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Innovative Use of Algal Biomass for Heavy Metal Bioremediation

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ABSTRACT

This study focuses on the potential of algal biomass in removing heavy metals and mitigating environmental effects occasioned by industrial waste pollution. Besides, biosorption and bioaccumulation of toxic metals including lead, cadmium, and mercury are feasible employing algae including Chlorella vulgaris and Sargassum. Ion exchange mechanisms, complexation and intracellular sequestration are among the most important ones. It has areas in use such as waste water treatment, natural water treatment, and recovery of resources. However, problems such as the possible future scale-up, toxicity levels, and biomass issues remain a problem. Algal-based remediation is one of the sustainable, cost-effective, eco-friendly methods, which is effective against divalent and transition heavy metal pollution and could address circular economy requirements.

Keywords : Biomass, Algae, Metal, Bioremediation

Introduction

Environmental pollution is particularly with heavy metals which are resultant of industrialization, urbanization and use of sewage water in agriculture. Lead, cadmium, mercury and other toxic metals do not degrade in the environment, but remain over time and active in ecosystems as hazardous substances affecting human health and endangered species.

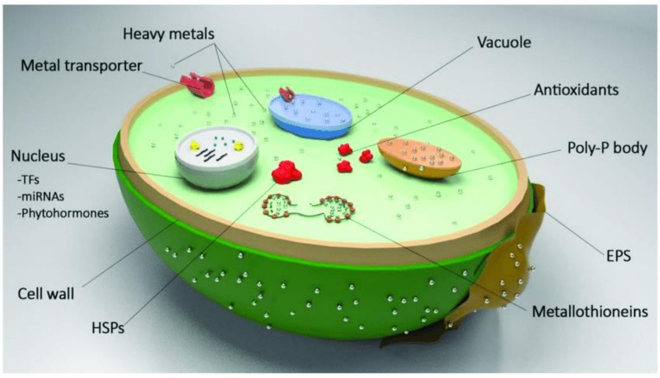

Figure 1. Bioremediation process (ResearchGate, 2018)

Conventional methods of remediation are very expensive, energy consuming and in most cases uneconomical. In comparison, algae with well-known properties in up taking and accumulation of metals are a modern and effective solution. Micro- and macro- algal biomasses have emerged as promising candidates in the removal of heavy metals from polluted site water, soil and effluents. In this paper, algal application for metal uptake, its practices and prospects as well as potential difficulties in real life applications is discussed as a vital process of sustainable bioremediation.

Literature Review

The employment of algal biomass for the removal and recovery of heavy metals is one of the most promising areas in view of the current world environmental challenges. Among the referred materials, lead, mercury, arsenic, cadmium are classified as heavy metals, which are toxic and persistent pollutants in ecosystems and for human health.

These metals become nuisances in the environment when released through industrial processes, mining, agricultural draining, and wrong dumping of industrial waste pollute the soil, water, and air and are toxic and non-degradable (Zeraatkar et al., 2016). Earlier approaches like chemical precipitation, ion exchange processes, and membrane filtration are costly and have secondary waste, as well as negative effects on the ecology.

This has led to search for biological processes to remove heavy metals and algae has been shown to be potential on being used in bioremediation since they can absorb, accumulate, and transform those heavy metals in the affected environment.

Micro and macro algae have received significant interest in bioremediation application due to their bioactive properties. Some microalgae species include Chlorella, Scenedesmus, Spirogyra, and all of them possess high SA/V ratio that favours interaction and absorption of metals.

These organisms are capable of storing heavy metals both inside the cell and outside the cell depending with the specie and the prevailing conditions. Some of the macromia algae, such as Sargassu, Ulva and Fucus for example, have also revealed high effectiveness for the removal of heavy metals in water. These algae species contain accessory structures through which metal ions can be adsorbed and these include cell walls and mucilaginous surfaces (Bulgariu et al., 2017). The elucidated factors include efficiency in metal removal, growth rate, and the reusability and regenerative property of algal biomass in remediation processes.

