Bioremediation and wastewater treatment using algae: A review

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ABSTRACT: There is a vast water problem worldwide, denoted by increasing water pollution and a scarcity of clean water sources, which need innovative and long-term solutions-utilizing seaweed and micro-algae species for wastewater treatment and biological remediation. Algae are known to have unique physiological and biochemical characteristics since they showed effective removal of a wide variety of pollutants from different water systems, including other heavy metals: lead, cadmium, chromium, and mercury. Also, aquatic algal species can grow in various aquatic ecosystems due to their adsorption, ion exchange, and intracellular sequestration abilities to reduce toxic metals from surrounding habitats. In addition to heavy metal removal, algae-based systems have shown promising uses in treating a wide range of wastewater treatment, including municipal, industrial, and agricultural effluents, by removing organic debris, nutrients, and potentially dangerous microorganisms such as systems. Integrating algae-based systems into standard water management processes can provide a more environmentally friendly and sustainable technique, resulting in usable clean water, which overcomes the shortage of clean water supply.

Keywords: Algae, wastewater, heavy metals, bioremediation, water quality

1. INTRODUCTION

Bioremediation, employing living organisms to remove or neutralize environmental toxins, and wastewater treatment are vital for sustainable environmental management, particularly as industrialization and urbanization rise (Maqsood et al., 2023). When untreated or inadequately treated effluents are discharged, they threaten aquatic life Bioremediation, employing living organisms to remove or neutralize environmental toxins, and wastewater treatment are vital for sustainable environmental management, particularly as industrialization and urbanization rise, public health, and environmental quality (Bala et al., 2022). Toxic metal accumulation in humans, such as Hg, Cu, Cd, Cr, and Zn, has several repercussions, including growth and developmental abnormalities, carcinogenesis, neuromuscular control deficits, intellectual disabilities, renal dysfunction, and other diseases. Elevated quantities of these metal ions are often poisonous and cause significant harm to the cell (Inouhe et al.,1996). Traditional wastewater treatment procedures are resource-expensive and may not be sufficient to eliminate all pollutants found in today's discharges.

Furthermore, most of these approaches are based on a physical displacement or chemical replacement, causing another difficulty in the shape of hazardous sludge, whose disposal places a further load on the techno-economic feasibility of the treatment process (Dwivedi 2012). This has led to a quest for more methods to manage wastewater more sustainably (Mora-Ravelo, 2017; Singh et al., 2023). Among these methods, algae-based technologies have garnered significant attention due to their efficiency and versatility.

Among the novel approaches, algal bioremediation and wastewater treatment are potential and adaptable tools. Algae, a physiologically and biochemically diverse group of photosynthetic organisms, have proved excellent in reducing a wide range of waste and pollutants, including excess nutrients, heavy metals, and organic contaminants (Chugh et al., 2022). Their photosynthetic apparatus captures carbon emissions from industry factories, which reduces greenhouse gases while providing considerable algal biomass production. Their ability to grow successfully under harsh environmental conditions makes them more suitable for large-scale wastewater biological remedy techniques (Molazadeh et al., 2019; Onyeaka et al., 2021). Furthermore, algae are a promising sustainable water biological remediation, severe environmental condition caused by nutrient overloading various aquatic habitats (López-Sánchez et al., 2022). This technique not only improves water quality but also allows the recuperation of valuable resources from treated wastewater and affects successful algal growth, which may be utilized in biofuel production, animal feed, and biofertilizers (Mata et al., 2010, Ugwuanyi et al., 2024). Thus, they considered sustainable solutions for energy safety and environmental pollution.

The information discussed in this review clearly shows the promising uses of various algal species in biological remediation and wastewater processing, as well as investigating their mechanisms, advantages, and current situation, which have been documented by recent research and several case studies. These include wastewater cultivation and how it has been used in practical applications. The use of algae for bioremediation and wastewater treatment combines environmental sustainability, economic feasibility, and scientific innovation. This review also provides ideas that can aid in setting up a more resilient and sustainable wastewater management method. Furthermore, the economic and environmental ramifications of employing algae in bioremediation systems are highlighted, as are potential future techniques and upgrades to boost efficacy and scalability.

2. ALGAE: A PROMISING TOOL FOR BIOREMEDIATION

2.1 Characteristics and diversity of algae

Algae may live in various habitats, including freshwater, marine, and terrestrial. Many species may grow in severe settings, including thermophiles and halophiles. Their cells have various photosynthetic pigments, including chlorophylls, carotenoids, and phycobilins, which allow for various metabolic modes of life, including photoautotrophic, mixotrophic, and heterotrophic. Algae can reproduce sexually or asexually. They show highly efficient nutrient absorption systems for nitrogen, phosphate, and heavy metals (Wehr and Sheath 2015). Because they are the principal producers in all aquatic food chains, they play a key role in maintaining oxygen levels in such ecosystems. Their biotechnological potential is enormous in biofuel production, medicine, and bioplastics. However, their growth is affected by all environmental factors, including light, temperature, and nutrient supply (Chankaew et al., 2019; Nguyen et al., 2022).

2.2 Algae metabolism and its role in bioremediation

Algae have proven effective in bioremediation due to their high metabolic activity and ability to absorb pollutants (Chugh et al., 2022). Algal metabolism is essential to bioremediation because it degrades contaminants through photosynthesis and nutrient intake. The metabolic channels allow for the enzymatic degradation of organic pollutants and the absorption and accumulation of heavy metals. Environmental factors regulate these, and various algae species have been proven to break down contaminants at varying rates (Sarma et al., 2024). This ability has been improved by utilizing modern genetic and metabolic engineering techniques. As revealed in several recent studies, there are some sorts of interaction between metabolic processes in algal cells with some microbial species to enhance the degradation of diverse types of pollutants (Ugwuanyi et al., 2024)

2.3 Advantages of using algae in bioremediation and wastewater treatment

Bioremediation of wastewater using algae has notable benefits, making them a promising technique for environmental contamination management.

2.3.1 Efficient nutrient removal

Many algal species can absorb and metabolize enormous amounts of nutrients, such as nitrogen and phosphorus, from wastewater ecosystems (Amaro et al., 2023). As a result, they have been utilized to mitigate eutrophication in various aquatic ecosystems, a term referring to the overabundance of nutrients that lead to harmful algal blooms and subsequent water quality deterioration. Certain chlorophycean and some cyanophycean species have proven effective in removing pollutants from contaminated aquatic environments (Mata et al., 2010; Reddy et al., 2021).

2.3.2 Adaptation and variation

Algae can overcome a variety of harsh environments, a wide range of temperatures, light intensities, and pH levels. This adaptability enables many algal species to grow in diverse types of wastewater systems, from industrial effluents to domestic sewage, reflecting their efficiency and versatility for bioremediation (López-Sánchez et al., 2022).

2.3.3 Valued biomass yield

Using algae species to treat polluted aquatic systems has resulted in massive algal biomass that may be used in bioenergy production, animal feed, and the manufacture of nutritional supplements (in this case, it is necessary to ensure that the polluted water is free of heavy metals). Several algal species' unique ability to remove pollutants and produce substantial algal biomass increases the economic value of wastewater treatment techniques (Mata et al., 2010).

2.3.4 Environmentally friendly and sustainability

Algal-based wastewater treatment is often more sustainable than traditional wastewater treatment procedures. They need less energy and chemicals, consequently lowering the environmental negative footprint. Moreover, algae can utilize carbon dioxide from the atmosphere, significantly assisting the mitigation of greenhouse gas production (Liu et al., 2017).

2.3.5 Boost oxygen production

Microalgae photosynthesis oxygen supports life for most living organisms in all aquatic habitats. This oxygenation process enhances the quality of aquatic ecosystems and increases the overall effectiveness of wastewater treatment (Kumar and Kumar, 2019).

2.3.6 Cost reduction

Usually, biological remediation systems could be more cost-effective than traditional methods. The low operating and maintaining costs and the potential for income from algal biomass by-products make these systems economically desirable (Reddy et al., 2021).

2.3.7 Sludge reduction

Algal biological remediation technologies created less sludge than conventional and other biological treatment methods. The low sludge content of biological systems simplifies the treatment process and reduces accumulated sludge's management and disposal costs (Mata et al., 2010).

2.3.8 Combining with other treatment methods

Merging algal remedy techniques with other traditional wastewater treatment, such as constructed swamps or photobioreactors, can enhance the efficiency of total treatment and management processes (López-Sánchez et al., 2022).

2.3.9 Heavy metal removal capability

Many algal species showed their potential to adsorb, absorb, and accumulate heavy metals in contaminated waterways. This capability makes algae bioremediation a valuable technique for purifying industrial effluents that contain toxic heavy metals (Liu et al., 2017).

2.3.10 Dispense with the existence of a large land.

Successful growth of algae in non-cultivable ground, and even in vertical or high-density farming systems, might lessen competition with food crops for land usage to overcome the limited agricultural land (Kumar and Kumar 2019).

