P., Pugazhendhi, A., Raja, R. and Carvalho, I.S., 2021. Current strategies and prospects in algae for remediation and biofuels: An overview. *Biocatalysis and Agricultural Biotechnology 35,* p.102045. DOI: https://doi.org/10.1016/j.bcab.2021.102045

Kaplan, D., 2013. Absorption and adsorption of heavy metals by microalgae, in: Handbook of Microalgal Culture. *John Wiley & Sons, Ltd, Oxford, UK,* pp.602-611. DOI: https://doi.org/10.1002/9781118567166.ch32

Karaca, M., 2008. Biosorption of aqueus Pb2+, Cd2+, and Ni2+ ions by *Dunaliella salina*, *Oocystis* sp., *Porphyridium cruentum*, and *Scenedesmus protuberans* prior to atomic spectrometric determination . *Izmir Institute of Technology , Izmir*.

Khan, M.M., 2022. Hydrological study of the catchment area and its delineation (Using ArcGIS Software).

Khan, S., Ullah, A., Ayaz, T., Aziz, A., Aman, K., Habib, M., Yilmaz, S., Farid, A., Yasmin, H. and Ali, Q., 2023. Phycoremediation of industrial wastewater using *Vaucheria debaryana* and *Cladophora glomerata*. *Environmental Monitoring and Assessment, 195,* p.825. DOI: https://doi.org/10.1007/s10661-023-11357-9

Khani, M.H., 2011. Uranium biosorption by Padina sp. algae biomass: kinetics and thermodynamics. *Environmental Science and Pollution Research, 18,* pp.1593-1605. DOI: https://doi.org/10.1007/s11356-011-0518-0

Khatiwada, B., Hasan, M.T., Sun, A., Kamath, K.S., Mirzaei, M., Sunna, A. and Nevalainen, H., 2020. Proteomic response of Euglena gracilis to heavy metal exposure – Identification of key proteins involved in heavy metal tolerance and accumulation. *Algal Research, 45,* p.101764. DOI: https://doi.org/10.1016/j.algal.2019.101764

Klimmek, S., Stan, H.-J., Wilke, A., Bunke, G. and Buchholz, R., 2001. Comparative analysis of the biosorption of cadmium, lead, nickel, and zinc by algae. *Environmental Science & Technology, 35,* pp.4283-4288. DOI: https://doi.org/10.1021/es010063x

Kothari, R., Pandey, A., Ahmad, S., Singh, H.M., Pathak, V. V., Tyagi, V. V., Kumar, K. and Sari, A., 2022. Utilization of *Chlorella pyrenoidosa* for remediation of common effluent treatment plant wastewater in coupling with co-relational study: An experimental approach. *Bulletin of Environmental Contamination and Toxicology, 108,* pp.507-517. DOI: https://doi.org/10.1007/s00128-021-03292-7

Kratochvil, D., Fourest, E. and Volesky, B., 1995. Biosorption of copper by *Sargassum fluitans* biomass in fixed-bed column. *Biotechnology Letters, 17,* pp.777-782. DOI: https://doi.org/10.1007/BF00130368

Kumar, J.I.N. and Oommen, C., 2012. Removal of heavy metals by biosorption using freshwater alga *Spirogyra hyalina*. *Journal of Environmental Biology 33,* pp.27-31.

Kumar, N., Hans, S., Verma, R. and Srivastava, A., 2020. Acclimatization of microalgae *Arthrospira platensis* for treatment of heavy metals in Yamuna River. *Water Science and Engineering, 13,* pp.214-222. DOI: https://doi.org/10.1016/j.wse.2020.09.005

Kumari, S., Tyagi, M. and Jagadevan, S., 2019. Mechanistic removal of environmental contaminants using biogenic nano-materials. *International Journal of Environmental Science and Technology, 16,* pp.7591-7606. DOI: https://doi.org/10.1007/s13762-019-02468-3

Kuritz, T. and Wolk, C.P., 1995. Use of filamentous cyanobacteria for biodegradation of organic pollutants. *Applied and Environmental Microbiology 61,* pp.234-238. DOI: https://doi.org/10.1128/aem.61.1.234-238.1995

Lakshmi, D., Radha, K., Azeez, T. and Munisamy, S., 2023. A review on alginate-nanoparticle as a potential tool for managing water pollution. *Engineering and Technology Journal, 0,* pp.1-10. DOI: https://doi.org/10.30684/etj.2023.143276.1574

Lee, C., Li, X., Shi, W., Cheung, S. and

Thornton, I., 2006. Metal contamination in urban, suburban, and country park soils of Hong Kong: A study based on GIS and multivariate statistics. *Science of the Total Environment, 356,* pp.45-61. DOI: https://doi.org/10.1016/j.scitotenv.2005.03.024

Leusch, A., Holan, Z.R. and Volesky, B., 1995. Biosorption of heavy metals (Cd, Cu, Ni, Pb, Zn) by chemically-reinforced biomass of marine algae. *Journal of Chemical Technology & Biotechnology, 62,* pp.279-288. DOI: https://doi.org/10.1002/jctb.280620311

Li, C., Zheng, C., Fu, H., Zhai, S., Hu, F., Naveed, S., Zhang, C. and Ge, Y., 2021. Contrasting detoxification mechanisms of *Chlamydomonas reinhardtii* under Cd and Pb stress. *Chemosphere, 274,* p.129771. DOI: https://doi.org/10.1016/j.chemosphere.2021.129771