Studying how algae uptake heavy metals revealed that has potential for biosorption. The mechanism by which algae transmit heavy metals include adsorption, bioaccumulation and intracellular sequestration.

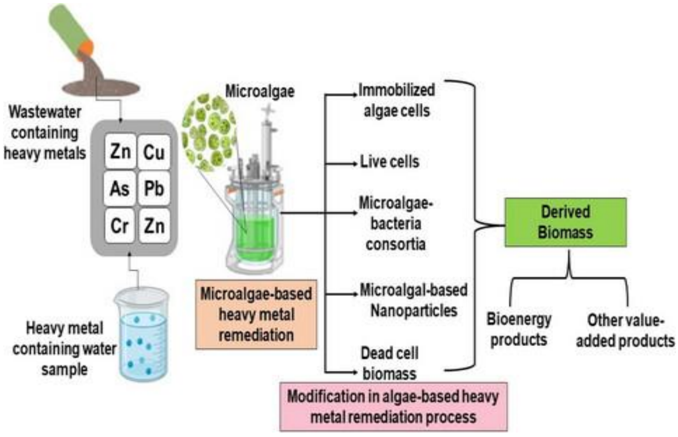

Figure 2. Bioremediation of heavy metals (Wiley, 2017)

Adsorption is a non –active process where metal ions are pulled by the surface of algal cells. Bioaccumulation also occurs where there is active transport of metal ions to the interior of the algal cells where they lodged them in vacuoles or other sub cellular structures. Occasionally, algae can also leach out toxic metals by biochemical activities involving reduction and complexation.

For instance, Chlorella vulgaris was discovered to lower the toxicity of chromium (Cr^{6+}) to that of chromium (Cr^{3+})—thereby reducing its pollutive effect. The processes occurring in such cases might include, but are not limited to: The mechanisms which are at work during these processes are still a subject of research with results contingent on the type of algae as well as the type of the targeted heavy metal.

However, few difficulties are still observed when it comes to the efficiency of using algal biomass in heavy metal removal and scalable enhancement of the process (Ye et al., 2015). Among some of the problems include; the rate and ability of metals to be absorbed by the algae, which in tackled by the aspects that include concentration, pH, temperature, and light intensities.

Some metals may have toxic effects on algae: their high concentrations negatively influence the growth rate of algae and their ability to adsorb metals; changes in environmental conditions affect the adsorption characteristic of algae in the culture. Secondly, the effectiveness of removal of heavy metals varies among algal species, thus, may show variation in the efficiency of the method with respect to distinct types of metals.

For instance, Spirulina platensis proved to be the most effective in the process of phytoextraction of lead, while Ulva Lactuca really prefers cadmium. hence, determining the appropriate algal species for a given type of metal pollution is central to analysing the efficiencies of bioremediation.

Another potential difficulty arises at or after the bioremediation process when it is needed to either dispose or recycle the algal biomass (Bwapwa et al., 2017). Once the algae have consumed heavy metals and become toxic to other organisms, it will be possible to treat the biomass to make it safe for use by human beings and animals.

The identified long-term solution is to use this biomass for other purposes beneficial to other industries, for example, as a production material for biofuel, supplementary feed, or fertilizer. Thus with proper marketing strategies to deal with the issue of turning the algae into valuable products the expense incurred in the process will be compensated ending up making the process cheaper.

The feasibility of such approaches should be evaluated on large scale and the issue of secondary contamination by the employed metal laden algae must also be resolved. Opportunities for enhancing the efficiency of metal removal exist in utilizing algal biomass along with other bioremediation approaches, for example the one based on genetic engineering.