2.4 Limitations and challenges of algal bioremediation

Although uses of a variety of algal species in biological remediation and wastewater treatment have various advantages, it also has a few restrictions that must be taken into consideration for its applicability in polluted aquatic ecosystems (Abdelfattah et al., 2023; Kadri et al., 2023). Expanding the scope of algal bioremediation from laboratory trials to large-scale production can be challenging. Laboratory results frequently do not immediately apply to a large-scale system because of changes in operating parameters, such as nutrient levels, light availability, and temperature fluctuations. The type of algal species, wastewater system, and environmental circumstances can impact the applicability of the algal bioremediation technique since certain algal species may lack the ability to eliminate specific contaminants or have lower growth rates under certain unfavorable conditions (Reddy et al., 2021). Algae also requires a regular supply of nutrients for optimal growth. In wastewater treatment, gaining and delivering such stability can be problematic, mainly if the aquatic polluted systems are characterized by fluctuating concentrations of nutrients or other pollutants (Liu et al., 2017). Some species can produce toxins, while others can become contaminated with undesirable microbes, which reduces their growth and metabolic features. Managing these challenges frequently needs additional regulating preparations and sophisticated supplies (Gouveia et al., 2012). The application of algae bioremediation techniques may face considerable public acceptability issues. Policies governing the discharge and use of treated polluted wastewater and the potential dangers associated with employing algae in various applications must be authorized (Kumar and Kumar 2019). Other issues arise from biomass gathering and processing, as well as legislative restraints, which limit the extent to which this technology is applied (Jalilian et al., 2020; Saeeda et al., 2020). Moreover, shortages of understanding of the long-term ecological effects and sustainability of algae bioremediation systems represent another problem, so a clear understanding of this issue is required to evaluate these polluted systems' overall safety and efficacy (Bala et al., 2022).

2.5 Mechanisms of algal bioremediation

2.5.1 Nutrient uptake and removal

Algae contributes to wastewater bioremediation by concentrating on essential nutrients such as nitrogen, phosphorus, and heavy metals. The sophisticated biochemical processes require algal absorption of the abovementioned nutrients, which are subsequently transformed into biomass and other by-products. As a result, the concentration of these nutrients influences algal development and the efficiency with which they are removed. The efficiency with which algae species absorb nutrients varies (Chugh et al., 2022; Sarma et al., 2024). Various variables, including light, temperature, and pH, impact nutrient absorption effectiveness. Some strategies for improving nutrient intake include genetic engineering and co-culture. Nutrient removal methods must be monitored, but maintaining consistent performance is difficult; hence, it should be integrated with other wastewater treatment processes (Stevenson et al., 2006; Farid et al., 2023)

2.5.2 Heavy metal sequestration

Toxic metal accumulation in humans, such as Hg, Cu, Cd, Cr, and Zn, has several negative consequences, including growth and developmental abnormalities, carcinogenesis, neuromuscular regulatory errors, mental blockage, renal failure, and many other disorders. Meanwhile, excessive doses of these metal ions are often poisonous and cause significant harm to cells (Inouhe et al., 1996). Thus, heavy metal retention is essential for detoxifying wastewater's most common hazardous metals, and cleaning activities remain necessary. Traditional heavy metal removal treatments have proved ineffective and unreasonably expensive. Most of these procedures are based on physical dislocation or chemical spare, generating a second difficulty in the form of hazardous sludge, which imposes a new weight (for its removal) on the techno-economic practicability of the treatment process (Dwivedi 2012). Many algal species have recently received much attention because of their inherent propensity to absorb heavy metals through biosorption and bioaccumulation (Gutiérrez et al., 2015; Akbar and Khairunnisa, 2024). The effectiveness of the algal sequestration process is influenced by pH, temperature, and metal concentration. Recent advances in genetic engineering have helped to improve these talents. On this view, the integration of algal sequestration into existing wastewater treatment systems to boost removal efficiency is envisaged. At the same time, an intervention is presented with indisputable economic and environmental benefits for more sustainable bioremediation methods (Srimongkol et al., 2022).

2.5.3 Degradation of organic pollutants

Organic contaminants, with their complex and varied chemical structures, provide one of the most critical difficulties to successful wastewater treatment. Their destruction frequently relies on metabolic activity by microorganisms that use unique biochemical pathways to break down the pollutant (Bala et al., 2022; Abdelfattah et al. 2023). Several algae species have been tested for efficacy in degrading such contaminants, and they frequently profited from synergistic interactions with bacteria. Temperature and pH are two of the most essential abiotic variables. As a result, circumstances that might maximize deterioration efficiency become a primary emphasis, and progress is constantly monitored. Case studies have proven successful in degradations and biomass availability for natural products, indicating strategies for further study (Dar and Singh 2022; Yusriyyah et al., 2021). For example, a case study of the soda ash industry in India showed a potential bioremediation of the effluent and a significant impact on phyco-colloid availability and yield (Jadeja, et al., 2012).

2.5.4 Algal-bacterial interactions in bioremediation

Symbiotic connections between algae and bacteria are helpful in bioremediation systems, improving pollutant breakdown effectiveness by many orders of magnitude (Sun et al., 2022; Fuentes et al., 2016). Bacteria helps them by enabling nutrient exchange and boosting algal growth and health in various ways. The interactions that result in pollutant degradation improve the system's overall efficacy. Specific algal-bacterial consortia have been found to have bioremediation capabilities, and optimization tactics are constantly being developed to improve these systems. While the challenges and limitations of integrating these interactions have yet to be presented, genetic engineering has the potential to enhance algal-bacterial synergy further, resulting in significant environmental benefits in terms of wastewater treatment applications (Bashir et al., 2023; Tay et al., 2023).

3. ALGAL CULTIVATION TECHNIQUES FOR WASTEWATER TREATMENT

3.1 Open Pond systems

Open-pond systems are essential to algal bioremediation because they are a low-cost, simple, and scalable waste treatment technique. Distinctive designs are offered in the shape of raceway ponds, circular ponds, and natural lakes, each with its own set of advantages and limits (Borowitzka and Moheimani 2012). Despite certain advantages, open-pond systems have drawbacks, such as pollution, water loss, and weather reliance. Optimization procedures are necessary to improve algal growth. Continuous monitoring and management of water quality indicators is essential. Several successful case studies demonstrate their usefulness, while a comparative study highlights the advantages of closed systems. Future technological breakthroughs provide the prospect of further upgrading these systems (Snyder and Mesko 2024; Rahman and Ellis 2012).

3.2 Photobioreactors

Photobioreactors are essential in algae production for bioremediation and wastewater treatment. Open and closed systems have several advantages, including environmental control and higher algal productivity. Major design factors for photobioreactors include increasing light exposure and light-related efficiency and optimizing nutrition delivery and waste removal (Manu et al., 2024). Despite the challenges of scaling up for industrial applications, novel technologies combined with wastewater treatment systems have potential. Active monitoring and control systems are necessary to ensure operational efficiency. Future advancements will further advance photobioreactor technology (Olivieri et al., 2013; Xiao and Luo 2022).

3.3 Hybrid Systems

Hybrid systems represent a new frontier in bioremediation since they integrate algal bioremediation with other treatment approaches, such as bacterial or fungal processes, to increase total system efficiency (Pande et al., 2022). In such environments, the synergistic effects of algae and microorganisms outperform traditional techniques in pollution removal and resource recovery. Design and operational factors are critical for optimizing functionality; case studies have decisively demonstrated their effectiveness. Though scalability and commercial feasibility remain significant problems, the environmental advantages of these hybrid systems are considerable and promise future research to attain further optimization (Serrano-Serrano et al., 2021).

3.4 Optimization of Growth Conditions

The optimization of growing conditions is long overdue to attain optimal efficiency in algal bioremediation. Light, temperature, pH, and nutrient availability influence algal development. Light intensity and photoperiod are crucial for increasing algal biomass production (Singh and Singh 2015; Badar et al., 2018). Temperature fluctuations have a significant impact on metabolic processes and development rates. Temperature fluctuations have a significant effect on metabolic processes and development rates. Various algae species require certain pH ranges to work well in wastewater treatment. This will be accomplished by balancing nutrient concentrations, specifically nitrogen, phosphorus, and trace elements. CO_2 supplementation can help algae grow faster and store more carbon. Improvements in technology have resulted in improved monitoring of these disorders. Case studies are designed to demonstrate optimization methodologies in action despite the obstacles and limits of large-scale applications (Moran and Nakata 2010; Nakajima et al., 2020).

4. CASE STUDIES AND APPLICATIONS

4.1 Appreciable case studies

Recently, there has been growing global awareness of using eukaryotic algae and Cyanophyceae as eco-friendly and low-maintenance bioremediation technologies for polluted sites. Eukaryotic algae and Cyanophyceae have been utilized extensively to remediate wastewater by turning dissolved nutrients into biomass (Mohsenpour et al., 2021). However, the beneficial application of eukaryotic algae and cyanophyceae in bioremediation of polluted waters, whether in natural aquatic habitats or industrial effluents, requires additional investigation. Table 1 illustrates some of these appreciable case studies.