Liang, S., Kang, Y., Zeng, L., Qin, Y., Wang, L., Zhang, Q. and Luo, J., 2017. How *Chlorella sorokiniana* and its high tolerance to Pb might be a potential Pb biosorbent. *Polish Journal of Environmental Studies, 26,* pp.1139-1146. DOI: https://doi.org/10.15244/pjoes/67532

Liyanage, L.M.M., Lakmali, W.G.M., Athukorala, S.N.P. and Jayasundera, K.B., 2020. Application of live *Chlorococcum aquaticum* biomass for the removal of Pb(II) from aqueous solutions. *Journal of Applied Phycology, 32,* pp.4069-4080. DOI: https://doi.org/10.1007/s10811-020-02242-w

López-Miranda, J.L., Silva, R., Molina, G.A., Esparza, R., Hernandez-Martinez, A.R., Hernández-Carteño, J. and Estévez, M., 2020. Evaluation of a dynamic bioremediation system for the removal of metal ions and toxic dyes using *Sargassum* Spp. *Journal of Marine Science and Engineering 8,* p.899. DOI: https://doi.org/10.3390/jmse8110899

Lu, J., Ma, Y., Xing, G., Li, W., Kong, X., Li, J., Wang, L., Yuan, H. and Yang, J., 2019. Revelation of microalgae's lipid production and resistance mechanism to ultra-high Cd stress by integrated transcriptome and physiochemical analyses. *Environmental Pollution, 250,* pp.186-195. DOI: https://doi.org/10.1016/j.envpol.2019.04.018

Luo, F., Liu, Y., Li, X., Xuan, Z. and Ma, J., 2006. Biosorption of lead ion by chemically-modified biomass of marine brown algae *Laminaria japonica*. *Chemosphere, 64,* pp.1122-1127. DOI: https://doi.org/10.1016/j.chemosphere.2005.11.076

Mahdavi, H., Prasad, V., Liu, Y. and Ulrich, A.C., 2015. In situ biodegradation of naphthenic acids in oil sands tailings pond water using indigenous algae–bacteria consortium. *Bioresource Technology, 187,* pp.97-105. DOI: https://doi.org/10.1016/j.biortech.2015.03.091

Mahmood, T., Hussain, N., Shahbaz, A., Mulla, S.I., Iqbal, H.M.N. and Bilal, M., 2023. Sustainable production of biofuels from the algae-derived biomass. *Bioprocess and Biosystems Engineering, 46,* pp.1077-1097. DOI: https://doi.org/10.1007/s00449-022-02796-8

Mahmood, Z., Zahra, S., Iqbal, M., Raza, M.A. and Nasir, S., 2017. Comparative study of natural and modified biomass of *Sargassum* sp. for removal of Cd^{2+} and

Zn^{2+} from wastewater. *Applied Water Science, 7,* pp.3469-3481. DOI: https://doi.org/10.1007/s13201-017-0624-3

Malik, B. and Kaur Sandhu, K., 2023. Occurrence and impact of heavy metals on environment. *Materials Today: Proceedings*. DOI: https://doi.org/10.1016/j.matpr.2023.01.317

Mane, P.C. and Bhosle, A.B., 2012. Bioremoval of some metals by living algae *Spirogyra* sp. and *Spirullina* sp. from aqueous solution. *International Journal of Environmental Research*. pp.571-576.

Manzoor, F., Karbassi, A. and Golzary, A., 2020. Removal of heavy metal contaminants from wastewater by using *Chlorella vulgaris* Beijerinck: A review. *Current Environmental Management, 6,* pp.174-187. DOI: https://doi.org/10.2174/2212717806666190716160536

Marella, T.K., López-Pacheco, I.Y., Parra-Saldívar, R., Dixit, S. and Tiwari, A., 2020. Wealth from waste: Diatoms as tools for phycoremediation of wastewater and for obtaining value from the biomass. *Science of the Total Environment, 724,* p.137960. DOI: https://doi.org/10.1016/j.scitotenv.2020.137960

Mata, Y.N., Blázquez, M.L., Ballester, A., González, F. and Muñoz, J.A., 2008. Characterization of the biosorption of cadmium, lead and copper with the brown alga *Fucus vesiculosus*. *Journal of Hazardous Materials, 158,* pp.316-323. DOI: https://doi.org/10.1016/j.jhazmat.2008.01.084

Matheickal, J.T. and Yu, Q., 1996. Biosorption of lead from aqueous solutions by marine algae. *Water Science & Technology, 34.* DOI: https://doi.org/10.1016/S0273-1223(96)00780-9

Mathimani, T., Alshiekheid, M.A., Sabour, A., Le, T. and Xia, C., 2024. Appraising the phycoremediation potential of cyanobacterial strains *Phormidium* and *Oscillatoria* for nutrient removal from textile wastewater (TWW) and synchronized biodiesel production from TWW-tolerant biomass. *Environmental Research, 241,* p.117628. DOI: https://doi.org/10.1016/j.envres.2023.117628

Medeiros, I.D., Mathieson, A.C. and Rajakaruna, N., 2017. Heavy metals in seaweeds from a polluted estuary in coastal Maine. *Rhodora, 119,* pp.201-211. DOI: https://doi.org/10.3119/16-25

Megharaj, M., Boul, H.L. and Thiele, J.H., 1999. Effects of DDT and its metabolites on soil algae and enzymatic activity. *Biology and Fertility of Soils, 29,* pp.130-134. DOI: https://doi.org/10.1007/s003740050534

Megharaj, M., Kantachote, D., Singleton, I. and Naidu, R., 2000. Effects of long-term contamination of DDT on soil microflora with special reference to soil algae and algal transformation of DDT. *Environmental Pollution, 109,* pp.35-42. DOI: https://doi.org/10.1016/S0269-7491(99)00231-6

Megharaj, M., Madhavi, D.R., Sreenivasulu, C., Umamaheswari, A. and Venkateswarlu, K., 1994. Biodegradation of methyl parathion by soil isolates of microalgae and cyanobacteria. *Bulletin of Environmental Contamination and Toxicology, 53,* pp.292-297. DOI: https://doi.org/10.1007/BF00192047

Megharaj, M., Venkateswarlu, K. and Rao, A.S., 1987. Metabolism of monocrotophos and quinalphos by algae isolated from soil. *Bulletin of Environmental Contamination and Toxicology, 39*, pp.251-256. DOI: https://doi.org/10.1007/BF01689414

Mehta, S.K. and Gaur, J.P., 2005. Use of algae for removing heavy metal ions from wastewater: Progress and prospects. *Critical Reviews in Biotechnology, 25,* pp.113-152. DOI: https://doi.org/10.1080/07388550500248571

Mei, L., Xitao, X., Renhao, X. and Zhili, L., 2006. Effects of strontium-induced stress on marine microalgae*Platymonas subcordiformis* (Chlorophyta: Volvocales). *Chinese Journal of Oceanology and Limnology, 24,* pp.154-160. DOI: https://doi.org/10.1007/BF02842815

Mofeed, J., 2017. Biosorption of heavy metals from aqueous industrial effluent by non-living biomass of two marine green algae *Ulva lactuca* and *Dunaliella salina* as biosorpents. *Catrina: the International Journal of Environmental Sciences, 16,* pp.43-52. DOI: https://doi.org/10.21608/cat.2017.14267

Monteiro, C.M., Castro, P.M.L. and Malcata, F.X., 2009. Use of the microalga *Scenedesmus obliquus* to remove cadmium cations from aqueous solutions. *World Journal of Microbiology & Biotechnology, 25,* pp.1573-1578. DOI: https://doi.org/10.1007/s11274-009-0046-y

Monteiro, C.M., Castro, P.M.L. and Xavier Malcata, F., 2011. Biosorption of zinc ions from aqueous solution by the microalga *Scenedesmus obliquus*. *Environmental Chemistry Letters, 9,* pp.169-176. DOI: https://doi.org/10.1007/s10311-009-0258-2

Morsy, F.M., Hassan, S.H.A. and Koutb, M., 2011. Biosorption of Cd(II) and Zn(II) by *Nostoc commune* : Isotherm and kinetics studies. *CLEAN – Soil, Air, Water, 39,* pp.680-687. DOI: https://doi.org/10.1002/clen.201000312

Muñoz, R. and Guieysse, B., 2006. Algal–bacterial processes for the treatment of hazardous contaminants: A review. *Water Research, 40,* pp.2799-2815. DOI: https://doi.org/10.1016/j.watres.2006.06.011

Naseema Rasheed, R., Pourbakhtiar, A., Mehdizadeh Allaf, M., Baharlooeian, M., Rafiei, N., Alishah Aratboni, H., Morones-Ramirez, J.R. and Winck, F.V., 2023. Microalgal co-cultivation -recent methods, trends in omic-studies, applications, and future challenges. *Frontiers in Bioengineering and Biotechnology, 11*. DOI: https://doi.org/10.3389/fbioe.2023.1193424

Navarro, J. and Caipang, C.M., 2024. Bioremediation of oil spills: Current status, challenges, and future prospects. *Journal of Microbiology, Biotechnology and Food Sciences*. p.e10450. DOI: https://doi.org/10.55251/jmbfs.10450

Novis, P.M. and Harding, J.S., 2007. Extreme Acidophiles. pp.443-463. DOI: https://doi.org/10.1007/978-1-4020-6112-7_24

Nuhoglu, Y., Malkoc, E., Gürses, A. and Canpolat, N., 2002. The removal of Cu(II) from aqueous solutions by *Ulothrix zonata*. *Bioresource Technology, 85,* pp.331-333. DOI: https://doi.

org/10.1016/S0960-8524(02)00098-6

Omar, H.., 2002. Bioremoval of zinc ions by *Scenedesmus obliquus* and *Scenedesmus quadricauda* and its effect on growth and metabolism. *International Biodeterioration & Biodegradation, 50,* pp.95-100. DOI: https://doi.org/10.1016/S0964-8305(02)00048-3

P.S, C., Sanyal, D., Dasgupta, S. and Banik, A., 2021. Cadmium biosorption and biomass production by two freshwater microalgae *Scenedesmus acutus* and *Chlorella pyrenoidosa*: An integrated approach. *Chemosphere, 269,* p.128755. DOI: https://doi.org/10.1016/j.chemosphere.2020.128755

Pagnanelli, F., Esposito, A., Toro, L. and Vegliò, F., 2003. Metal speciation and pH effect on Pb, Cu, Zn and Cd biosorption onto *Sphaerotilus natans*: Langmuir-type empirical model. *Water Research, 37,* pp.627-633. DOI: https://doi.org/10.1016/S0043-1354(02)00358-5

Papageorgiou, S.K., Kouvelos, E.P. and Katsaros, F.K., 2008. Calcium alginate beads from Laminaria digitata for the removal of Cu^{+2} and Cd^{+2} from dilute aqueous metal solutions. *Desalination, 224,* pp.293-306. DOI: https://doi.org/10.1016/j.desal.2007.06.011

Pawlik-Skowrońska, B., 2001. Phytochelatin production in freshwater algae *Stigeoclonium* in response to heavy metals contained in mining water; effects of some environmental factors. *Aquatic Toxicology, 52,* pp.241-249. DOI: https://doi.org/10.1016/S0166-445X(00)00144-2

Peña-Castro, J.M., Martínez-Jerónimo, F., Esparza-García, F. and Cañizares-Villanueva, R.O., 2004. Heavy metals removal by the microalga *Scenedesmus incrassatulus* in continuous cultures. *Bioresource Technology, 94,* pp.219-222. DOI: https://doi.org/10.1016/j.biortech.2003.12.005

Petrovič, A. and Simonič, M., 2016. Removal of heavy metal ions from drinking water by alginate-immobilised *Chlorella sorokiniana*. *International Journal of Environmental Science and Technology, 13,* pp.1761-1780. DOI: https://doi.org/10.1007/s13762-016-1015-2

Pradhan, B., Bhuyan, P.P., Nayak, R., Patra, S., Behera, C., Ki, J.-S., Ragusa, A., Lukatkin, A.S. and Jena, M., 2022. Microalgal phycoremediation: A glimpse into a sustainable environment. *Toxics, 10,* p.525. DOI: https://doi.org/10.3390/toxics10090525

Pradhan, S. and Rai, L.C., 2001. Copper removal by immobilized *Microcystis aeruginosa* in continuous flow columns at different bed heights: study of the adsorption/desorption cycle. *World Journal of Microbiology & Biotechnology, 17,* pp.829-832. DOI: https://doi.org/10.1023/A:1013800800176

Puente-Sánchez, F., Díaz, S., Penacho, V., Aguilera, A. and Olsson, S., 2018. Basis of genetic adaptation to heavy metal stress in the acidophilic green alga *Chlamydomonas acidophila*. *Aquatic Toxicology, 200,* pp.62-72. DOI: https://doi.org/10.1016/j.aquatox.2018.04.020

Purushanahalli Shivagangaiah, C., Sanyal, D., Dasgupta, S. and Banik, A., 2021. Phycoremediation and photosynthetic toxicity assessment of lead by two freshwater microalgae *Scenedesmus acutus* and *Chlorella pyrenoidosa*. *Physiologia Plantarum,* p.13368. DOI: https://doi.org/10.1111/ppl.13368

Qiu, C.E., Kuang, Q.J., Bi, Y.H., Liu, G.X. and Hu, Z.Y., 2006. Response of *Chlorococcum* sp. AZHB to copper and cadmius stress. *Bulletin of Environmental Contamination and Toxicology 77,* pp.772-778. DOI: https://doi.org/10.1007/s00128-006-1130-8

Rahman, M.M., Alam, K. and Velayutham, E., 2021. Is industrial pollution detrimental to public health? Evidence from the world's most industrialised countries. *BMC Public Health, 21,* 1175. DOI: https://doi.org/10.1186/s12889-021-11217-6

Rai, U.N., Dubey, S., Shukla, O.P., Dwivedi, S. and Tripathi, R.D., 2008. Screening and identification of early warning algal species for metal contamination in fresh water bodies polluted from point and non-point sources. *Environmental Monitoring and Assessment, 144,* pp.469-481. DOI: https://doi.org/10.1007/s10661-007-0010-y

Rajamani, S., Siripornadulsil, S., Falcao, V., Torres, M., Colepicolo, P. and Sayre, R., 2007. Phycoremediation of heavy metals using transgenic microalgae, in: Transgenic Microalgae as Green Cell Factories. *Springer New York, New York, NY,* pp.99-109. DOI: https://doi.org/10.1007/978-0-387-75532-8_9

Rakic, I., Kevresan, Z., Kovac, R., Kravic, S., Svircev, Z., Djurovic, A. and Stojanovic, Z., 2023. Bioaccumulation and biosorption study of heavy metals removal by cyanobacteria *Nostoc* sp. *Chemical Industry & Chemical Engineering Quarterly, 29,* pp.291-298. DOI: https://doi.org/10.2298/CICEQ220511002R

Ram, H., Kaur, A., Gandass, N., Singh, S., Deshmukh, R., Sonah, H. and Sharma, T.R., 2019. Molecular characterization and expression dynamics of MTP genes under various spatio-temporal stages and metal stress conditions in rice. *PLoS One, 14,* p.e0217360. DOI: https://doi.org/10.1371/journal.pone.0217360