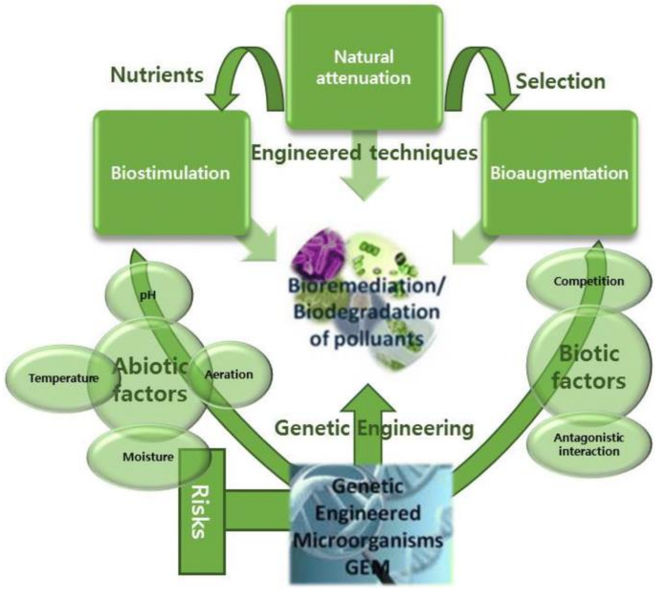

Figure 3. Green Algae in Bioremediation (Springer, 2017)

Transgenic modifications of algae can further optimize their metal resistance and accumulative ability from the genetic aspects by over-expressing metal transport and sequestration genes. Research has also found that plants that overexpress metallothionein genes had their capability to chelate and neutralise heavy metals enhanced.

Besides, it was also pointed that the combination of nanotechnology and algae might improve bioremediation processes even more. Nanoparticles and nanocomposites can enhance the available surface area for metal uptake and enhance the stability of metal- algae complex.

However, this technology provokes questions on the impacts that nanoparticles have to the society before this technology is extended to this level (Yadav et al., 2017). The recent innovation in algal bioremediation systems has expanded to the developing bipolar microorganisms' systems where algae is mixed with the other microorganisms for greater bioremediation. Organic pollutants and heavy metals can both be degraded by algae-microbe consortia because the algae and the microbes can work in convergence. For example, specific bacteria multiply the metal uptake capability of algae through reactions which transform the metals into more mobile species.

Such an approach could enhance the effectiveness of bioremediation practices and provide solutions to problems of varied types of pollution at the same time. Algae interacts with microorganisms in a way that is not well understood making these systems ready for practical applications crucial for extensive research.

This paper provides substantive evidence about the effectiveness of algal biomass for combating the burgeoning threat of heavy metal toxicity and offers a viable and environment-friendly approach to rectify it. Although the biophysical mechanisms of metal uptake are well understood and the use of algae in bioremediation has gained significant attention in recent years, problems like selection of the appropriate species for bioremediation or the effect of environmental conditions have not fully been addressed, not to mention disposing of the resultant biomass.

Further studies must be devoted to designing the most effective algal-based bioremediation systems and the creation of the new technologies for practical application of these processes in terms of their feasibility (Napan et al., 2016). As the field progresses further, the output of algal biomass will be even capable of showing an effective way of managing the heavy metal pollution and provide for the environmental sustainability.

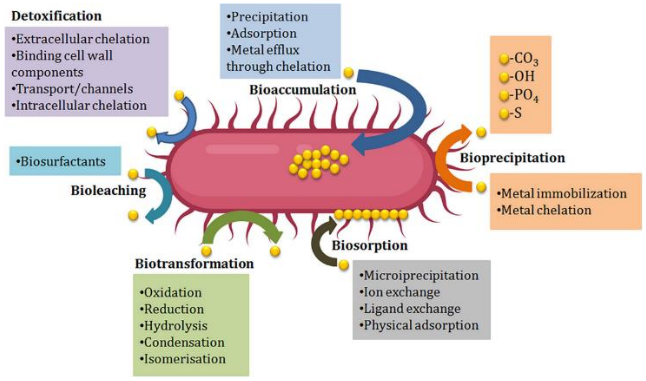

Figure 4 Metal Bioremediation (Frontiers, 2017)

Mechanisms

The processes through which algae remove heavy metals from the environment include physical sorption, chemical adsorption, biosorption, biotransformation and bioaccumulation all of which takes physical& chemical properties of algae and heavy met alliances to enable it access, absorb and accumulate metal ions from the polluted environments.

