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Does bioleaching represent a biotechnological strategy for remediation of contaminated sediments?

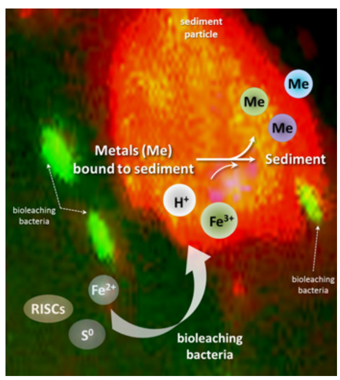
Viviana Fonti *, Antonio Dell'Anno, Francesca Beolchini

Department of Life and Environmental Sciences, Università Politecnica delle Marche, Via Brecce Bianche, 60131, Ancona, Italy

HIGHLIGHTS

- Bioleaching may represent a sustainable strategy for contaminated dredged sediments
- The performance is greatly influenced by several abiotic and biotic factors
- Geochemical characteristics and metal partitioning have a key role
- Sulphide minerals in the sediment are a favorable element
- Microorganisms other than Fe/S oxidisers may open new perspectives

GRAPHICAL ABSTRACT



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ABSTRACT

Bioleaching is a consolidated biotechnology in the mining industry and in bio-hydrometallurgy, where microorganisms mediate the solubilisation of metals and semi-metals from mineral ores and concentrates. Bioleaching also has the potential for ex-situ/on-site remediation of aquatic sediments that are contaminated with metals, which represent a key environmental issue of global concern. By eliminating or reducing (semi-)metal contamination of aquatic sediments, bioleaching may represent an environmentally friendly and low-cost strategy for management of contaminated dredged sediments. Nevertheless, the efficiency of bioleaching in this context is greatly influenced by several abiotic and biotic factors. These factors need to be carefully taken into account before selecting bioleaching as a suitable remediation strategy. Here we review the application of bioleaching for sediment bioremediation, and provide a critical view of the main factors that affect its performance. We also discuss future research needs to improve bioleaching strategies for contaminated aquatic sediments, in view of large-scale applications.

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* Corresponding author.
E-mail address: v.fonti@univpm.it (V. Fonti).

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1. Introduction

The management of contaminated aquatic sediments and dredged materials represents an environmental problem of major concern. In Europe, 300 to 400 million m^3 of contaminated sediment is dredged every year from marine and freshwater ecosystems (such as for maintenance of river embankments and of navigational depth; Bortone et al., 2004; http://www.ceamas.eu). With their high contamination levels, dredged sediments often need to be specifically relocated. Legislation for the handling of dredged materials is complex and there are no harmonised regulations at the European level. Dredged materials are dealt with at the intersection of the Water, Waste and Marine Strategy Framework Directives (i.e., directives 2000/60/EC, 2008/98/EC and 2008/56/CE, respectively, of the European Parliament, and valid within EU countries).

The main management options for contaminated sediments are landfill disposal and confined aquatic disposal, although alternatives are needed because of the limited sites available, the high cost and the low environmental sustainability that characterise such solutions (Bortone et al., 2004; Adriaens et al., 2006; Agius and Porebski, 2008). An alternative is decontamination of the dredged materials, in view of their potential beneficial use in the building industry, for beach nourishment and for other applications (Lee, 2000; Ahlf and Förstner, 2001; Barth et al., 2001; Siham et al., 2008).

Bioleaching is the application of acidophilic microbes with Fe/S oxidising metabolism to promote solubilisation of metals from solid matrices, and it is one of the most well-established and industrially applied biotechnologies. Consortia of Fe/S oxidising bacteria and other acidophilic microbes are applied in large-scale plants to improve the extraction of precious and non-precious metals from sulphides or (Fe)-bearing ores (Olson et al., 2003; Rawlings and Johnson, 2007; Brierley and Brierley, 2013). More recently, bioleaching has been investigated as an environmental technology for the recovery of valuable base metals from urban and industrial waste (e.g., printed circuit boards, spent batteries, cathode ray tubes, spent refinery catalysts, sewage sludge; Brandl et al., 2001; Zhao et al., 2008; Pathak et al., 2009; Beolchini et al., 2012; Johnson, 2014). Moreover, bioleaching is often considered as a promising ex-situ/on-site bioremediation strategy for eliminating/reducing metal contamination in dredged sediments, in view of their potential beneficial use (Blais et al., 1993; White et al., 1998; Bosecker, 2001; Tabak et al., 2005; Akcil et al., 2014).

Although bioleaching is often assumed to be an environmentally friendly and low-cost technique, its feasibility and sustainability as a sediment bioremediation strategy have not been studied sufficiently to date. There have been investigations into the factors and operational variables that can influence sediment bioleaching performance (e.g., microorganisms, growth substrates, temperature, concentration of sediment, type of bioreactor). However, the majority of these studies have been based on a trial-and-error approach, and the geochemical properties of the sediments themselves have barely been considered. Sediments appear to be very challenging matrices compared to mineral ores. In particular, metal contaminants tend to associate with sediment components other than the crystalline lattice of primary minerals (e.g., adsorption on organic molecules, association as exchangeable ions). As a consequence, bioleaching know-how and principles that are so well-established in biomining and bio-hydrometallurgy can only be applied partially to sediment bioleaching (e.g., metabolic pathways, metal solubilisation mechanisms; microbial adaptation to minerals; see Rohwerder et al., 2003, Rawlings and Johnson, 2007, Vera et al., 2013 and references within).

In this review we provide a critical analysis of the main constraints that influence the effectiveness of bioleaching as a sediment remediation strategy. In particular, we aim to identify the mechanisms that regulate the potential of metal removal, the factors that are the most relevant, how these interact, and which aspects can limit real bioleaching applications. Here we thus: 1) explore the potential of bioleaching microorganisms in view of real sediment bioleaching applications; 2) discuss sediment metal interactions; and 3) provide a critical analysis of the scientific literature relating to the application of bioleaching to metal-contaminated sediments. