Biogeochemical cycling of metals impacting by microbial mobilization and immobilization

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ABSTRACT

Microbial mobilization and immobilization processes can affect the bioavailability and mobility of metals thereby influencing their toxicity and can therefore be utilized to treat solid and liquid wastes contaminated by metals. However, the microbial mobilization and immobilization of metals depends on the microbial metabolism, the environment conditions. In this review, mobilization and immobilization of metals are discussed with regard to the presence and function of involved microorganisms and in relation to applications such as bioleaching. Furthermore, the biosorption process is evaluated as a possible approach for microbial immobilization of metal on the basis of four mechanisms: (1) physical adsorption, (2) ion exchange, (3) complexation, and (4) microprecipitation. In addition, sulfide precipitation by sulfate reducing bacteria was included as an example of an application of microbial immobilization. Based on the evaluation and recommendations in this paper, bioremediation strategies for metals can be improved thus increasing the opportunity for field applications.

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Introduction

Human activities such as mining, metallurgy, industrial manufacturing and production, and domestic and agricultural use of metal containing compounds have affected the distribution of metals in the environment (Mohammed et al., 2011). As a result, a large amount of metals have been redistributed on the surface of the earth since the industrial revolution in the 18th century (Thevenon et al., 2011; Wuana and Okieimen, 2011). Therefore, there is a growing concern about the adverse effects of metals in the environment. The metals in terrestrial and aquatic environments have been shown to have toxicological effects on the environmental and human health due to toxicological effects and the ability to bioaccumulation in the food chain (Yi et al., 2011). There are 13 trace metals and metalloids in the environment: silver (Ag), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se), thallium (Tl), and zinc (Zn), which are considered as the priority pollutants (Blais et al., 2008). These inorganic pollutants mainly originate from metalurgical processes, microelectronics manufacturing, energy production, mining, industrial waste discharge and natural sources such as metal liferous minerals (Voulvoulis et al., 2013). Sediments are the major contaminated phase for metals in aquatic systems. The concentration of metal contamination is controlled by atmospheric transport, precipitation and the weathering processes in addition to contamination from urban water systems such as storm water and wastewater (Harrison, 2012; Nagajyoti et al., 2010). Municipal and industrial wastewater as well as sewage overflows are the main contributors of toxic metal pollution to the aquatic systems (Stumm and Morgan, 2012).
Metals can be classified into two categories (A and B) on the basis of their chemical properties. Class A metal cations easily react with oxygen, while class B metal cations prefer nitrogen or sulfur as reactants (Ho, 2012). Class A metals can form stable products with hard acids or hard bases based on ionic bonds. The most common class A metal cations such as K⁺, Na⁺, and Mg²⁺ are important components of biological cells. They exist in essential molecules for biological processes such as phospholipids and nucleic acids (Mao et al., 2013). For example, Mg²⁺ is important to the living organisms because it can stabilize the soft structure of macromolecules such as Ribonucleic acid (RNA) and Deoxyribonucleic acid (DNA) (Stumm and Morgan, 2012). Class B metals can react with soft acids to form stable products with covalent bonds. Some of these metals can also bind with methyl- and alkyl-toform metal complexes in biological systems (Fallah and Cundari, 2015). The “class B metals” discussed above was referred to as “metals” in the following chapter of this paper.

Many of the class B metals (e.g., Pb²⁺, Hg²⁺, Cr⁶⁺) are toxic and can accumulate into biological systems due to adverse effects on proteins and enzymes. For example, copper is an essential nutrient at low concentrations, however, excess copper is toxic to fish and is highly toxic to many invertebrate species such as crab, shrimp and oysters (Esezonyi-Ejakwu et al., 2011). Studies indicated that chronic copper in aquatic environment can cause gill, kidneys and spleens damages (Yanong, 2010). In addition, excess copper can be a powerful reactive toxin to human’s body causing many symptoms including immune diseases, fatigue, adrenal burnout, depression, and Alzheimer’s disease (Govind and Madhuri, 2014). The toxic copper species include Cu(OH)²⁺, Cu₂(OH)₃⁺ and CuCO₃ (Okocha and Adedeji, 2012). On the other hand, Cu²⁺ as an ion is widely present in aquatic environment and it is considered as the most toxic of dissolved copper species. Some class B metals (e.g., Hg, Ag, and Cd) can cause organ dysfunction such as disturbance of vision, brain damage, lung and kidney failure and fragile bones, affects calcium regulation in biological systems (Gulati et al., 2010). Lead (Pb) can cause short-term memory loss and enhance the risk of cardiovascular diseases (Padmavathamma and Li, 2007). Other class B metals such as As can impair natural cells activity and affect essential cellular processes such as oxidative phosphorylation and ATP synthesis (Tripathi et al., 2007). In addition, studies indicated that some of the class B metals can also lead to psychiatric disorders. For instance, Hg exposure can result in insomnia, loss of memory, and restlessness.

