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Review

Is biosorption suitable for decontamination of metal-bearing wastewaters? A critical review on the state-of-the-art of biosorption processes and future directions

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ABSTRACT

For the past few decades, biosorption has been widely investigated for the removal of different contaminants in aqueous media. A number of biomasses of different genre have been identified to possess good biosorption capacity. Insights into biosorption mechanisms have been provided by various researchers in order to develop a fundamental scientific understanding of the biosorption process. However, biosorption has not been employed widely for its large-scale commercial applications. The key factors that affect the growth and evolution of biosorption as a practical technology for decontamination of wastewaters include, (1) lack of investigations on multi-component solutions and wastewaters with complex matrix effects, (2) incomplete understanding of physico-chemical characteristics of biomasses of different types, (3) lack of studies to improve the performance of biosorbents through surface functionalization, and (4) non-integration of biosorption in wastewater/water treatment plants. This critical review aims to identify and discuss the practical limitations of biosorption and provide future research directions to make biosorption a technologically viable process with emphasis on selection and modification of biomasses to suit desired treatment applications, identify appropriate operation modes for large-scale applications of biosorption, and perform techno-economic evaluation of overall biosorption processes.

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1. Introduction

Metals play an important part in the life processes of living organisms. Several metals and metalloids, which are essential for biochemical and cellular processes, such as Zn, Cu, Fe, and Mg, are taken up by living organisms to different extents. They may be required for normal function, but excessive doses can become toxic (O'Connell et al., 2008; Smith et al., 2015). Other metallic elements with no biological role can enter the system and damage the performance of normal processes (Maestri et al., 2010). Toxicity essentially occurs due to displacement of vital metal ions from their native binding sites, or due to ligand interactions (Bruins et al., 2000).

Metals can enter the environment through different pathways, of which, anthropogenic sources play a significant role of increasing metal concentrations (Hermanson, 1991; Bhattacharya et al., 2015). In particular, modern industries are, to a large extent, responsible for pollution of the environment. The wastewaters emanating from various industries contain elevated concentrations of metals, and these are often disposed directly without any treatment into river or other water sources. This is a greater risk as these water sources are usually considered as the basis for drinking water. In most developing countries, treatment plants to decontaminate trace metals are generally not available (Malik, 2004). This, consequently, exposes every end-user to unknown quantities of pollutants in the water they consume.

Several remediation techniques to remove metal ions from aqueous solutions are available, which range from traditional physico-chemical methods to emerging bioremediation methods. The most commonly used physico-chemical processes include chemical precipitation, reverse osmosis, oxidation/reduction,

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electrochemical treatment and filtration (Kurniawan et al., 2006; Fu and Wang, 2011; Meng et al., 2012). Bioremediation methods include bioaccumulation, biosorption and phytoremediation. These methods are environmentally-benign, free of secondary pollution, and have low-costs, and have therefore gained significant attention to remediate industrial wastewaters. In particular, biosorption was identified as a potent bioremediation method which is comparable to the well-established ion-exchange resin-based treatment method for the removal of metal ions (Volesky, 2007).

Biosorption can be defined as the passive uptake of pollutants by dead or inactive biological materials through different physico-chemical mechanisms (Vijayaraghavan and Yun, 2008). Mechanisms of metal removal usually include physical adsorption, ion exchange, chelation, complexation, and micro-precipitation (Vegliò and Beolchini, 1997; Abdolali et al., 2014). Since biosorption involves a variety of metabolism-independent processes taking place essentially in the cell wall, the mechanisms responsible for the metal binding differ according to the biomass type. Biosorbents that are commonly used for removal of metal ions include algae (fresh and marine), fungi, bacteria, industrial wastes, agricultural wastes and other polysaccharide materials. These biosorbents show good removal efficiency toward different metal ions. Several review articles discussed the performance of these biosorbents in metal biosorption (Kapoor and Viraraghavan, 1995; Crini, 2005; Davis et al., 2003; Vijayaraghavan and Yun, 2008; He and Chen, 2014; Kumar et al., 2015). It should be noted that most of the published studies in biosorption dealt with the removal capacity of a particular biosorbent toward a single metal ion in synthetic solution under laboratory conditions.