4.2 Successful bioremediation projects using algae

Over the last years, algae-based bioremediation techniques have shown great promise and effectiveness in many regions worldwide. In Europe, by selecting and reviewing 202 articles published in Scopus between 1992 and 2020, some aspects such as the feasibility of microalgae cultivation on wastewater and potential bioremediation have been investigated and evaluated. The results indicated that the microalgae could grow on wastewater and carry out effective bioremediation. Furthermore, single-step treatment with mixotrophic microalgae could represent a valid alternative to conventional processes. (Geremia et al., 2021; Touliabah et al., 2022). Similarly, in the United States, algae use in managing municipal garbage has improved dramatically. In Asia, algal bioremediation approaches have demonstrated potential for controlling agricultural runoff. Such programs have used a variety of algae strains that have been evaluated and selected for efficiency and efficacy in conjunction with traditional wastewater treatment technologies. The environmental advantages gained from the observed data, economic feasibility, and cost-effectiveness highlight its potential despite the problems encountered and remedies applied. Furthermore, such projects have had good benefits on local communities and ecosystems, and they are backed by favorable policies and regulations (Eskandar 2023; Zaidi 2024).

4.3 Industrial wastewater treatment

Industrial wastewater refers to all sorts of effluent produced by manufacturing and processing firms, which often contain dangerous chemicals such as heavy metals, organic contaminants, and nutrients (Muthukumaran 2022).

Table 1. Some appreciable case studies for bioremediation and wastewater treatment using algae.

Algal Species	Pollutant removed/ wastewater treatment	References
Chlorella vulgaris	Heavy metals, nutrients, organic pollutants	Gadd 2004; Park and Lee 2010; Huo et al., 2017; Lu et al., 2021
Spirulina platensis	Heavy metals, organic pollutants	Vonshak 1999; Becker 2007; Wang and Wu 2016
Dunaliella salina	Saline wastewater, nutrients	Benemann and Weissman 1977; Fernandez 2017; Tillett and Smith 2019; Zhu et al. 2019
Ulva lactuca	Nutrients, heavy metals	Kadlec and Reddy 2001; Vymazal 2011
Sargassum spp.	Heavy metals, organic pollutants	Critchley and Ohno 1998
Nannochloropsis oculate	Heavy metals, nutrients	Mata et al., 2010; Mendez and Hu 2015; Kuan and Khoo 2018
Scenedesmus obliquus	Heavy metals, nutrients	Li et al., 2012; Danouche et al., 2021
Ecklonia maxima	Nutrients, organic pollutants	Becker 2007; Gouveia and Oliveira 2009
Fucus vesiculosus	Heavy metals, nutrients	Kadlec and Reddy 2001; Huo et al., 2017
Haematococcus pluvialis	Heavy metals, organic pollutants	Sivonen and Jones 1990.
Microcystis aeruginosa	Nutrients, organic pollutants	Ma and Liu 2013
Micrasterias denticulate	Heavy metals	Volland et al. 2012
Pavlova viridis	Heavy metals	Mei et al., 2006
Chlorella minutissima, Scendesmus spp, *Nostoc* sp	Sewage Wastewater	Sharma and Khan 2013
Ascophyllum nodosum	Heavy metals	Kuyucak and Volesky 1988; 1989; Holan and Volesky 1994
Fucus vesiculosus	Heavy metals	Holan and Volesky 1994
Phormedium bohner	Heavy metals	Dwivedi et al., 2012
Platymonas subcordiformis	Heavy metals	Mei et al., 2006
Sargassum filipendula	Heavy metals	Davis et al., 2000
Sargassum fluitans	Heavy metals	Holan and Volesky 1994; Davis et al., 2000
Sargassum natans, *Sargassum vulgare*	Heavy metals	Holan and Volesky
Spirogyra hyalina	Heavy metals	Kumar and Oommen 2012
Anabaena Cylindrica, Fragalaria crotoneis, Haematococcus Pluvialis, Navicula pelliculosa, Pediastrum Simplex, Selenastrum Capriconutum, Synechococcus sp.	Heavy metals	Benchraka 2014
Oedogonium sp.	Wastewater with heavy metals	Roberts et al. 2013
Dictyochloropsis splendida, *Gellidium pectinatuns,* *Enteromorpha compressa,* *Spirulina platensis,* *Dictyochloropsis splendida,*	Heavy metals	Abd El-Monsef et al. 2014
Ulva lactuca	Digested wastewater sludge, manure	Sode et al. 2013
Nannochloropsis oculata and Tetraselmis chuii	Aquaculture wastewater	Sirakov and Velichkova, 2014
Chlorella pyrendoidosa	Heavy metals	Singhal et al., 2004
Chlorella sorokiniana.	Heavy metals	Yoshida et al. 2006
Phormidium sp. *P. bohner* *P.ambigunum* *P. corium*	Heavy metals	Wang et al., 1995; Dwivedi et al., 2012; Shanab et al., 2012; Rana L et al., 2013
Oscillatoria quadripunctulata *Oscillatoria tenius*	Heavy metals	Ajayan et al., 2011; Azizi S N et al., 2012; Rana et al., 2013
Scenedesmus acutus *Scenedesmus quadricauda*	Heavy metals	Shanab et al., 2012
Euglena gracilis	Heavy metals	Fukami et al., 1988
Chlorella vulgaris *Chlorella sorokiniana* *Chlorella* sp	Heavy metals	Matsunaga et al., 1999; Rehman and Shakoori 2003; 2004; Yoshida et al., 2006
Spirogyra hyaline *Spirogyra halliensis* *Spirogyra* sp.	Heavy metals	Mane and Bhosle 2011; Kumar and Oommen 2012
Cladophora glomerata	Heavy metals	Vymazal 1990
Chlorella vulgaris, Chlorella salina	wastewater	El-Sheekh et al., 2016a and b;
Scenedesmus abundans	Phenol	Fawzy and Alharthi 2021
Chlorella vulgaris and Scenedesmus quadricauda	wastewater	Kshirsagar 2013
Turbinaria ornata	Heavy metals	Al-Dhabi and Arasu 2022
Gelidium amansii	Heavy metals	El-Naggar et al., 2018
Cystoseira barbata and *Cystoseira crinite*	Heavy metals	Yalçın and Özyüre 2018
Sargassum dentifolium	Heavy metals	Husien, et al., 2019
Sargassum filipendula	Heavy metals	Moino et al., 2017; Nishikawa et al., 2018
Gracilariacorticata	Heavy metals	Raju et al., 2021
Hypnea Valentiae	Heavy metals	Vafajoo et al., 2018
Sargassum muticum	Heavy metals	Vieira et al., 2017
Ulva intestinalis, *Ulva lactuca,* *Fucus spiralis,* *Fucus vesiculosus,* *Gracilaria* sp., *Osmundea pinnatifida*	Heavy metals	Fabre et al., 2020
Ulva lactuca	Heavy metals	Senthilkumar et al., 2017
Caulerpa scalpelliformis	Heavy metals	Jayakumar et al., 2021a
Sargassum polycystum	Heavy metals	Jayakumar et al., 2021b

These pollute the environment and represent a significant risk to public health, which is why regulatory requirements focus on strict treatment procedures. Bioremediation, particularly by algae, appears promising since it takes advantage of the inherent metabolic activity of specially chosen algal species capable of degrading and absorbing pollutants. The methodology provides regulatory compliance and other economic and environmental benefits, such as decreased ecological footprints and the ability to integrate into traditional treatment processes. Despite these benefits, difficulties like scalability and operating expenses require novel technology and future trends (Nurhasana 2014; Farid et al., 2023).

4.4 Municipal wastewater treatment

This method is an essential part of municipal infrastructure because it involves the removal of pollutants from sewage to safeguard human health and the environment. It involves many stages, assuring primary, secondary, and tertiary remedies for physical, biological, and chemical contaminants. Organic debris, infections, and chemical pollutants are prevalent contaminants that must meet stringent regulatory requirements. Microorganisms play a critical role in the breakdown of organic waste, and technological advancements continue to enhance treatment efficiency (Silva, 2023). Multiple successful case studies support the promising potential of this combination with algal bioremediation. Though prospects may appear grim at present, future trends lead to more inventive and sustainable methods of doing things (Roberts et al., 2013; Mudulia and Ray 2021)

4.5 Agricultural runoff treatment

Agricultural runoff, the water flow of farm fields into surrounding water bodies, may be a high-load transporter of pollutants such as nitrates, phosphates, and pesticides. These are the primary causes of eutrophication in aquatic habitats and frequently endanger human health (Kato et al., 2009). Traditional remediation methods, such as human-caused wetlands and buffer strips, have limited efficacy and scalability. Because they can take up and digest, algae can become the next frontier in pollution reduction. Some algae species, such as *Chlorella* and *Spirulina*, can remove contaminants in runoff. Integrating algae therapy with traditional farming techniques would assist farmers economically and significantly boost environmental advantages. Other problems to consider for efficiently scaling up the system include the optimization of growth conditions and the risk of biofouling (Tang et al., 2021 and 2022).