Microorganisms have been applied for the recovery of metals in polluted water and lands as an appropriate technology for soil bioremediation (Akpor and Muchie, 2010; Wuana and Okieimen, 2011). Two detoxifying mechanisms: microbial mobilization and immobilization have been exploited for in-situ or ex-situ bioremediation purpose. Microorganisms are capable of interacting with metals and change their oxidation state or organic complex thereby affecting the speciation and mobility of the metal elements (Olaniran et al., 2013). However, the mechanisms associated with metal bioremediation by microorganisms are still not well understood. Thus, this review focused on the role of microorganisms in the biogeochemical cycling of metals. In addition, the processes of mobilization and immobilization by the microorganisms under physico-chemical conditions of the environment were discussed.

### 1. Microbial mobilization

In natural environments, metals can exist in soil and sediments in different physical forms such as dissolved, colloidal, or as precipitates. They cannot be destroyed or biodegraded by microorganisms unlike biodegradation of organic pollutants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and organochloride pesticides (Marco-Urrea et al., 2015). Microorganisms can increase the bioavailability of metals by biodegrading, rock and mineral bioweathering and biodeterioration, and methylation (Gadd et al., 2012). These microbial processes play a significant role in the mobility of metals. Biodegrading is a process of using bacteria to dissolve metals and it is widely used to extract valuable metals such as copper and gold (Wang et al., 2009). While the metals of rock aggregates can be decomposed and redistributed by microorganisms through bioweathering process (Liu et al., 2011). Like biodegrading and bioweathering, methylation can also increase bioavailability and toxicity of metals. Some methylated metals such as methylmercury are lipophilic. As a result, microorganisms can facilitate volatilization of metals from the environment (Hsu-Kim et al., 2013). In addition, the impact of biological processes on metal is dependent on the metal forms and the chemical environment of the contaminated sites. For example, mineral components may contain considerable amounts of metals that are unavailable to microorganisms. The release and containment of insoluble metal species can be controlled as a result of microbial mobilization processes. On the contrary, soluble metal species have greater mobility and bioavailability thus making this form more toxic (Wu et al., 2010).

Previous studies have indicated that the mobility of metals can be influenced by biofilm formation and the presence of extracellular polymeric substances (EPS) such as polysaccharides and proteins (Boult et al., 2006). Laboratory-scale experiments and subsurface field studies performed by Boult et al. (2006) indicated that the mobility of copper in waste disposal sites was decreased due to the microbial activity. Because some bacteria and fungi such as Suillus bovinus, Paxillus involutus, and Thelphora terrestris produced more than 30 enzymes and accumulated into the EPS thus enabling transport of copper into cells (Boult et al., 2006). In addition, extracellular metabolites such as aliphatic carboxylic acids and aromatic carboxylic acids produced by mixed bacterial cultures containing species from the genera Microbacterium, Acinetobacter, Bacillus and Pseudomonas can mobilize metals (Cu, Ni, Co, V) from alkaline ores (Włodarczyk et al., 2015). The research of Jensen-Spaulding et al. (2004) has shown that naturally produced bacterial extracellular polymers can bind with the metals copper and lead resulting in mobilization and increase in the bioavailability of metals at specific contamination sites. Microbial mobilization of metals can also be achieved by altering redox (reduction and oxidation) reaction. The redox reaction is occurring in the soil and aquatic environment between metals and microorganisms. Microorganisms are usually served as oxidizing agents resulting metals to lose...
electrons (Dixit et al., 2015). Then the electrons are accepted by electron acceptors (e.g., nitrate and sulfate).