This makes algae particularly suitable for bioremediation because of their complex cell structures and high ratios that provide the organism huge surface area to combat the heavy metals (Chen et al., 2018). In the present context, the major process beneficial for uptake of metals by algae includes adsorption, bioaccumulation, biosorption and intracellular sequestration and all of them are beneficial in the bioremediation process.

The common outcomes of algal uptake of heavy metals are adsorption where the heavy metals are passively attracted to the surface of the algal cells. This process occurs because of the charge attraction between the metal ions and the alumina negative wall of the cell or the surface organism of the algae.

The majority presently identified functional groups in the cell wall of many algae species comprise carboxyl, hydroxyl, and the amino groups capable of coordinating with metal ions. These interactions make algae suitable for the adsorptive removal of metals including lead, cadmium and mercury from aqueous solutions. In other words, the effectiveness of adsorption is influenced by the type of algae used, the concentration of the metal ions used as well as the environmental conditions such as pH and temperature and concentration of ions in the solution. For instance, Chlorella vulgaris and Scenedesmus species of algae were found to have excellent potential for adsorbing metals for example Cadmium and lead from the contaminated water. The capability of sorption is restricted by the active sites on the surface of algae and after these sites got occupied, the dregs cannot adsorb other metals anymore.

In addition to adsorption, algae make use of bio-accumulation where biologically active metal ions are transported by algae into their cells then stored in the cytoplasm or vacuoles (Verma et al., 2017). In contrast to adsorption that takes place on the cell membrane, bioaccumulation entails penetration of the metal ions via the algal cell membrane through probable activated transport proteins or channels.

They once inside the cell the metal ions these can interaction with intracellular ligands that include proteins peptides and biomolecules that aid in their sequestration and detoxification. This mechanism making algae store some metals at high concentration especially the Spirulina and Chlorella categories where algae was used to bioaccumulate arsenic and chromium.

Bioaccumulation is believed to be very selective with respect to metals and some algae species may prefer certain ions to the others. For example, Ulva species had a great Biosorption capacity of cadmium and lead and Scenedesmus species had a great Biosorption capacity of copper and zinc.

Unlike adsorption, which is a passive process, biomass accumulation is a more energy-demanding process, involving a transport of metal ions into cells However, under bioaccumulation, algae of the water can detoxify metals and convert them into less active forms that include metal-R proteins or enzymes.

Another process that deserves attention when outlining approaches to utilizing algae for heavy metal removal is biosorption that stands on its own as a mechanism and combines aspects of both adsorption and bioaccumulation, where the major emphasis is given to the ability of metal ions to interact with the algal biomass (Gupta et al., 2017).

Biosorption is the process of sequestering metal ions at the surface of the algal biomass and its effectiveness is hindered by the composition of the algal cell wall and the immediate medium.

While the process of adsorption may mainly depend on the electrostatic forces, biosorption includes also chemisorptions that pertain to the formation of coordination complexes between bioactive metal ions and functional groups on the surface of algae.

This may happen through quantities such as ion exchange where metal cations remove other cations from the surface of the algae. For instance, Sargassum and Phaeodactylum tricornutum have characteristics of biosorption, meaning that they can lower the population of other pollutants such as copper, nickel, and zinc.

Algae biosorption stands as a function of several factors such as type of algae, the kind of functional groups that such algae possess, and the environmental constraints such as pH among others. In certain conditions, biosorption may be a reversible process, hence algae can release the metals and this made it possible in the design of bioremediation systems where recovery of the metals is necessary.

After assimilation of metals the algae undergo intracellular sequestration where the metals termed as micronutrients are trapped in cell organelles to minimize damage to the whole organism (Kumar et al., 2015). Algae contain several ways of preventing the toxic effect of metals by transporting them into the vacuoles and thus inactivation.