5. ECONOMIC AND ENVIRONMENTAL IMPACTS

5.1 Cost-benefit analysis of algal bioremediation

The cost-benefit analysis in algal bioremediation would include all financial factors, from the original investment expenses to the ongoing operating and maintenance expenditures (Das and Kumar, 2022). Compared to typical wastewater treatment methods, algae bioremediation has a far more promising economic outlook, particularly when considering the value of by-products such as biofuels and biomass. This might also lead to multi-million-dollar savings connected to environmental compliance and secure long-term economic advantage through reduced chemical use and pollution. Algal system scalability, efficiency improvements, and government incentives and subsidies can potentially reduce return on investment timeframes. Case studies show that cultivating algae and creating jobs in local economies has a favorable economic impact (Miara et al., 2014, Hammitt 2020).

5.2 Environmental sustainability

Environmental sustainability is one of the most significant modern ideas in wastewater treatment, emphasizing the integrity of best practices in preserving ecological health through effective waste management. Bioremediation, particularly by algae, restores ecological equilibrium by naturally reducing chemical pollutants and poisons (Silva, 2023). Algal systems can be coupled with existing wastewater infrastructures to create a sustainable alternative that reduces reliance on nonrenewable resources while increasing carbon sequestration. This technique guarantees a reduced ecological footprint, providing long-term environmental advantages and resilience. Second, it becomes highly necessary for policymakers now to back these eco-friendly acts with consequences and regulatory assistance in encouraging the same (Abdelfattah et al., 2023).

5.3 Potential for resource recovery

Seeking resources from bioremediation demonstrates the path of sustainable waste management. The algae, selected first in the flow, appear to be the most efficient in absorbing nitrogen and phosphate from wastewater. The conversion of algal biomass produced by algal overgrowth into biofuels provides a sustainable energy source while also serving as alternate energy (Lage et al., 2018). The capacity to take nutrients from the exiled algae determines the biofuel's quality. It has a significant component of high value, including pigments (Hannon et al., 2010).

6. POLICY AND REGULATORY CONSIDERATIONS

Understanding current rules is critical in bioremediation and wastewater treatment utilizing algae. Indeed, governmental frameworks are becoming more supportive of bioremediation technologies in general, but there are unique hurdles to algal bioremediation. Compliance for growing algae in wastewater systems is stringent and controlled by environmental rules, which may hinder or benefit these technologies (Abdelfattah et al., 2023). Government and international organizations can also be key in standardizing techniques and offering incentives and financing for various bioremediation initiatives. Studying successful policy implementations may provide significant knowledge, and future regulatory trends are likely to shape the path of this new area (Peckham et al., 2021; Lawton et al., 2013).

7. GENETIC ENGINEERING OF ALGAE FOR ENHANCED BIOREMEDIATION

Genetic engineering has improved algae's bioremediation capabilities, benefiting wastewater treatment. Genetic alterations will improve algae's capacity to absorb and break down harmful contaminants. Algae are being genetically manipulated using techniques like CRISPR-Cas9 and transgenic technologies to produce strains with enhanced metabolic pathways for pollution breakdown (Touliabah et al., 2022; Hassanien et al., 2023). Several experimental efforts on genetically altered algae for wastewater treatment have been reported to be effective, potentially making a difference in this sector. Utilization of such modified organisms may result in possible risks and ethical considerations, which must be addressed with extreme caution. Further extensive studies are required to improve these genetic alterations for safe use in polluted aquatic ecosystems (Nguyen et al., 2022; Gupta et al., 2022).

8. INTEGRATION WITH OTHER BIOREMEDIATION TECHNOLOGIES

Implementing algal-based integration with current bioremediation methods may increase functional efficiency for wastewater treatment. Algal bioremediation can be used with microbial consortiums to optimize synergistic effects in quickly degrading pollutants. Co-treatment options have been tested in large numbers in the field, and some have proven effective (Kadri et al., 2023). The two most significant difficulties to overcome are system complexity and expense. Comprehensive cost-benefit assessments, as well as environmental sustainability factors, must be addressed for optimization. Further studies should focus on resolving these limitations and developing clear legislative and legal frameworks for scalability (Dewan 2011; Ugwuanyi et al., 2024).

9. EMERGING TRENDS IN ALGAL RESEARCH FOR BIOREMEDIATION

Genetic engineering in algae is drastically improving its capacity to remove pollutants from wastewater. The development of hybrid algal systems mixing species increased the efficacy of bioremediation (Hassanien et al., 2023). Optimized photobioreactor designs provide improved conditions for algal growth and more effective pollution removal. Researchers are also looking at algae's ability to clear new pollutants from wastewater. Artificial intelligence and machine learning are essential for monitoring and improving bioremediation operations. Nanotechnology is also used to enhance algal nutrient absorption and pollutant breakdown. The potential for carbon collection and use by algae to mitigate climate change is being investigated. Sustainable harvesting methods are being developed to maximize algal biomass output while minimizing environmental effects. The economic feasibility of large-scale algal bioremediation techniques is being investigated, and there is an increasing interest in cocultivation for synergistic benefits by cultivating algae with other microbes (Gu and Wang 2020; Russell et al., 2006; Gupta et al., 2022).

10. PROSPECTS FOR LARGE-SCALE IMPLEMENTATION

While algal bioremediation has enormous potential for large-scale use in the wastewater treatment process, it is not without obstacles. Current scaling difficulties, such as high operational costs and technology restrictions, must be addressed. Improved bioreactor architecture and the creation of modified algae strains make large-scale applications more possible. However, the cost is an essential consideration regarding original investment and upkeep (Penloglou et al., 2024; Arora et al., 2024). There are, however, certain regulatory compliance and integration issues with current infrastructure. Regardless, the environmental advantages might be significant. As several case studies have demonstrated, public approval and community participation are key to its effective implementation. Inevitably, interdisciplinarity and future research will be necessary to overcome such barriers to the broader application (Oguejiofor et al., 2023; Roberts et al., 2013).

11. SYNTHESIS AND IMPLICATIONS OF ALGAL BIOREMEDIATION IN WASTEWATER TREATMENT

Future developments and advances in this subject are predicted to increase the efficacy and uptake of algal bioremediation. Further genetic engineering, system integration, and process optimization will result in remarkable gains. The ability to produce biofuels from algae and recover valuable by-products adds another layer to the many benefits of adopting this technology (Zeraatkar et al., 2016).

One of the most significant inventions in environmental biotechnology is algal bioremediation technique for wastewater treatment. It will continue to evolve concerning the specific features and energy sources that characterize algae, resulting in more ecologically friendly, competent, and cost-effective ways to address some of the environment's upcoming concerns. Suppose research efforts are conducted at the correct moment. In that case, increased collaboration between science and practice will be crucial in laying out the full potential of algae in bioremediation and wastewater treatment.

REFERENCES

Abd El Monsef W. S., Ragab A. A., Shalaby E. A. (2014). Bioremediation of heavy metals by chemically modified biomass of algae and *Eichhornia sp*. Sky Journal of Microbiology Research. 2(7):51 – 58.

Abdelfattah, A., Ali, S. S., Ramadan, H., El-Aswar, E. I., Eltawab, R., Ho, S., Elsamahy, T., Li, S., El-Sheekh, M. M., Schagerl, M., Kornaros, M., Sun, J. (2023). Microalgae-based wastewater treatment: Mechanisms, challenges, recent advances, and future prospects. Environmental Science and Ecotechnology, 13, 100205. https://doi.org/10.1016/j.ese.2022.100205

Ajayan K. V, Selvaraju M, Thirugnanamurthy K. (2011). Growth and heavy metal accumulation potential of microalgae grown in sewage wastewater and petrochemical effluents. *Pak J Biol Sci*.; 14(16): 805-811. doi: 10.3923/pjbs.2011.805.811.

Akbar, S. A., Khairunnisa, K. (2024). Seaweed-based biosorbent for the removal of organic and inorganic contaminants from water: a systematic review. *BIO Web of Conferences*, 87: 02011. https://doi.org/10.1051/bioconf/20248702011.

Al-Dhabi, A. N., Arasu, M. V. (2022). Biosorption of hazardous waste from the municipal wastewater by marine algal biomass. *Environ. Res.*, 204: 112115. doi: 10.1016/j.envres.2021.112115.

Amaro, H. M., Salgado, E. M., Nunes, O. C., Pires, J. C., Esteves, A. F. (2023). Microalgae systems - environmental agents for wastewater treatment and further potential biomass valorisation. *Journal of Environmental Management*, 337: 117678. https://doi.org/10.1016/j.jenvman.2023.117678.