2. Bioleaching

Bioleaching or microbial leaching is a process in which metals are extracted from low-grade ores by microorganisms. Bioleaching is a simple and cheap method which can be operated 10 to 20 years (Jadhav and Hocheng, 2012). It needs low capital investment and operating costs for addition of acid to maintain a low pH environment. Because bioleaching is often taking place in a low pH environment ranging from 1.5 to 3.0 which allow most metal cations to dissolve and thereby oxidize ferrous iron and sulfide (Pradhan et al., 2008). Therefore, it has become an industrial technology to recover valuable metals via mining of low-grade ores containing copper sulfide (CuS), metal-bearing minerals, and other industrial waste which otherwise cannot be processed economically by traditional methods (Gadd, 2010). Application of bioleaching processes in the metal industry is used to extract valuable metals from their ores such as aluminum from bauxite or copper from chalcocite and bornite (Gadd, 2010; Kostidis et al., 2015). Fig. 1 shows an example of bioleaching process for copper sulfide minerals from low-grade ores (below 0.6% Cu). Copper is extracted based on two mechanisms: contact leaching (Fig. 1a) and non-contact leaching (Fig. 1b). Contact leaching elaborates that bacteria attach on the mineral surfaces and oxidize sulfide minerals to sulfur and sulfate ([Pradam et al., 2008]). For the non-contact leaching, the bacteria oxidizes dissolved Fe(II) to Fe(III) and the free ferric ions can oxidize the sulfide minerals (Florian et al., 2011; Mikkelsen et al., 2007). As a result, leaching liquor from ores contains copper ions and ferrous iron as shown in Fig. 1a and b. The concentration of dissolved iron for leaching liquor is usually 35–60 mmol/L which contains 40% to 70% of ferrous iron and the copper concentration of the out-flowing liquid is approximately 8 mmol/L. In 2014, approximately 20% of the world’s supply of copper is currently extracted by using bioleaching (Evans, 2014).

Many microorganisms are involved in bioleaching processes and bacteria within the genus. Studies indicated that microbial communities of bioleaching process have a complex microbial interactions and nutrient patterns due to a high microbial diversity (Pradhan et al., 2008). Table 1 shows the key microbial genera involved in the bioleaching. In bioleaching industry, chalcopryite (CuFeS₂) is the most important copper-bearing mineral as well as the major mineral source for commercial copper recovery (Romo et al., 2013). Thiobacillus can utilize sulfur from chalcopryte as electron donor to obtain energy (Fu et al., 2008; Kellermann and Griebler, 2009). Most Thiobacillus species are chemolithoautotrophic bacteria growing at aerobic conditions and utilizing carbon dioxide as the carbon sources. Microorganisms for metal-sulfide-dissolving are usually extremely acidophilic bacteria that can oxidize inorganic sulfur compounds and Fe (II) (Bertoldo et al., 2004; Vera et al., 2013). Leptospirillum is a genus of chemolithoautotrophic bacterium involved in ferrous iron oxidizing. They can grow at a low pH (1.5–1.8) and high concentrations of uranium in the environment (Bertrand et al., 2015; Lollar, 2005). Thiothrix is another genus which gains energy from oxidation of reduced sulfur and thiosulfate (Xin et al., 2009). Thiobacillus-like bacteria are moderately thermophilic and generally grow on pyrite and chalcopyrite. Other bacterial genus like Acidianus and Sulfolobus can grow on ferrous iron and reduce elemental sulfur and metal sulfur compounds as an electron acceptor to hydrogen sulfide (H₂S) (Jensen et al., 2015; Vera et al., 2013).

Non-sulfide minerals can also be exposed to bioleaching, which often takes place by heterotrophic bacteria (e.g., Bacillus sp.) and by fungi (e.g., Aspergillus and Penicillium) (Panda et al., 2012; Watling, 2014). During the bioleaching process, the microorganisms need organic supplements as carbon resources for their growth and energy from metal leaching. A previous study indicated that Bacillus cereus isolated from the Kupferschiefer black shale ore can be used to extract metals (Watling, 2014). Kupferschiefer black shale ore contains rare and precious metals (e.g., Cu, Ni, Zn, Pb, Ag, Zn, Co, Mo, Re, V, Se, Sn, Bi, Au, Pt, Pd) of which Europe is the main consumer. The leaching recoveries after 24–28 days were 2.5% for copper and 9.3% for nickel. Aspergillus and Penicillium are two of the most widely used fungi in bioleaching processes (Watling, 2014). Studies have shown that Aspergillus and Penicillium can be applied for enhancement of bioleaching processes in a variety of environment such as contaminated soil or waste materials including fly ash and electrical waste (Qu et al., 2013; Wu and Ting, 2006).