Ramírez-Rodríguez, A.E., Bañuelos-Hernández, B., García-Soto, M.J., Govea-Alonso, D.G., Rosales-Mendoza, S., Alfaro de la Torre, M.C., Monreal-Escalante, E. and Paz-Maldonado, L.M.T., 2019. Arsenic removal using *Chlamydomonas reinhardtii* modified with the gene *acr3* and enhancement of its performance by decreasing phosphate in the growing media. *International Journal of Phytoremediation, 21,* pp.617-623. DOI: https://doi.org/10.1080/15226514.2018.1546274

Rangsayatorn, N., Upatham, E.S., Kruatrachue, M., Pokethitiyook, P. and Lanza, G.R., 2002. Phytoremediation potential of *Spirulina* (*Arthrospira*) platensis: biosorption and toxicity studies of cadmium. *Environmental Pollution, 119,* pp.45-53. DOI: https://doi.org/10.1016/S0269-7491(01)00324-4

Ranjbar, S. and Malcata, F.X., 2022. Is genetic engineering a route to enhance microalgae-mediated bioremediation of heavy metal-containing effluents? *Molecules, 27,* p.1473. DOI: https://doi.org/10.3390/molecules27051473

Raungsomboon, S., Chidthaisong, A.,

Bunnag, B., Inthorn, D. and Harvey, N.W., 2008. Removal of lead (Pb^{2+}) by the cyanobacterium *Gloeocapsa* sp. *Bioresource Technology, 99,* pp.5650-5658. DOI: https://doi.org/10.1016/j.biortech.2007.10.056

Ravindran, B., Gupta, S., Cho, W.-M., Kim, J., Lee, S., Jeong, K.-H., Lee, D. and Choi, H.-C., 2016. Microalgae potential and multiple roles—current progress and future prospects—An overview. *Sustainability, 8,* p.1215. DOI: https://doi.org/10.3390/su8121215

Razaviarani, V., Arab, G., Lerdwanawattana, N. and Gadia, Y., 2022. Algal biomass dual roles in phycoremediation of wastewater and production of bioenergy and value-added products. *International Journal of Environmental Science and Technology.* DOI: https://doi.org/10.1007/s13762-022-04696-6

Razzak, S.A., Faruque, M.O., Alsheikh, Z., Alsheikhmohamad, L., Alkuroud, D., Alfayez, A., Hossain, S.M.Z. and Hossain, M.M., 2022. A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. *Environmental Advances, 7,* p.100168. DOI: https://doi.org/10.1016/j.envadv.2022.100168

Rosakis, A. and Köster, W., 2005. Divalent metal transport in the green microalga *Chlamydomonas reinhardtii* is mediated by a protein similar to prokaryotic Nramp homologues. *BioMetals, 18,* pp.107-120. DOI: https://doi.org/10.1007/s10534-004-2481-4

Ross, M.E., Stanley, M.S., Day, J.G. and Semião, A.J.C., 2021. Removal of metals from aqueous solutions using dried *Cladophora parriaudii* of varying biochemical composition. *Journal of Environmental Management, 290,* p.112620. DOI: https://doi.org/10.1016/j.jenvman.2021.112620

Roy, A.S., Hazarika, J., Manikandan, N.A., Pakshirajan, K. and Syiem, M.B., 2015. Heavy metal removal from multicomponent system by the cyanobacterium *Nostoc muscorum*: Kinetics and interaction study. *Applied Biochemistry and Biotechnology, 175,* pp.3863-3874. DOI: https://doi.org/10.1007/s12010-015-1553-y

Ryu, B.-G., Kim, W., Nam, K., Kim, S., Lee, B., Park, M.S. and Yang, J.-W., 2015. A comprehensive study on algal–bacterial communities shift during thiocyanate degradation in a microalga-mediated process. *Bioresource Technology 191,* pp.496-504. DOI: https://doi.org/10.1016/j.biortech.2015.03.136

Rzymski, P., Poniedzialek, B., Niedzielski, P., Tabaczewski, P. and Wiktorowicz, K., 2014. Cadmium and lead toxicity and bioaccumulation in *Microcystis aeruginosa*. *Frontiers of Environmental Science & Engineering, 8,* pp.427-432. DOI: https://doi.org/10.1007/s11783-013-0566-4

Samal, D.P.K., Sukla, L.B., Pattanaik, A. and Pradhan, D., 2020. Role of microalgae in treatment of acid mine drainage and recovery of valuable metals. *Materials Today: Proceedings, 30,* pp.346-350. DOI: https://doi.org/10.1016/j.matpr.2020.02.165

Sargın, İ., Arslan, G. and Kaya, M., 2016. Efficiency of chitosan–algal biomass composite microbeads at heavy metal removal. *Reactive & Functional Polymers, 98,* pp.38-47. DOI: https://doi.org/10.1016/j.reactfunctpolym.2015.11.007

Seepersaud, M.A., Ramkissoon, A., Seecharan, S., Powder-George, Y.L. and Mohammed, F.K., 2018. Environmental monitoring of heavy metals and polycyclic aromatic hydrocarbons (PAHs) in *Sargassum filipendula* and *Sargassum vulgare* along the eastern coastal waters of Trinidad and Tobago, West Indies. *Journal of Applied Phycology, 30,* pp.2143-2154. DOI: https://doi.org/10.1007/s10811-017-1372-3

Shukla, D., Vankar, P.S. and Srivastava, S.K., 2012. Bioremediation of hexavalent chromium by a cyanobacterial mat. *Applied Water Science, 2,* pp.245-251. DOI: https://doi.org/10.1007/s13201-012-0044-3

Singh, S.K., 2019. An analysis of role of microorganisms in bioremediation. *Journal of Emerging Technologies & Innovative Research, 6,* pp.212-217.