However, contaminated waste streams often comprise several metal ions with different concentrations. As a result, the performance of a biosorbent toward a metal ion of interest in a complex aqueous medium is highly compromised due to competition between metal ions (Vijayaraghavan and Yun, 2008). Consequently, the knowledge of how one adsorbate may influence the binding of another is necessary. Most of the past studies evaluated the performance of biosorbents with a synthetic solution containing a metal of interest based on which recommendations were made for treatment of real industrial effluents. However, the behavior of biosorbent tends to differ in a multi-component system (Saeed et al., 2005; Vijayaraghavan and Balasubramanian, 2010). For instance, industrial wastewaters often contain a large amount of light metal ions (high total dissolved solids (TDS)) in addition to metal ions of interest. In those cases, the biosorption of solutes of interest not only depends on the biomass surface properties and physico-chemical parameters of a solution such as temperature and pH, but also on the number of other contaminants and their relative concentrations (Vijayaraghavan et al., 2006). Thus, biosorption becomes highly competitive where one solute competes with others to get biosorbed.

The competitive biosorption of multiple chemical components is an important aspect to be considered for successful application of this remediation technique to industrial effluents with a complex matrix. However, only few application studies have been conducted in a systematic manner to evaluate the versatility of biosorption (Tsezos, 2001). Therefore, for development of the next generation biosorption technologies for practical applications, it is important to synthesize the current knowledge available in the field of biosorption. This review brings together the past and recent advances in the development and application of biosorption technologies, suggestions to synthesize a new breed of practical biosorbents and strategies to develop stand-alone or hybrid biosorption technology for practical wastewater treatment applications.

2. Current status of metal remediation technologies

Sources of surface water pollution can be broadly grouped into two categories: point and non-point source pollution (Young, 1981; Ongley et al., 2010). Pollution originating from a single source such as a discharge pipe from an industry or a sewage plant is point source pollution. On the other hand, pollution that originates from multiple sources is non-point source pollution. Non-point pollution occurs as water originates from natural processes (such as rainfall or snow melt), moves across the land or through the ground and picks up natural as well as anthropogenic pollutants, which can then be deposited in lakes, rivers and other water sources. Both point and non-point pollution are serious problems and should be addressed. Heavy metals represent one of the major contaminants in both sources of pollution. As these metals found many applications in industries and even in daily uses, their presence in water streams is of no surprise.

Industries such as electroplating, mining, tanning, metal-finishing, electronic-circuit, steel and aluminum, produce large quantities of wastewaters containing metals (O'Connell et al., 2008). Electroplating industries, which are one of the main causes of contamination of the natural environment with metal ions, are also one of the complicated wastewaters to handle (Islamoglu et al., 2006). This is due to the presence of a variety of metal ions along with counter anions, surfactants, brighteners and organic/inorganic addition agents. The concentration of metal ions also varies and depends upon the type of chemical operations, size and shape of the surfaces, and on the washing system applied (Bodzek et al., 1999). For example, Agarwal et al. (2006) reported that in chrome plating industries, the concentration of total chromium varied from 78 to 286 g/L in an electrolytic bath stream to 0.1–0.9 g/L in a diluted rinse discharge stream. Whereas, Doušová et al. (2005) identified that raw mining water from Kaňk locality found to consist of very high concentrations of 5.8 g Fe/L, 1.6 g Zn/L and 54 mg As/L along with 17.7 mg SO_4^{2-} /L. For treatment, most of the metal-based industries prefer cheaper technology such as precipitation (Eccles, 1995). Precipitation of metals with lime, sulfide, and caustic soda is the most common method for metal removal (Kurniawan et al., 2006). However, precipitation is not selective and produces large quantities of solid sludge. Due to these constraints, other treatment processes such as ion-exchange (Jha et al., 2008), membrane (Cartwright, 1985; Cassano et al., 2001) and activated carbon adsorption (Kurniawan et al., 2006; Hadi et al., 2015) are getting popular in wastewater scheme. These techniques are firmly established, well understood and represent significant capital investments by industry. Several research reports demonstrated the potential of ion-exchange (Cavaco et al., 2007, 2009; Jha et al., 2008; Al Abdulgader et al., 2013), membrane (Cassano et al., 2007; Das et al., 2007; Feini et al., 2008; Carrera et al., 2009) and activated carbon (Suzuki et al., 1996; Mohan et al., 2008) techniques for the decontamination of metal-bearing industrial effluents.

Contaminated water originating from non-point source pollution usually comprises low concentrations of contaminants, but in high volume. One of the important sources of non-point pollution includes stormwater runoff, which has the potential to change the health of water bodies, impacts on aquatic habitats, recreation and aesthetics, or cause algae to grow uncontrollably (NSW-EPA, 1998). Pollutants found in stormwater runoff originate from a number of sources, which includes washings of road and roof surfaces, parking lots, motor vehicles, building materials, air pollutants, exhausts from industrial operations, and agricultural lands (Asaf et al., 2004). Stormwater runoff, because of the high contaminant level, is considered toxic and unacceptable for dispose into receiving surface waters without some treatment (USEPA, 1983). Typically, a

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