This sequestration is usually enhanced by synthesis of proteins that specifically bind to metals, therefore preventing them from foiling cellular process; examples are metallothionein's and pyochelin's. Metallothionein's are small cysteine rich proteins that can interact with various metal ions including copper, zinc and cadmium.

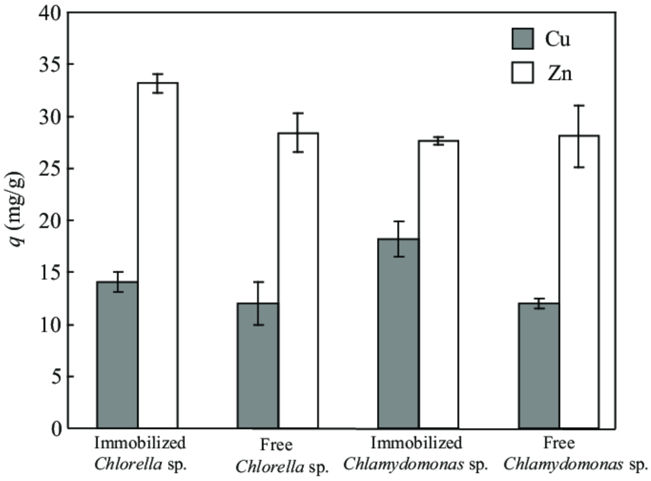

Figure 5 Graph for bioremediation (ResearchGate, 2017)

The incorporation of the metals in vacuoles can help in minimizing the dangerous impacts of high concentrations of such metals within the algal cell and thereby enables the algae to exist under higher levels of such metals.

Sometimes, algae can also sequester metals through reduction that is the biochemical process in which toxic metals are transformed to less toxic forms. For instance, Chlorella vulgaris can convert deleterious hexavalent chromium (Cr6+) to less toxic trivalent chromium (Cr3+).

These mechanisms of biosorption of heavy metal by algae depend on some factors including; ph., temperature, and the concentration of the metal. For example, such adsorption of many metal ions on the algae is most effective in weaker acidic conditions because the metal ions are more charged when in a cationic state, making them more capable of attracting the negative charges from the algal surface (Hassan et al., 2017).

In the same manner, temperature influences the expression and activity of metal transporters and enzymes instrumental to bioaccumulation and sequestration; and transporting metals, with temperature having a direct relationship with the rate of metal uptake in warmer conditions. However, very high value of metals adversely affects the growth rate of algae and hence the effectiveness of this bioremediation process as excessive accumulation of metals can be toxic to the algae.

The knowledge of the conditions under which metals are accumulated to the highest level is important in formulating efficient algal bioremediation. There are four main mechanisms by which algae have been found to perform the removal of heavy metals: adsorption, bioaccumulation, biosorption, and intracellular sequestration. These mechanisms due to the characteristics of having cell and ability of the algae to bind metal ions make algae capable of precipitating and neutralize heavy metal in water and soil.

Despite its success at certain availability of metallic ions in the solution, types of algae and several environmental factors these process rates are not wholly efficient (Roberts et al., 2015). This indicates that the detailed understanding of these mechanisms has the potential to enhance the efficiency of algae bioremediation technologies, and develop a tool for the large-scale use of algae in environmental remediation.

Applications

The uses of algal biomass in the removal of heavy metals from contaminated environments have recently been considered because of the following benefits associated with its use. Algae have bioremediation potential for use in eliminating metal pollution in water bodies, industrial effluents and soil using natural mechanisms inherent in algae for metal uptake and sequestration.

The industries which have benefited from the adsorption process include the treatment of industrial wastewaters that are characterized by high concentration of toxic heavy metals including lead, cadmium, chromium, and mercury (Igiri et al., 2018). Various industries such as mining industries, plus electroplating industries, tannery industries, and textile industries among others discharges substantial volumes of metal pollutes in water systems, threats the environment and human health.