Singh, S.K., Bansal, A., Jha, M.K. and Dey, A., 2012. An integrated approach to remove Cr(VI) using immobilized *Chlorella minutissima* grown in nutrient rich sewage wastewater. *Bioresource Technology, 104,* pp.257-265. DOI: https://doi.org/10.1016/j.biortech.2011.11.044

Singhal, M., Jadhav, S., Sonone, S.S., Sankhla, M.S. and Kumar, R., 2021. Microalgae based sustainable bioremediation of water contaminated by pesticides. *Biointerface Research in Applied Chemistry, 12,* pp.149-169. DOI: https://doi.org/10.33263/BRIAC121.149169

Soeprobowati, T.R. and Hariyati, R., 2013. Bioaccumulation of Pb, Cd, Cu, and Cr by *Porphyridium cruentum* (S.F. Gray) Nägeli. *International Journal of Marine Science*. DOI: https://doi.org/10.5376/ijms.2013.03.0027

Spain, O., Plöhn, M. and Funk, C., 2021. The cell wall of green microalgae and its role in heavy metal removal. *Physiologia Plantarum, 173,* pp.526-535. DOI: https://doi.org/10.1111/ppl.13405

Su, M., Dell'Orto, M., Scaglia, B., D'Imporzano, G., Bani, A. and Adani, F., 2022. Growth performance, biochemical composition and nutrient recovery ability of twelve microalgae consortia isolated from various local organic wastes grown on nano-filtered pig slurry. *Molecules, 27,* p.422. DOI: https://doi.org/10.3390/molecules27020422

Subashchandrabose, S.R., Ramakrishnan, B., Megharaj, M., Venkateswarlu, K. and Naidu, R., 2013. Mixotrophic cyanobacteria and microalgae as distinctive biological agents for organic pollutant degradation. *Environment International, 51,* pp.59-72. DOI: https://doi.org/10.1016/j.envint.2012.10.007

Subashchandrabose, S.R., Ramakrishnan, B., Megharaj, M., Venkateswarlu, K. and Naidu, R., 2011. Consortia of cyanobacteria/microalgae and bacteria: Biotechnological potential. *Biotechnology Advances, 29,* pp.896-907. DOI: https://doi.org/10.1016/j.biotechadv.2011.07.009

Tahira, S., Khan, S., Samrana, S., Shahi, L., Ali, I., Murad, W., Rehman, Z. ur and Azizullah, A., 2019. Bio-assessment and remediation of arsenic (arsenite As-III) in water by *Euglena gracilis*. *Journal of Applied Phycology, 31,* pp.423-433. DOI: https://doi.org/10.1007/s10811-018-1593-0

Tamil Selvan, S., Velramar, B., Ramamurthy, D., Balasundaram, S. and Sivamani, K., 2020. Pilot scale wastewater treatment, CO_2 sequestration and lipid production using microalga, *Neochloris aquatica* RDS02. *International Journal of Phytoremediation, 22,* pp.1462-1479. DOI: https://doi.org/10.1080/15226514.2020.1782828

Torres, E.M., 2016. Microalgae sorption of ten individual heavy metals and their effects on growth and lipid accumulation. Utah State University.

Torres, M.J., Bellido-Pedraza, C.M. and Llamas, A., 2024. Applications of the microalgae *Chlamydomonas* and its bacterial consortia in detoxification and bioproduction. *Life, 14,* p.940. DOI: https://doi.org/10.3390/life14080940

Touliabah, H.E.-S., El-Sheekh, M.M., Ismail, M.M. and El-Kassas, H., 2022. A review of microalgae- and cyanobacteria-based biodegradation of organic pollutants. *Molecules, 27,* p.1141. DOI: https://doi.org/10.3390/molecules27031141

Tüzün, İ., Bayramoğlu, G., Yalçın, E., Başaran, G., Çelik, G. and Arıca, M.Y., 2005. Equilibrium and kinetic studies on biosorption of Hg(II), Cd(II) and Pb(II) ions onto microalgae *Chlamydomonas reinhardtii*. *Journal of Environmental Management, 77,* pp.85-92. DOI: https://doi.org/10.1016/j.jenvman.2005.01.028

Upadhyay, A.K., Singh, L., Singh, R., Singh, D.P. and Saxena, G., 2022. Bioaccumulation and toxicity of As in the alga *Chlorococcum* sp.: Prospects for As bioremediation. *Bulletin of Environmental Contamination and Toxicology, 108,* pp.500-506. DOI: https://doi.org/10.1007/s00128-020-02964-0

V.R., M., Y.A.R., L., Lange, L.C. and L.V.S., S., 2019. Simultaneous biosorption of Cd(II), Ni(II) and Pb(II) onto a brown macroalgae Fucus vesiculosus: Mono- and multi-component isotherms, kinetics and thermodynamics. *Journal of Environmental Management, 251,* p.109587. DOI: https://doi.org/10.1016/j.jenvman.2019.109587