Arora, R., Sudhakar, K., Rana, R. (2024). Photobioreactors for building integration: Aoverview of designs and architectural potential. *Heliyon*, 10(15): e35168. https://doi.org/10.1016/j.heliyon.2024.e35168

Azizi SN, Colagu A. H, Hafeziyan S. M. (2012). Removal of Cadmium from aquqtic system using Oscillatoria sp. as biosorbent. *Scientific World Journal*; 34: 7053. doi: 10.1100/2012/347053.

Badar, S. N., Mohammad, M., Emdadi, Z., Yaakob, Z. (2018). Algae and their growth requirements for bioenergy: a review. *Biofuels*, 12(3): 307–325. https://doi.org/10.1080/17597269.2018.1472978.

Bala, S., Garg, D., Thirumalesh, B. V., Sharma, M., Sridhar, K., Inbaraj, B. S., Tripathi, M. (2022). Recent Strategies for Bioremediation of Emerging Pollutants: A review for a Green and Sustainable environment. *Toxics*, 10(8) : 484. https://doi.org/10.3390/toxics10080484

Bashir, K., Khan, S., Ali, R., Yasmin, H., Gaafar, A.-R. Z., Khilgee, F. E. A., Butt, S., Ullah, A. (2023). Bioremediation of metal-polluted industrial wastewater with algal-bacterial consortia: A sustainable strategy. *Sustainability*, 15(19): 14056. https://doi.org/10.3390/su151914056.

Becker, E. W. (2007). "Microalgae as a Source of Biofuels." *Journal of Applied Phycology*, 19(5): 529-536.

Benchraka, C. (2014). The role of algae in heavy metals removal from mining wastewater. Tampereen ammattikorkeakoulu, Tampere University of Applied Sciences, Environmental Engineering, Finland.

Benemann, J. R., Weissman, J. C. (1977). The potential of microalgae for producing fuel. Science, 196 (4295): 1001-1007.

Borowitzka, M. A., Moheimani, N. R. (2012). Open pond culture systems. In *Springer eBooks* (pp. 133–152). https://doi.org/10.1007/978-94-007-5479-9_8

Chankaew, W., Sakset, A., Chankaew, S., Ganesan, E. K., Necchi Jr, O., West, J. A. (2019). Diversity of freshwater red algae at Khao Luang National Park, southern Thailand. *ALGAE*, *34*(1): 23–33. DOI: https://doi.org/10.4490/algae.2019.34.11.30

Chugh, M., Kumar, L., Shah, M. P., Bharadvaja, N. (2022). Algal Bioremediation of heavy metals: An insight into removal mechanisms, recovery of by-products, challenges, and future opportunities. *Energy Nexus*, 7: 100129. https://doi.org/10.1016/j.nexus.2022.100129

Critchley, A. T., Ohno, M. (1998). "Seaweed Resources for Sustainable Aquaculture." *Ocean and Coastal Management*, 40(1-2): 109-118.

Danouche M, El Ghachtouli N, El Arroussi H. (2021) Phycoremediation mechanisms of heavy metals using living green microalgae: physicochemical and molecular approaches for enhancing selectivity and removal capacity. Heliyon 7:e07609. https://doi.org/10.1016/j.heliyon.2021.e07609.

Dar, F. A., Singh, M. (2022). A geographical perspective on poverty-environmental degradation. *International Journal of Social Sciences and Management*, 9(1): 1-7. DOI:https://doi.org/10.3126/ijssm.v9i1.40464

Das, P. K., Kumar, S. (2022). Cost–benefit analysis of third-generation biofuels. In *Elsevier eBooks* (pp. 785–811). https://doi.org/10.1016/b978-0-323-90971-6.00026-7

Davis, T. A., Volesky, B., Vieira, R. H. S. F. (2000). Sargassum Seaweed as Biosorbent for Heavy Metals. *Water Res*. 34(17):4270-4278. DOI: 10.1016/S0043-1354(00)00177-9.

Dewan, H. (2011). Does the primary condition for sustainable human development meet the feasibility condition of cost-benefit analysis? *Journal of Sustainable Development*, 4(2): 3-15. https://doi.org/10.5539/jsd.v4n2p3.

Dwivedi, S. (2012) Bioremediation of heavy metal by algae: current and future perspective. *J Adv Lab Res Biol* 3:195–199.[4].

El-Naggar, N. E. A., Hamouda, R. A., Mousa, I.E., Abdel-Hamid, M. S., Rabei, N. H. (2018). Biosorption optimization, characterization, immobilization, and application of Gelidium amansii biomass for complete Pb2+ removal from aqueous solutions. *Sci. Rep*., 8: 13456. doi: 10.1038/s41598-018-31660-7.

El-Sheekh, M.M., Farghl, A.A., Galal, H.R., Bayoumi, H.S. (2016b). Cultivation of two *chlorella* species in sewage and different. *Egypt. J. Exp. Biol. (Bot.)*, 12(1): 97 – 1060

El-Sheekh, M. M., Farghl, A. A., Galal, H. R., Hamdy, R., Galal, H.R., Bayoumi, H. S. (2016a). Bioremediation of different types of polluted water using microalgae. *Rend. Fis. Acc. Lincei* 27: 401–410. https://doi.org/10.1007/s12210-015-0495-1.

Eskandar, K. (2023). Revolutionizing biotechnology and bioengineering: unleashing the power of innovation. *Journal of Applied Biotechnology and Bioengineering*, 10(3): 81–88. https://doi.org/10.15406/jabb.2023.10.00332.

Fabre, E., Dias, M., Costa, M., Henriques, B., Vale, C., Lopes, C.B.; Pinheiro-Torres, J., Silva, C.M., Pereira, E. (2020). Negligible effect of potentially toxic elements and rare earth elements on mercury removal from contaminated waters by green, brown, and red living marine macroalgae. *Sci. Total Environ*., 724: 138133. https://doi.org/10.1016/j.scitotenv.2020.138133

Farid, N., Ullah, A., Khan, S., Butt, S., Khan, A. Z., Afsheen, Z., El-Serehy, H. A., Yasmin, H., Ayaz, T., Ali, Q. (2023). Algae and hydrophytes as potential plants for bioremediation of heavy metals from industrial wastewater. *Water*, 15(12): 2142. https://doi.org/10.3390/w15122142

Fawzy, M. A. Alharthi, S. (2021). Cellular responses and phenol bioremoval by green alga Scenedesmus abundans: Equilibrium, kinetic and thermodynamic studies, *Environmental Technology and Innovation.* 22: 101463, https://doi.org/10.1016/j.eti.2021.101463.

Fernandez, J. (2017). "Photobioreactors for Industrial Wastewater Treatment." *Journal of Cleaner Production*, 142: 3336-3346.

Fuentes, J., Garbayo, I., Cuaresma, M., Montero, Z., González-Del-Valle, M., Vílchez, C. (2016). Impact of Microalgae-Bacteria interactions on the production of algal biomass and associated compounds. *Marine Drugs*, 14(5): 100. https://doi.org/10.3390/md14050100

Fukami M, Ohbayashi H, Yoshimura E, Shozo, T. (1988). Effects of zinc on metal metabolism on the zinc tolerant chlorotic mutants of Euglena gracilis. Z. *Agric Biol Chem*.; 52(9): 2343-2344.

Gadd, G. M. (2004). "Fungal and Algal Metal Accumulation." *Journal of Industrial Microbiology and Biotechnology*, 31(1): 11-22.

Geremia, E., Ripa, M., Catone, C. M., Ulgiati, S. (2021). A Review about Microalgae Wastewater Treatment for Bioremediation and Biomass Production—A New Challenge for Europe. *Environments*, *8*(12): 136. https://doi.org/10.3390/environments8120136

Gouveia, L., Oliveira, A. C. (2009). "Microalgae as a Raw Material for Biofuels Production." *Industrial Crops and Products*, 30(1), 1-10.

Gouveia, L., Batista, P. A., Marques, A. P, Moura, P. (2012). Exploring *Scenedesmus obliqus* and *Nannochloropsis sp*. Potential as a sustainable raw material for biofuels and high added value compounds, In *Livro de actas do Congresso Iberoamericano Sobre Biorrefinerias*, 701–707. http://hdl.handle.net/10400.9/1674.

Gu, W., Wang, G. (2020). Absorptive process and biological activity of *Ulva prolifera* and algal bioremediation of coking effluent. *BioResources, 15(*2) : 2605–2620. https://doi.org/10.15376/biores.15.2.2605-2620.

Gupta, N., Sundar, R. D. V., and Arunachalam, S. (2022). A Review on the genetically engineered microbes for bioremediation of THMs namely Hg and Cr. *ECS Transactions*, *107*(1), 11509–11531. https://doi.org/10.1149/10701.11509ecst.