Different species of algae including Chlorella vulgaris, Spirulina platensis, and Sargassum works effectively in biosorption and bioaccumulation for multiple numbers of metals and can purify industrial effluents proficiently. For instance, using of Sargassum biomass for removal of lead and cadmium from industrial effluents has been employed causes of the large surface area and functional groups that will readily prefer to form complexes with metal ions.

It is also circular in its approach because the metal loaded biomass resulting from the algae in wastewater treatment can be processed and recovered for metal use while the algae can also be used for bioenergy. The second important utilization of algal biomass comes in the treatment of polluted freshwater, including rivers, lakes, or ocean water that are polluted mainly through human activities like farming and development.

Algae systems for example algal mats, biofilms and constructed wetlands have been confirmed as effective prosthetic systems for the removal of heavy metals from water. These systems are versatile, low energy demanding, and can easily be designed to provide the needed degree of remediation (Bulgariu et al., 2015). Moreover, algae can be placed in modern complex bioreactor systems where optimal conditions for heavy metals absorption can be created.

For example, algae kept as packed bed or fluidized bed bioreactor are efficient for continuous withdrawal of metal contaminated water. Besides, application of algae in heavy metal removal offers chances to seize valuable metals in the remediation process and produce more potential and sustainable products.

When metal-loaded algal biomass is harvested, it can be further purified to produce Nickel, Copper or gold, etc which can be useful in industry, in reduction of waste and to meet the growing market demand. Furthermore, nutrient-effective algal biomass once remediated could act as a source of feedstock for bio fuels or biogas/ fertilizers thus supporting sustainable energy and agricultural value chain (Das et al., 2018). It is therefore possible to note that algal based remediation systems provide an integrated solution to the problem of contaminated heavy metals since they also provide economic and ecological advantage.

Challenges

- Low metal selectivity in algae lowers the efficiency in treatment if the contaminated water contains more than one metal ion.
- The tolerance limits of heavy metal are stressful to the algal growth and deter bioremediation efficiency.
- Excessive metal concentrations may inhibit the uptake by algal cells and when the metal-binding sites are fully occupied, metals may outcompete the metal-binding proteins.
- Dispersion in environmental parameters such as PH, temperature and salinity influences the uptake effectiveness of heavy metals.
- There is still the problem of expensive cultivation and maintenance of concentrated algal biomass at big scales.
- Harvesting algal biomass to be used in subsequent remediation can be a cumbersome process which may takes time and consume a lot of resources.
- However, there is potential of secondary pollution when the metal-loaded algal biomass is not well dealt with, or when it is dumped.
- Differences in genetics of different algae species work against the prospect of determining the extent of the results that may be expected in different remediation contexts.
- Achieving controlled algal growth and metal accumulation through designing efficient bioreactor systems is, however, capital intensive.
- Processes that are involved in metal recovery from metal-loaded algal biomass may not be cost effective.
- Microbial competing activities can challenge an algal-based system, particularly developed in polluted ecosystems.
- The lack of more comprehensive field-scale investigations has a negative impact on the popularization of related algal bioremediation technologies.
- Maintenance of constant algal biomass for constant purification is difficult when grown under natural condition.
- Translation with steady increases in lab studies and their application to the real world remains difficult and still in its infancy.
- This may take the long duration depending on the contamination levels and the rate or uptake by algae.

Conclusion

Feasibility of algal biomass in eliminating accumulations of heavy metal was found to be highly effective and secure. The capacity to absorb toxic metals in removal processes, WWT, and resource yield make algae as a green solution for environmental remediation. However, some factors including scalability, variability of the environment and biomass disposal are among the issues that must be meet for the full realization of this technique.

Upcoming breakthroughs in algal biotechnology, refinement of the bioreactor’s design and further experimentation on large-scale culture systems may help to avoid gaps existing at the present stage. Thus, algal-based bioremediation can be seen as a great solution to prevent and control HM pollution, ensure the development of more sustainable industries and promote circular economy.

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