Valiente Moro, C., Bricheux, G., Portelli, C. and Bohatier, J., 2012. Comparative effects of the herbicides chlortoluron and mesotrione on freshwater microalgae. *Environmental Toxicology and Chemistry, 31*, pp.778-786. DOI: https://doi.org/10.1002/etc.1749

Verma, A., Kumar, Shashi, Balomajumder, C. and Kumar, Surendra, 2018. Efficacy of *Sargassum filipendula* for the removal of Pb^{2+}, Cd^{2+} and Ni2+ ions from aqueous solution: a comparative study. *Desalination and Water Treatment, 129,* pp.216-226. DOI: https://doi.org/10.5004/dwt.2018.22788

Verma, A., Kumar, Shashi and Kumar, Surendra, 2016. Biosorption of lead ions from the aqueous solution by *Sargassum filipendula*: Equilibrium and kinetic studies. *Journal of Environmental Chemical Engineering, 4,* pp.4587-4599. DOI: https://doi.org/10.1016/j.jece.2016.10.026

Verma, J.P. and Jaiswal, D.K., 2016. Book review: Advances in biodegradation and bioremediation of industrial waste. *Frontiers in Microbiology, 6*. DOI: https://doi.org/10.3389/fmicb.2015.01555

Vijayaraghavan, K., Jegan, J., Palanivelu, K. and Velan, M., 2005. Batch and column removal of copper from aqueous solution using a brown marine alga *Turbinaria ornata*. *Chemical Engineering Journal, 106,* pp.177-184. DOI: https://doi.org/10.1016/j.cej.2004.12.039

Vilar, V.J.P., Botelho, C.M.S. and Boaventura, R.A.R., 2005. Influence of pH, ionic strength and temperature on lead biosorption by *Gelidium* and agar extraction algal waste. *Process Biochemistry, 40,* pp.3267-3275. DOI: https://doi.org/10.1016/j.procbio.2005.03.023

Volesky, B. and Holan, Z.R., 1995. Biosorption of heavy metals. Biotechnol. Prog. 11, 235–250. https://doi.org/10.1021/bp00033a001

Volland, S., Lütz, C., Michalke, B. and Lütz-Meindl, U., 2012. Intracellular chromium localization and cell physiological response in the unicellular alga *Micrasterias*. *Aquatic Toxicology, 109,* pp.59-69. DOI: https://doi.org/10.1016/j.aquatox.2011.11.013

Vymazal, J., 1990. Uptake of heavy metals by *Cladophora glomerata*. *Acta Hydrochimica et Hydrobiologica, 18,* pp.657-665. DOI: https://doi.org/10.1002/aheh.19900180605

Vymazal, J., 1984. Short-term uptake of heavy metals by periphyton algae. *Hydrobiologia, 119,* pp.171-179. DOI: https://doi.org/10.1007/BF00015208

Wang, X., Ma, S. and Kong, F., 2024. Microalgae biotechnology: Methods and applications. *Bioengineering, 11,* p.965. DOI: https://doi.org/10.3390/bioengineering11100965

Wang, Z., Gui, H., Luo, Z., Zhen, Z., Yan, C. and Xing, B., 2019. Dissolved organic phosphorus enhances arsenate bioaccumulation and biotransformation in *Microcystis aeruginosa*. *Environmental Pollution, 252,* pp.1755-1763. DOI: https://doi.org/10.1016/j.envpol.2019.06.126

Webster, L.J., Villa-Gomez, D., Brown, R., Clarke, W. and Schenk, P.M., 2024. A synthetic biology approach for the treatment of pollutants with microalgae. *Frontiers in Bioengineering and Biotechnology, 12*. DOI: https://doi.org/10.3389/fbioe.2024.1379301

Winters, C., Guéguen, C. and Noble, A., 2017. Equilibrium and kinetic studies of Cu(II) and Ni(II) sorption on living *Euglena gracilis*. *Journal of Applied Phycology, 29,* pp.1391-1398. DOI: https://doi.org/10.1007/s10811-016-1040-z

Wong, J.P., Wong, Y. and Tam, N.F., 2000. Nickel biosorption by two chlorella species, *C. vulgaris* (a commercial species) and *C. miniata* (a local isolate). *Bioresource Technology, 73,* pp.133-137. DOI: https://doi.org/10.1016/S0960-8524(99)00175-3

Wu, J., Ma, L.-L. and Zeng, R.J., 2018. Role of extracellular polymeric substances in efficient chromium(VI) removal by algae-based Fe/C nano-composite. *Chemosphere, 211,* pp.608-616. DOI: https://doi.org/10.1016/j.chemosphere.2018.07.186

Xiao, J., Chikanori, M., Yu, K.-F., Hideshi, S., Hideo, M. and He, P.-M., 2012. Biosorption of heavy metals onto nonliving *Laminaria japonica*. *Water Science & Technology, 65,* pp.1514-1520. DOI: https://doi.org/10.2166/wst.2012.042

Xiao, R., Ali, A., Wang, P., Li, R., Tian, X. and Zhang, Z., 2019. Comparison of the feasibility of different washing solutions for combined soil washing and phytoremediation for the detoxification of cadmium (Cd) and zinc (Zn) in contaminated soil. *Chemosphere, 230,* pp.510-518. DOI: https://doi.org/10.1016/j.chemosphere.2019.05.121