Gutiérrez, C., Hansen, H. K., Hernández, P., Pinilla, C. (2015). Biosorption of cadmium with brown macroalgae. *Chemosphere*, 138: 164–169. https://doi.org/10.1016/j.chemosphere.2015.06.002

Hammitt, J. K. (2020). Accounting for the distribution of benefits and costs in benefit–cost analysis. *Journal of Benefit-Cost Analysis*, 1–21. DOI: https://doi.org/10.1017/bca.2020.29.

Hannon, M., Gimpel, J., Tran, M., Rasala, B., Mayfield, S. (2010). Biofuels from algae: challenges and potential. *Biofuels*, 1(5) : 763–784. https://doi.org/10.4155/bfs.10.44.

Hassanien, A., Saadaoui, I., Schipper, K., Al-Marri, S., Dalgamouni, T., Aouida, M., Saeed, S., Al-Jabri, H. M. (2023). Genetic engineering to enhance microalgal-based produced water treatment with emphasis on CRISPR/Cas9: A review. *Frontiers in Bioengineering and Biotechnology*, 10:1104914. doi: 10.3389/fbioe.2022.1104914.

Holan Z. R., Volesky, B. (1994). Biosorption of lead and nickel by biomass of marine algae. Biotechnol Bioeng. 43(11):1001-9. doi: 10.1002/bit.260431102. PMID: 18615510. https://doi.org/10.1289/ehp.771961

Huo, Y., Wang, L., Shen, S. (2017). "Biotransformation of Nitrogen and Phosphorus by Algae in Wastewater Treatment." *Environmental Science and Technology*, 51(13): 7412-7420.

Husien, S., Labena, A., El-Belely, E., Mahmoud, H. M., Hamouda, A. S. (2019). Adsorption studies of hexavalent chromium [Cr (VI)] on micro-scale biomass of Sargassum dentifolium, Seaweed. *J. Environ. Chem. Eng*., 7 : 103444. DOI:10.1016/j.jece.2019.103444.

Inouhe, M., Sumiyoshi, M., Tohoyanna, H. Joho, M. (1996). Resistance to cadmium ions and formation of a cadmium binding complex in various wild type yeasts. *Plant Cell. Physiol*., 37: 341-346. DOI: 10.1093/oxfordjournals.pcp.a028951.

Jadeja, R., Ren, W., Zhou Q. (2012). Bioremediation with marine algae: A case study of the soda ash industry. In: Bioremediation: Biotechnology, engineering, and environmental management. Alexander C. Mason Editor. Nova Science Publishers, Inc., New York.

Jalilian, N., Najafpour, G. D., Khajouei, M. (2020). Macro and micro algae in pollution control and biofuel production – A Review. *ChemBioEng Reviews*, 7(1): 18–33. https://doi.org/10.1002/cben.201900014.

Jayakumar, V., Govindaradjane, S., Rajasimman, M. (2021a). Efficient adsorptive removal of Zinc by green marine macro alga Caulerpa scalpelliformis—Characterization, Optimization, Modeling, Isotherm, Kinetic, Thermodynamic, Desorption and Regeneration Studies. Surf. Interfaces, 22: 100798. https://doi.org/10.1016/j.surfin.2020.100798

Jayakumar, V., Govindaradjane, S., Rajamohan, N., Rajasimman, M. (2021b). Biosorption potential of brown algae, Sargassum polycystum, for the removal of toxic metals, cadmium, and zinc. *Environ. Sci. Pollut. Res*. 1–14. DOI: 10.1007/s11356-021-15185-7.

Kadlec, R. H., Reddy, K. R. (2001). "Constructed Wetlands for Agricultural Runoff Treatment." *Water Environment Research*, 73(3): 295-306.

Kadri, M. S., Singhania, R. R., Haldar, D., Patel, A. K., Bhatia, S. K., Saratale, G., Parameswaran, B., Chang, J. (2023). Advances in Algomics technology: Application in wastewater treatment and biofuel production. *Bioresource Technology*, 387: 129636. https://doi.org/10.1016/j.biortech.2023.129636.

Kato, T., Kuroda, H., Nakasone, H. (2009). Runoff characteristics of nutrients from an agricultural watershed with intensive livestock production. *Journal of Hydrology*, 368(1–4): 79–87. https://doi.org/10.1016/j.jhydrol.2009.01.028.

Kshirsagar, A. D. (2013) Bioremediation of Wastewater by Using Microalgae: An Experimental Study. *International Journal of Life Science Biotechnology and Pharma Research,* 2: 339-346.

Kuan, T. C., Khoo, K. S. (2018). "Algae-Based Technologies for Nutrient Removal." *Journal of Applied Phycology*, 30(1): 455-465.

Kumar J. I., Oommen C; (2012). Removal of heavy metals by biosorption using freshwater alga *Spirogyra hyaline*. *J Environ Biol*. ; 33(1) : 27-31.

Kumar, S., Kumar, R. (2019). *Algae: An eco-friendly approach for wastewater treatment*. *Environmental Science and Pollution Research*, 26(18): 18302-18318.

Kuyucak, N., Volesky, B. (1988). Biosorbents for recovery of metals from industrial soluteions. *Biotechnol. Lett.* 10: 137-142.

Kuyucak, N., Volesky, B. (1989). Accumulation of gold by algal biosorbent. *Biorecovery* 1: 189-204

Lage, S., Gojkovic, Z., Funk, C., Gentili, F. (2018). Algal Biomass from Wastewater and Flue Gases as a Source of Bioenergy. *Energies*, *11*(3), 664. https://doi.org/10.3390/en11030664

Lawton, R. J., Mata, L., de Nys, R., Paul, N. A. (2013). Algal Bioremediation of Waste Waters from Land-Based Aquaculture Using Using Ulva: Selecting Target Species and Strains. *PLoS ONE*, *8*(10): Article e77344. https://doi.org/10.1371/journal.pone.0231281.

Li, Y., Zhang, H., Wang, J., Chen, F. (2012). Removal of organic 1ollutants from wastewater by microalgae: a review. *Bioresource Technology*, 114: 610-617.

Liu J., Wu Y., Wu C, Muylaert K, Vyverman W, HQ Yu, Muñoz R., Rittmann B. (2017). Advanced nutrient removal from surface water by a consortium of attached microalgae and bacteria : A review. *Bioresource Technology* 241: 1127-1137. DOI: 10.1016/j.biortech.2017.06.054.

López-Sánchez, A., Silva-Gálvez, A. L., Aguilar-Juárez, Ó., Senés-Guerrero, C., Orozco-Nunnelly, D. A., Carrillo-Nieves, D., Gradilla-Hernández, M. S. (2022). Microalgae-based livestock wastewater treatment (MbWT) as a circular bioeconomy approach: Enhancement of biomass productivity, pollutant removal and high-value compound production. *Journal of Environmental Management, 308: 114612. https://doi.org/10.1016/j.jenvman.2022.114612*.

Lu M, Gao F., Li. C., Yang, H. (2021) Response of microalgae Chlorella vulgaris to Cr stress and continuous Cr removal in a membrane photobioreactor. *Chemosphere* 262:128422.
DOI: 10.1016/j.chemosphere.2020.128422.

Ma, M., Liu, X. (2013). Haematococcus pluvialis: a promising source of astaxanthin. Marine Drugs, 11(11), 3726-3742.

Mane P. C, Bhosle A. B, Jangam C. M, Vishwakarma C. V. (2011). Bioadsorption of selenium by pretreated algal biomass. *Advances in Applied Science Research*; 2: 207-211.

Manu, L., Mokolensang, J. F., Gunawan, W. B., Setyawardani, A., Salindeho, N., Syahputra, R. A., Iqhrammullah, M., Nurkolis, F. (2024). Photobioreactors are beneficial for mass cultivation of microalgae in terms of areal efficiency, climate implications, and metabolites content. *Journal of Agriculture and Food Research*, *18*, 101282. https://doi.org/10.1016/j.jafr.2024.101282

Maqsood, Q., Sumrin, A., Waseem, R., Hussain, M., Imtiaz, M., Hussain, N. (2023). Bioengineered microbial strains for detoxification of toxic environmental pollutants. *Environmental Research*, 227,115665, https://doi.org/10.1016/j.envres.2023.115665.

Mata, T. M., Martins, A. A., Caetano, N. S. (2010). Microalgae for biodiesel production and other applications: A review. *Renewable and Sustainable Energy Reviews*, 14(1): 217–232. https://doi.org/10.1016/j.rser.2009.07.020

Matsunaga T, Takeyama H, Nakao T, Yamazawa A. (1999). Screening of marine microalgae for bioremediation of cadmium polluted seawater. *J Biotechnology*, 70: 33-38.

Mei, L., Xitao, X., Renhao, X., Zhili, L., (2006). Effects of strontium-induced stress on marine microalgae Platymonas subcordiformis (Chlorophyta: Volvocales). *Chinese Journal of Oceanology and Limnology*. 24(2): 154 160. DOI: 10.1007/BF02842815

Mendez, R., and Hu, Q. (2015). "Advances in Algae Photobioreactor Systems for Wastewater Treatment." *Renewable and Sustainable Energy Reviews*, 42: 968-981.