3. Microbial immobilization

Microbial immobilization of metals can be described as changing the physical or chemical state of metals to reduce the mobilization of metals (Dixit et al., 2015). Metals cannot be biodegraded or destroyed completely but it is possible to change their oxidation state or form organic complexes, which can cause precipitation, reducing the bioavailability thereby making the metals less toxic (Olaniran et al., 2013). Microbial immobilization of metals is a complicated which is affected by several factors such as characteristics of metal concentration and solution, pH and temperature (Fu and Wang, 2011; Gadd, 2009). pH value affects the functional groups participating in metal binding groups thereby allowing varying binding sites on microbial surfaces at different pH levels. Most bacteria have a net negative surface charge due to the ionization of their functional groups. Therefore, the biosorption process is also highly depended on the charges on the microbial surface and the presence of metallic cation with positive charge or the extent of the complexation reactions. Some studies have shown that metal biosorption by living microorganisms occur in two steps (Abbas et al., 2014). First, the metal is binding to cell walls. After that, the metal ions are transported through the membrane (Abbas et al., 2014). The mechanisms for metals transport across the cell membrane are similar to the ion transport mechanism for Na⁺ and K⁺. On the other hand, dead bacterial cells can also perform as biosorbsents for metal cations except for mobile alkali metal (e.g., K⁺) (Sulaymon et al., 2013). Microorganisms can produce biofilm matrix consisting EPS that can act as a metal cation sink (Flemming and Wingender, 2010). EPS play one of the most important roles in biosorption of metals in biofilms. This is mainly attributed to the fact that EPS is anionic which can promote the biomineralization of metal
ions as a good agent for deposition of mineral ions that are cationic (Srivastava et al., 2013).

Studies indicated that microbial cells covered soil particles have a higher sorption capacity for metals than other particles such as clay minerals (Barakat, 2011). Therefore, bioavailability of metals can influence biosorption and microbial immobilization. However, to date, the exact mechanism of biosorption is not well understood due to multiple possibilities of the metals to be captured and transported inside the microbial cell (Wang and Chen, 2006). There are four possible mechanisms for metal immobilization of microorganisms in all microbe–metal–mineral interactions: (1) microprecipitation, (2) physical adsorption, (3) ion exchange, and (4) complexation. The mobility, bioavailability, and toxicity of metals can be decreased by microorganisms, since they can obtain energy from metals redox reactions by converting metals to a redox state with relatively low toxicity through enzymatic (Wall and Krumholz, 2006). For example, hexavalent chromium Cr(VI) can be reduced to Cr(III), resulting in less soluble chromium(III), so hexavalent chromium is removed from contaminated waters or sites by formation of chromium oxide.

3.1. Microprecipitation

Microprecipitation is another possible mechanism of metal biosorption that can take place at the cell surface. The process is constrained by local conditions as a result of chemical interaction between metal and microorganism cell surface (Silva et al., 2016). Therefore, change of pH or redox potential could influence the occurrence of microprecipitation. This process does not necessarily involve a bond between microorganism cell and the metal. Instead, the metal cations and metabolic products can form insoluble aggregates such as sulfides, carbonates, and phosphonates. It is worth to mention that microprecipitation is not dependent on the cellular metabolism, which shows that this process may occur with either living or dead cells.