Yamamoto, T., Goto, I., Kawaguchi, O., Minagawa, K., Ariyoshi, E. and Matsuda, O., 2008. Phytoremediation of shallow organically enriched marine sediments using benthic microalgae. *Marine Pollution Bulletin, 57,* pp.108-115. DOI: https://doi.org/10.1016/j.marpolbul.2007.10.006

Yan, H. and Pan, G., 2002. Toxicity and bioaccumulation of copper in three green microalgal species. *Chemosphere, 49,* pp.471-476. DOI: https://doi.org/10.1016/S0045-6535(02)00285-0

Yang, J., Cao, J., Xing, G. and Yuan, H., 2015. Lipid production combined with biosorption and bioaccumulation of cadmium, copper, manganese and zinc by oleaginous microalgae *Chlorella minutissima* UTEX2341. *Bioresource Technology, 175,* pp.537-544. DOI: https://doi.org/10.1016/j.biortech.2014.10.124

Yeheyo, H.A., Ealias, A.M., George, G. and Jagannathan, U., 2024. Bioremediation potential of microalgae for sustainable soil treatment in India: A comprehensive review on heavy metal and pesticide contaminant removal. *Journal of Environmental Management, 363,* p.121409. DOI: https://doi.org/10.1016/j.jenvman.2024.121409

Yen, H.-W., Chen, P.-W., Hsu, C.-Y. and Lee, L., 2017. The use of autotrophic *Chlorella vulgaris* in chromium (VI) reduction under different reduction conditions. *Journal of the Taiwan Institute of Chemical Engineers, 74,* pp.1-6. DOI: https://doi.org/10.1016/j.jtice.2016.08.017

Yin, P., Yu, Q., Lin, Z. and Kaewsarn, P., 2001. Biosorption and desorption of cadmium(II) by biomass of *Laminaria japonica*. *Environmental Technology, 22,* pp.509-514. DOI: https://doi.org/10.1080/09593332208618254

Yuan, X., Gao, X., Liu, C., Liang, W., Xue, H., Li, Z. and Jin, H., 2023. Application of nanomaterials in the production of biomolecules in microalgae: A review. *Marine Drugs, 21,* p.594. DOI: https://doi.org/10.3390/md21110594

Zaib, M., Athar, M.M., Saeed, A., Farooq, U., Salman, M. and Makshoof, M.N., 2016. Equilibrium, kinetic and thermodynamic biosorption studies of Hg(II) on red algal biomass of *Porphyridium cruentum*. *Green Chemistry Letters and Reviews, 9,* pp.179-189. DOI: https://doi.org/10.1080/17518253.2016.1185166

Zeng, G., He, Y., Liang, D., Wang, F., Luo, Y., Yang, H., Wang, Q., Wang, J., Gao, P., Wen, X., Yu, C. and Sun, D., 2022. Adsorption of heavy metal ions copper, cadmium and nickel by *Microcystis aeruginosa*. *International Journal of Environmental Research and Public Health, 19,* p.13867. DOI: https://doi.org/10.3390/ijerph192113867

Zhang, J. and Luo, X., 2022. Bioaccumulation characteristics and acute toxicity of uranium in Hydrodictyon reticulatum: An algae with potential for wastewater remediation. *Chemosphere, 289,* p.133189. DOI: https://doi.org/10.1016/j.chemosphere.2021.133189

Zhang, R., Richardson, J.J., Masters, A.F. and Maschmeyer, T., 2022. Removal of Pb $^{2+}$ from water using sustainable brown seaweed *Phlorotannins*. *Langmuir, 38,* pp.8324-8333. DOI: https://doi.org/10.1021/acs.langmuir.2c00849

Zhang, X., Zhao, X., Wan, C., Chen, B. and Bai, F., 2016. Efficient biosorption of cadmium by the self-flocculating microalga *Scenedesmus obliquus* AS-6-1. *Algal Research, 16,* pp.427-433. DOI: https://doi.org/10.1016/j.algal.2016.04.002

Zhou, G.-J., Peng, F.-Q., Zhang, L.-J. and Ying, G.-G., 2012. Biosorption of zinc and copper from aqueous solutions by two freshwater green microalgae Chlorella pyrenoidosa and *Scenedesmus obliquus*. *Environmental Science and Pollution Research, 19,* pp.2918-2929. DOI: https://doi.org/10.1007/s11356-012-0800-9

Zinicovscaia, I., Cepoi, L., Povar, I., Chiriac, T., Rodlovskaya, E. and Culicov, O.A., 2018. Metal uptake from complex industrial effluent by cyanobacteria *Arthrospira platensis*. *Water, Air, & Soil Pollution, 229,* p.220. DOI: https://doi.org/10.1007/s11270-018-3873-3

Zornoza, R., Landi, L., Nannipieri, P. and Renella, G., 2009. A protocol for the assay of arylesterase activity in soil. *Soil Biology and Biochemistry, 41,* pp.659-662. DOI: https://doi.org/10.1016/j.soilbio.2009.01.003

Żukowska, J. and Biziuk, M., 2008. Methodological evaluation of method for dietary heavy metal intake. *Journal of Food Science, 73,* pp.R21-R29. DOI: https://doi.org/10.1111/j.1750-3841.2007.00648.x.