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Review

Potential use of algae for heavy metal bioremediation, a critical review

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Algae have several industrial applications that can lower the cost of biofuel co-production. Among these co-production applications, environmental and wastewater bioremediation are increasingly important. Heavy metal pollution and its implications for public health and the environment have led to increased interest in developing environmental biotechnology approaches. We review the potential for algal biosorption and/or neutralization of the toxic effects of heavy metal ions, primarily focusing on their cellular structure, pretreatment, modification, as well as potential application of genetic engineering in biosorption performance. We evaluate pretreatment, immobilization, and factors affecting biosorption capacity, such as initial metal ion concentration, biomass concentration, initial pH, time, temperature, and interference of multi metal ions and introduce molecular tools to develop engineered algal strains with higher biosorption capacity and selectivity. We conclude that consideration of these parameters can lead to the development of low-cost micro and macroalgae cultivation with high bioremediation potential.

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1. Introduction

The presence of heavy metal ions such as lead, copper, cadmium, zinc, and nickel as common contaminants in industrial wastewater leads to pollution of natural environment (O'Connell et al., 2008; Tsekova et al., 2010). Residual nutrients and heavy metal ions in domestic and agro-industrial wastewaters are also responsible for the pollution of rivers, lakes, and seas (de-Bashan and Bashan, 2010). Biosorption and accumulation of heavy metal ions in aquatic food chains can pass to humans causing major health problems (Sridhara Chary et al., 2008). Heavy metal ions even at low concentrations can be toxic to humans. For example, lead is highly toxic and can cause damage to the nervous system, kidneys, and disturbance of vitamin D metabolism, especially in children (ATDR, 2007). Nickel compounds are known to be carcinogenic (ATDR, 2005), and long-term exposure to cadmium is associated with kidney damage, bone mineral loss, increased risk of bone fractures, and reduced lung function (ATDR, 2012). Exploring innovative means to effectively treat wastewater can further protect global freshwater resources and aquatic ecosystems. Over five decades of research on algal-based wastewater treatment and environmental biotechnology has a potentially valuable role to play both in industrial pollution remediation and research (Oswald, 2003; Hoffmann, 1998).

To reduce the cost of treatment, the recovery of precious metals such as gold and silver from processed waters, and extraction of radionuclides such as uranium from aqueous solutions, may have some economic benefits (Wang and Chen, 2009). However, treating wastewater containing heavy metal ions is a major economic challenge. The main physicochemical approaches to remove heavy metal ions from wastewaters include chemical precipitation (Charerntanyarak, 1999), ion exchange (Dabrowski et al., 2004), electrokinetic (Yuan and Weng, 2006), membrane processing (Qdais and Moussa, 2004), and adsorption (Lee et al., 2012; Goharshadi and Moghaddam, 2015). The high costs of chemicals at industrial scales, and incomplete removal of the heavy metal ions are among the main limiting factors in the development of physicochemical approaches. Moreover, increasingly stringent rules and restrictions on effluent discharge into the environment necessitate the use of alternative methods. Biosorption of heavy metal ions in wastewater using algae can offer an ecologically safer, cheaper, and more efficient means to remove metal ions from wastewater. Indeed algae can be used for sorption of toxic and radioactive metal ions (Pohl and Schimmack, 2006), and also to recover precious metal ions like gold and silver (Darnall et al., 1986; Mata et al., 2009a). However, to achieve the desired level of treatment with live algal systems it is necessary to know the maximum autotrophic production, requiring detailed algal culture physiological characterization.

The biosorption of heavy metal ions by various mechanisms such as ion exchange, complex formation, and electrostatic interaction takes place at the micro-scale (Mata et al., 2008; Demirbas, 2008). Among these mechanisms, ion exchange is the most important mechanism in the biosorption of heavy metal ions by algal biomass (Michalak and Chojnacka, 2010; Mehta et al., 2002a). In this review article, we have focused on heavy metal ion bioremediation using algal biomass to treat wastewaters, and have critically assessed the potential venues of future research and application. We have also presented enhancements to the biosorption capacity of biosorbents and reviewed the effective parameters in the biosorption of specific heavy metal ions by algal biomass (Uzunoğlu et al., 2014; Das et al., 2015; Yaqub et al., 2012). We have also discussed different approaches that can be used to reduce the cost of algae cultivation by linking biomass production with wastewater treatment in order to grow algae in wastewater for biological treatment of wastewater and simultaneous production of biofuel (Lyon et al., 2015).

2. Industrial wastewater

According to global statistics the distribution of water usage is 22% in industry, 8% domestic and 70% in agriculture (UNESCO, 2003). A big fraction of this water is discharged into the environment as wastewater. For example in Germany 1534.6 million m^3 wastewater was generated in 2010 (Eurostat and the statistical, 2011). Therefore, it is necessary to have a modern approach to treat the industrial effluents.

Disposal of such huge effluent volumes to surface waters has major implications for the environment and freshwater sources has forced authorities to regulate standards for discharging industrial wastewater (IW). The initial composition of the IW largely determines the technical and economic requirements for treatment to meet regulated discharge criteria.

The composition of the IWWs is as diverse as the sources and sites of IWWs. Industrial wastewaters mostly contain heavy metals as well as organic toxins and surfactants. Effluents from textile, electroplating and other metal processing industries have considerable amounts of toxic metal ions. The conventional methods of IWWTs involve precipitation, ion exchange and electrochemical methods (Ahluwalia and Goyal, 2007). These conventional methods are not cost effective in large scale removal of heavy metal ions. The non-conventional methods of heavy metal ion remediation includes the use of algae (both macro and micro algae) biomass. The main advantage and potential of using algae biomass for heavy metal ion bioremediation is the sustainability of the process and hence the cost effectiveness of the method in industry scale bioremediation. O'Connell et al. (O'Connell et al., 2008). published details of a number of industries that produce IW with different heavy metal ions. Some IWs can be considered an enriched medium to cultivate highly productive algal strains with high biosorption capacity in order to remove heavy metal ions. However, the presence of some heavy metal ions in IWs may interfere with the growth of algae, although their influence can be moderated with dilution or mixing of IW with organic compounds (Abinandan and Shanthakumar, 2015). Hence, characterization of the IW in order to determine the type of pollution and available nutrients is important as it directly influences the algae growth and IW treatment (Komolafe et al., 2014). In living algae cells, the ability to treat IW is dependent on the growth rate; growth rate directly determines the biomass concentration, and it in turn influences the total biosorption capacity of metal ions. However, this review focusses on the uniqueness of using algae biomass (live and nonliving) for bioremediation. As highlighted earlier, detailed small scale laboratory studies indicated that algae biomass (dead or alive) can actively remove various heavy metals. While, comparative cost analysis indicated that conventional methods of IWWTs are 10 times more expensive than algae based IWWTs, there is not report on the pilot or demonstration scale studies (Volesky, 2007). Furthermore, to date no detailed techno-economic feasibility on such process has been conducted. It is to be noted that sustainable reliability of any proposed process, must be tested at pilot and demonstration scale prior to commercialization. This follows by detailed techno-economic and LCA.

3. Bioremediation of heavy metal ions using algae

Biosorption is considered an innovative technology to remove heavy metal ions from wastewaters using predominantly inactive biomass and non-living algae. There are few reports (Lamaia et al., 2005) of using live algae with a limited sorption capacity as the

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