![Fig. 1 – Bioleaching process for copper sulfide minerals from low-grade ores based on two mechanisms: contact leaching (a) and non-contact leaching (b).](image)

### Table 1 – Phylogenetic relationships of microbial genera involved in bioleaching.

<table>
<thead>
<tr>
<th>Bacteria name</th>
<th>Found in environment</th>
<th>Optimal growth pH</th>
<th>Growth temperature (°C)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thiobacillus</td>
<td>Soil, marine sediments, sewage and industrial waste-treatment ponds</td>
<td>6.90</td>
<td>29.5</td>
<td>Fu et al. (2008), Kellermann and Griebler (2009)</td>
</tr>
<tr>
<td>Leptospirillum</td>
<td>Acid mine drainage and underground in the mines</td>
<td>1.5–2.1</td>
<td>40</td>
<td>Bertrand et al. (2015), Lollar (2005)</td>
</tr>
<tr>
<td>Acidianus</td>
<td>Hot acidic springs</td>
<td>3</td>
<td>60–95</td>
<td>Vera et al. (2013), Bertoldo et al. (2004)</td>
</tr>
<tr>
<td>Sulfolobus</td>
<td>Sea sediment</td>
<td>2–3</td>
<td>75–80</td>
<td>Jensen et al. (2015), Vera et al. (2013)</td>
</tr>
<tr>
<td>Aspergillus</td>
<td>Soil and decomposing plant matter</td>
<td>6–6.5</td>
<td>30</td>
<td>Panda et al. (2012), Watling (2014)</td>
</tr>
<tr>
<td>Penicillium</td>
<td>Soil, fruits and bulbs of plants, seeds and stored foods</td>
<td>–</td>
<td>34</td>
<td>Watling (2014)</td>
</tr>
</tbody>
</table>

* The pH range of the optimal growth for Penicillium is broad, because there are more than 150 species.
Sulfate reducing bacteria (SRB) are capable of producing hydrogen sulfide ($H_2S$) in anaerobic conditions with the presence of organic substrate or $H_2$ as electron donor. Hydrogen sulfide is a strong reducing agent and it is one of the most effective precipitants to precipitate complex metals in wastewater, soil, and sediments (Villa Gómez and Denys, 2013). The sulfide produced from biological sulfate reduction can react with metals thereby forming metal-sulfide precipitates with low solubility. Many sulfide precipitates of toxic metals such as lead sulfide (PbS), cadmium sulfide (CdS) and zinc sulfide (ZnS) have low solubility products ($K_{sp}$), which often are several orders of magnitude lower than that of their hydroxides (Azabou et al., 2007). The produced hydrogen sulfide combines with metal dissolved in aqueous solution to form metal sulfides (Tsuji et al., 2005). Therefore, SRB can be used to sulfate reduction for metal removal from soil or sediments (Fig. 2). First, sulfur-oxidizing bacteria produce sulfuric acid through breakdown of sulfide minerals to leach metals from contaminated soils. Metals are then released as an acidic sulfate solution thereby allowing them to be removed by SRB in a subsequent process. Effluent from industrial waste water usually riches in sulfates and dissolved metals, such as Cu, Ni, Fe, and Pb (Kiran et al., 2016). Discharge of such metal containing industrial still has high sulfate in addition to metals. The sulfate can be reduced to $H_2S$, which often can lead to pipe corrosion (Al Zuhair (2002), effective environmental conditions for SRB include: the redox potential lower than 200 mV; excess of organic substrate or existed $H_2$ as electron donor; and pH higher than 5. Recent studies indicated that microbial sulfate reduction can conduct in environments with pH lower than 5 (Kieu et al., 2011; Singh et al., 2011). SRB can form microniches that are small sites in microbial ecology that have different microbial actions from bulk habitat of soils or sediments (Bertics and Ziebis, 2010). Sulfate-reducing at a low pH environment could be explained by the existence of microniches with elevated pH around the bacteria (Koschorreck, 2008).

3.2. Physical adsorption

Physical adsorption of metals by microorganisms can be described as a physico-chemical process of particles or molecules adhering to a cell surface attributed by van der Waals’ forces and electrostatic interactions. The major components of microorganisms’ cell walls are polysaccharides, proteins, lipids, and many functional groups such as hydroxyl, sulfate, and phosphate contributing to metal binding such as hydroxyl, sulfate, and phosphate as mentioned above. Therefore, the cell surface adsorption process between the metal and its functional groups is independent of the metabolism. The energy involved in this process is generally smaller than 1 kcal/g mol (Kotbra, 2011). As a result, physical adsorption of metals is usually passive process in natural environment. For example, zinc, and copper can be adsorbed by biomasses of algae and fungi through electrostatic interactions between the metal ions and microbial cell wall (Abbas et al., 2014). In addition, electrostatic interactions have been demonstrated to be responsible for biosorption of copper by Zoogloea ramigera and Chiarella vulgaris (Abbas et al., 2014).

3.3. Ion exchange

Ion exchange is also affecting metal biosorption. Studies showed that bacterial cell walls contain a mixture of monovalent and divalent cations that can be substituted by another cation (e.g., $H^+$) (Michalak et al., 2013). The major driving force involved in ion exchange is the attraction of metals to the bacterial cell surface. Cells have specific binding preferences for certain cation exchange, which is highly depending on their structure. For example, the ion exchange properties of natural polysaccharides can result in bivalent metals exchange with counter ions of the polysaccharides (Jee, 2007). These bivalent metals can exchange with the counter ions such as $Co^{2+}$, $Cd^{2+}$ and $Cu^{2+}$.

3.4. Coordination complexes

Metal ions can also combine with ligands to form coordination complexes. A coordination complex compound can consist of one or several metal cations as central atoms surrounded by ligands (Cotton, 2005). If a single ligand binds to the metal ion through two or more coordinating atoms, this complex compound is called chelate. The most likely groups to be engaged in this process include carboxyl, amino, thiol, hydroxyl, phosphate, and hydroxyl-carboxyl. The complexation therefore binds to the cell surface as a consequence of interaction between metal-ligand and the active groups on the cell wall.

Although there are many explanations for metal biosorption, the mechanisms are still not well known. The main reasons are due to the complexity of the bacterial cell structure indicating that multiple possibilities of the metals to be captured outside and at the cell as well as transported inside the cell (Porcheron et al., 2013). The possible mechanisms to explain the metal biosorption process include physical adsorption, ion exchange, surface adsorption and complexation, and microprecipitation (Fig. 3). On the other hand, the mechanism of metal biosorption based on the location of metal removed can be explained as extracellular accumulation/precipitation, cell surface sorption/precipitation, and intracellular accumulation (Porcheron et al., 2013).

4. Conclusion and future perspectives

Rapid industrialization and technology development have changed the concentrations and distribution of metals on the surface and subsurface of the earth. As a result, metals are widespread environmental pollutants concerning as they cannot be biodegraded or destroyed (Förstner and Wittmann, 2012; Mohammed et al., 2011). Instead microbial mobilization and immobilization processes play an important role in bioremediation and biogeochemical cycling of metals. Bioleaching is an important application of microbial mobilization that can be utilized to recover valuable metal source from low-grade mining ores and other industrial waste which otherwise would not be
processed by conventional methods. Application of biosorption as a possible technology for microbial immobilization of metals can be used to reduce the toxicity and mobilization of metals from contaminated sites. However, there is little research conducted on the mechanism of biosorption and important details are still not well known besides some descriptive studies.

Fig. 2 – Bioremediation of heavy metal-contaminated soils by utilizing bioleaching and bioprecipitation.

Fig. 3 – Mechanisms of metal biosorption.
Recently, many approaches have been proposed and studied to improve mobilization and immobilization of the metals in environment to decrease its toxicity effects. Adsorption can be one of the alternative methods due to their low-cost and metal binding capacities (Kurniawan et al., 2006). Industrial by-products and agricultural by-products can be chemically modified to enhance the removal performance for a hot spot of interest for metal removal (Barakat, 2011). Different types of membranes such as nanofiltration membranes and reverse osmosis membranes have been increasingly studied for metal removal from industrial wastewater effluent on the basis of the pore size and the metals that needed be retained. Ultrafiltration with 5–20 nm of pore size has become one of the most effective approaches to separate metals from industrial wastewater effluents (Barakat, 2011). Additionally, with the development of nanoparticle technologies, there has been an increasing application of magnetic nanoparticles for metal remediation (Tang and Lo, 2013; Xu et al., 2012). The magnetic nanoparticles have a nanoscale of particle size with high surface-area-to-volume ratio which can remove metal faster. More importantly, the magnetic property allows separation and recovery of magnetic nanoparticles (Tang and Lo, 2013). Unlike in microbial immobilization, magnetic nanoparticles treatment can prove several advantages such as rapid process and neglect of temperature effects. However, it is important to note that recovery of magnetic nanoparticles still lacks controllability and requires high installation and maintaining costs.

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