Miara, A., Pienkos, P. T., Bazilian, M., Davis, R., Macknick, J. (2014). Planning for Algal Systems: An Energy-Water-Food Nexus Perspective. *Industrial Biotechnology*, *10*(3): 202–211. https://doi.org/10.1089/ind.2014.0004

Mohsenpour, S. F., Hennige, S., Willoughby, N., Adeloye, A., Gutierrez, T. (2021). Integrating micro-algae into wastewater treatment: A review. *The Science of the Total Environment*, 752: 142168. https://doi.org/10.1016/j.scitotenv.2020.142168

Moino, B. P., Costa, C. S., da Silva, M. G., Vieira, M. G. (2017). Removal of nickel ions on residue of alginate extraction from Sargassum filipendula seaweed in packed bed. Can. *J. Chem Eng.,* 95: 2120–2128. DOI:10.1002/CJCE.22859.

Molazadeh, M., Ahmadzadeh, H., Pourianfar, H. R., Lyon, S., Rampelotto, P. H. (2019). The use of microalgae for coupling wastewater treatment with CO2 biofixation. *Frontiers in Bioengineering and Biotechnology*, 7. https://doi.org/10.3389/fbioe.2019.00042.

Moran, S., Nakata, K. (2010). Ubiquitous monitoring and user behaviour: A preliminary model. *Journal of Ambient Intelligence and Smart Environments*, *2*(1): 67–80. https://doi.org/10.3233/ais-2010-0049.

Mora-Ravelo, S. G. (2017). Bioremediation of wastewater for reutilization in agricultural systems: a review. *Applied Ecology and Environmental Research*, 15(1): 33–50. DOI: http://dx.doi.org/10.15666/aeer/1501_033050.

Mudulia, M., Ray, S. (2021). Constructed wetlands for municipal wastewater treatment: A sustainable approach. *International Journal on Environmental Sciences*, 12(2). https://doi.org/10.53390/ijes.v12i2.4.

Muthukumaran, M. (2022). Advances in bioremediation of nonaqueous phase liquid pollution in soil and water. In *Elsevier eBooks* (pp. 191–231). https://doi.org/10.1016/b978-0-12-824316-9.00006-9.

Nakajima, M., Masueda, D., Hokoi, S., Matsushita, T. (2020). Airborne algal growth on roofs of membrane-structured residences in cold area of Japan. *Journal of Building Physics*, 174425912098003. https://doi.org/10.1177/1744259120980034

Nguyen, L. N., Aditya, L., Vu, H. P., Johir, A. H., Bennar, L., Ralph, P., Hoang, N. B., Zdarta, J., Nghiem, L. D. (2022). Nutrient removal by algae-based wastewater treatment. *Current Pollution Reports*. DOI: https://doi.org/10.25077/dampak.11.2.127-137.2014.

Nishikawa, E., da Silva, M. G. C., Vieira, M. G. A. (2018). Cadmium biosorption by alginate extraction waste and process overview in Life Cycle Assessment context. *J. Clean. Prod*., 178, 166–175. https://doi.org/10.1016/j.jclepro.2018.01.025.

Nurhasana, R. (2014). Study on economic and environmental benefits of waste bank initiatives in Dki Jakarta province. *Jurnal Dampak*, 11(2): 127. DOI: https://doi.org/10.25077/dampak.11.2.127-137.2014

Oguejiofor, N. B. B., Omotosho, N. A. A., Abioye, N. K. M., Alabi, N. a. M., Oguntoyinbo, N. F. N., Daraojimba, N. a. I., Daraojimba, N. C. (2023). A REVIEW ON DATA-DRIVEN REGULATORY COMPLIANCE IN NIGERIA. *International Journal of Applied Research in Social Sciences*, 5(8): 231–243. https://doi.org/10.51594/ijarss.v5i8.571

Olivieri, G., Salatino, P., Marzocchella, A. (2013). Advances in photobioreactors for intensive microalgal production: configurations, operating strategies and applications. *Journal of Chemical Technology and Biotechnology*, 89(2): 178–195. https://doi.org/10.1002/jctb.4218.

Onyeaka, H., Miri, T., Obileke, K., Hart, A., Anumudu, C., Al-Sharify, Z. T. (2021). Minimizing carbon footprint via microalgae as a biological capture. *Carbon Capture Science and Technology*, *1*, 100007. https://doi.org/10.1016/j.ccst.2021.100007.

Pande, V., Pandey, S. C., Sati, D., Bhatt, P., Samant, M. (2022). Microbial interventions in bioremediation of heavy metal contaminants in agroecosystem. *Frontiers in Microbiology*, *13*. https://doi.org/10.3389/fmicb.2022.824084.

Park, J. H., Lee, Y. J. (2010). Phytoremediation of wastewater by microalgae: a review. *Water Research*, 44(9): 2351-2362.

Peckham, S., Hudson, B., Hunter, D., Redgate, S. (2021). Policy success: What is the role of implementation support programmes? *Social Policy and Administration*. https://doi.org/10.1111/spol.12771.

Penloglou, G., Pavlou, A., Kiparissides, C. (2024). Recent Advancements in Photobioreactors for Microalgae Cultivation: A Brief Overview. *Processes*, 12(6): 1104. https://doi.org/10.3390/pr12061104.

Rahman, A., Ellis, J. T. (2012). Bioremediation of Domestic Wastewater and Production of Bioproducts from Microalgae Using Waste Stabilization Ponds. *Journal of Bioremediation and Biodegradation*, 03(06). https://doi.org/10.4172/2155-6199.1000e113.

Raju, C. A. I., Anitha, J., Mahalakshmi Kalyani, R., Satyanandam, K., Jagadeesh, P. (2021). Sorption of cobalt using marine macro seaweed Graciliaria corticatared algae powder. *Mater. Today, Proc.*, 44: 1816–1827.

Rana L, Chhikara S, Dhankar R., (2013). Assessment of growth rate of indigenous cyanobacteria in Metal Enriched Culture Medium. *Asian J Exp Biol*.; 4(3): 465-471.

Reddy K., Renuka N., Kumari S., Bux F. (2021). Algae-mediated processes for the treatment of antiretroviral drugs in wastewater: Prospects and challenges, *Chemosphere*, 280:130674, https://doi.org/10.1016/j.chemosphere.2021.130674.

Rehman A, Shakoori A. R. (2003). Isolation, growth, metal tolerance and metal uptake of the green algae, Chlamydomonas (Chlorophyta) and its role in bioremediation of heavy metals. *Pakistan J Zool*.; 35: 337-341.

Rehman A, Shakoori A. R. (2004). Tolerance uptake of cadmium and nickel by Chlorella sp. isolated from tannery effluents*. Pakistan. J Zool*.; 36(4): 327-331.

Roberts, D. A., de Nys, R., Paul, N. A. (2013). The effect of CO2 on algal growth in industrial wastewater for bioenergy and bioremediation applications. *PLoS ONE*, *8*(11), Article e81631. https://doi.org/10.1371/journal.pone.0081631.

Russell, I., Markov, Z., Neller, T. (2006). Teaching AI through machine learning projects. In *the 11th annual SIGCSE conference*. ACM Press. https://doi.org/10.1145/1140124.1140230

Saeeda, H., Arif, F., Minhas, N. M., Humayun, M. (2020). Agile scalability for large scale projects: lessons learned. *Journal of Software*, 893–903. https://doi.org/10.17706/jsw.10.7.893-903.

Sarma, U., Hoque, M. E., Thekkangil, A., Venkatarayappa, N., Rajagopal, S. (2024). Microalgae in removing heavy metals from wastewater – An advanced green technology for urban wastewater treatment. *Journal of Hazardous Materials Advances*, *15*, 100444. https://doi.org/10.1016/j.hazadv.2024.100444.

Senthilkumar, R., Prasad, D. R., Govindarajan, L., Saravanakumar, K., Prasad, B. N. (2017). Green alga-mediated treatment process for removal of zinc from synthetic solution and industrial effluent. Environ. Technol., 40, 1262–1270. DOI:10.1080/09593330.2017.1420696.

Serrano-Serrano, A. B., Marquez-Arrico, J. E., Navarro, J. F., Martinez-Nicolas, A., Adan, A. (2021). Circadian Characteristics in Patients under Treatment for Substance Use Disorders and Severe Mental Illness (Schizophrenia, Major Depression and Bipolar Disorder). *Journal of Clinical Medicine*, 10(19): 4388. https://doi.org/10.3390/jcm10194388.

Shanab S, Essa A, Shalaby E. (2012). Bioremoval capacity of three heavy metals by some microalgae species (Egyptian Isolates). *Plant Signal Behavior*; 7(3): 392-399. doi: 10.4161/psb.19173.

Sharma G. K, Khan S. A. (2013) Bioremediation of sewage wastewater using selective algae for manure production. *Int J Environ Eng Manag*. 4:573–580.

Silva, J. A. (2023). Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature review. *Sustainability*, 15(14): 10940. https://doi.org/10.3390/su151410940

Singh, B. J., Chakraborty, A., Sehgal, R. (2023). A systematic review of industrial wastewater management: Evaluating challenges and enablers. *Journal of Environmental Management*, *348*, 119230. https://doi.org/10.1016/j.jenvman.2023.119230

Singh, S., Singh, P. (2015). Effect of temperature and light on the growth of algae species: A review. *Renewable and Sustainable Energy Reviews*, 50: 431–444. https://doi.org/10.1016/j.rser.2015.05.024.

Singhal R. K, Joshi S, Tirumalesh K, Gurg R. P. (2004) Reduction of uranium concentration in well water by *Chlorella* (*Chlorella pyrendoidosa*) a freshwater alga immobilized in calcium alginate. *J Radioanal Nucl Chem* 261(1):73–78. DOI10.1023/B:JRNC.0000030937.04903.c4

Sirakov I. N., Velichkova K. N. (2014). Bioremediation of wastewater originate from aquaculture and biomass production from microalgae species -*Nannochloropsis oculata* and *Tetraselmis chuii*. *Bulgarian Journal of Agricultural Science,* 20 (1): 66-72.

Sivonen, K., Jones, G. J. (1990). Toxic cyanobacteria in drinking water: a global health problem. *Water Science and Technology*, 22(1-2): 1-11.

Snyder, L. L., Mesko, D. R. (2024). A rare bosworth variant isolated distal fibula dislocation with a successful closed reduction: a case report and technique. *Journal of Orthopaedic Case Reports*, 14(5): 72-77. https://doi.org/10.13107/jocr.2024.v14.i05.4438.

Sode S., Bruhn A., Balsby T., Larsen M., Gotfredsen A., Rasmussen M. (2013). Bioremediation of rejection water from anaerobically digested wastewater sludge with macroalgae (Ulva lactuca, Chlorophyta). *Bioresource Technology* 146: 426–435. https://doi.org/10.1016/j.biortech.2013.06.062.

Srimongkol, P., Sangtanoo, P., Songserm, P., Watsuntorn, W., Karnchanatat, A. (2022). Microalgae-based wastewater treatment for developing economic and environmental sustainability: Current status and future prospects. *Frontiers in Bioengineering and Biotechnology*, *10*. https://doi.org/10.3389/fbioe.2022.904046

Stevenson, R. J., Rier, S. T., Riseng, C. M., Schultz, R. E., Wiley, M. J. (2006). Comparing effects of nutrients on algal biomass in streams in two regions with different disturbance regimes and with applications for developing nutrient criteria. *Hydrobiologia*, *561*(1), 149–165. https://doi.org/10.1007/s10750-005-1611-5.

Sun, X., Li, X., Tang, S., Lin, K., Zhao, T., Chen, X. (2022). A review on algal-bacterial symbiosis system for aquaculture tail water treatment. *The Science of the Total Environment*, *847*: 157620. https://doi.org/10.1016/j.scitotenv.2022.157620

Tang, J., Liang, Q., Li, C., Huang, X., Xian, X., Li, J., Shang, Z., Pang, C., Liu, Y., Zhang, R. (2022). Application of marine algae in water pollution control. *IOP Conference Series: Earth and Environmental Science*, 966(1): 012001. https://doi.org/10.1088/1755-1315/966/1/012001.

Tang, Z., Wood, J., Smith, D., Thapa, A., Aryal, N. (2021). A Review on Constructed Treatment Wetlands for Removal of Pollutants in the Agricultural Runoff. *Sustainability*, 13(24): 13578. https://doi.org/10.3390/su132413578.

Tay, N. C. C., Razali, N. I. A., Haikal, N. N. K. K. G., Kasri, N. S. S., Geraldi, N. A. (2023). Bioremediation of Carbamazepine using Bacteria: A Review. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, 30(3): 236–243. https://doi.org/10.37934/araset.30.3.236243

Tillett, D., Smith, S. (2019). "Algal Ponds for Nutrient Removal and Wastewater Treatment." *Journal of Environmental Management*, 232: 11-20.

Touliabah, H. E., El-Sheekh, M. M., Ismail, M. M., El-Kassas, H. (2022). A review of Microalgae- and Cyanobacteria-Based Biodegradation of organic pollutants. *Molecules*, 27(3): 1141. https://doi.org/10.3390/molecules27031141.

Ugwuanyi, N. E. D., Nwokediegwu, N. Z. Q. S., Dada, N. M. A., Majemite, N. M. T., Obaigbena, N. A. (2024). The role of algae-based wastewater treatment systems: A comprehensive review. *World Journal of Advanced Research and Reviews*, 21(2): 937–949. https://doi.org/10.30574/wjarr.2024.21.2.0521.

Vafajoo, L., Cheraghi, R., Dabbagh, R., McKay, G. (2018). Removal of cobalt (II) ions from aqueous solutions utilizing the pre-treated 2-Hypnea Valentiae algae: Equilibrium, thermodynamic, and dynamic studies. *Chem. Eng. J.,* 331: 39–47. https://doi.org/10.1016/j.cej.2017.08.019.

Vieira, B. R., Pintor, A. M., Boaventura, R. A., Botelho, C. M., Santos, S. C. (2017). Arsenic removal from water using iron-coated seaweeds. I. *Environ. Manag*., 192: 224–233. DOI: 10.1016/j.jenvman.2017.01.054.

Volland, S, Lutz C, Michalke, B, Lutz-Meindl, U. (2012) Intracellular chromium localization and cell physiological response in the unicellular alga *Micrasterias*. *Aquat Toxicol* 109:59–69. DOI: 10.1016/j.aquatox.2011.11.013.

Vonshak, A. (1999). Spirulina platensis (Cyanobacteria) as a source of nutrients. *Journal of Applied Phycology*, 11(3): 209-216.

Vymazal, J; (1990). Uptake of lead chromium, cadmium, and cobalt by Cladophora glomerata. *Bull Environ Contam Toxicol*.; 44: 468-472.

Vymazal, J. (2011). "Constructed Wetlands for Wastewater Treatment." *Water*, 3(2): 689-709.

Wang T. C., Weissman, J. C., Ramesh, G., Varadarajan, R., Benemann (1995). Bioremoval of Toxic Elements with Aquatic Plants and Algae. In: Hinchee RE, Anderson DB, Hoeppel RE (eds) Bioremediation of Recalcitrant Organics, Battelle Press, Columbus, OH, p 65.

Wang, W., Wu, Q. (2016). "Algae-Based Systems for Organic Pollutant Removal." *Water Research*, 89: 147-157.

Wehr, J. D., Sheath, R. G. (2015). Habitats of freshwater algae. In *Elsevier eBooks* (pp. 13–74). https://doi.org/10.1016/b978-0-12-385876-4.00002-5

Xiao, Y., Luo, Y. (2022). Research progress and application of photobioreactor in wastewater treatment. *E3S Web of Conferences*, 352: 02024. https://doi.org/10.1051/e3sconf/202235202024.

Yalçın, S., Özyürek, M. (2018). Biosorption potential of two brown seaweeds in the removal of chromium. *Water Sci. Technol*., 78: 2564–2576. DOI: 10.2166/wst.2019.007.

Yoshida, N., Ikeda, R., Okuno, T. (2006). Identification and characterization of heavy metal resistant unicellular alga isolated from soil and its potential for phytoremediation. *Bioresource Technology*, 17:1843-1849. DOI: 10.1016/j.biortech.2005.08.021

Yusriyyah, A. A., Tassakka, A. C. M. A., Latama, G. (2021). Identification of the potential of degrading carrageenan in red algae kappaphycus alvarezii symbiotic bacteria. *International Journal of Environment, Agriculture and Biotechnology*, 6(1): 081–085. https://doi.org/10.22161/ijeab.61.11

Zaidi, S. Q. Z. (2024). Use of microalgae as a biosensor for bioremediation of emerging contaminants. *Pure and Applied Biology*, 13(3): 255-260. https://doi.org/10.19045/bspab.2024.130024.

Zeraatkar, A. K., Ahmadzadeh, H., Talebi, A. F., Moheimani, N. R., McHenry, M. P. (2016). Potential use of algae for heavy metal bioremediation, a critical review. *Journal of Environmental Management*, 181: 817-831. https://doi.org/10.1016/j.jenvman.2016.06.059.

Zhu, Q. L., Guo S. N., Wen, F., Zhang, X. L., Wang, C. C., Si. L. F., Zheng, J. L., Liu, J. (2019). Transcriptional and physiological responses of *Dunaliella salina* to cadmium reveal time-dependent turnover of ribosome, photosystem, and ROS-scavenging pathways. *Aquat Toxicol* 207:153–162. DOI: 10.1016/j.aquatox.2018.12.007.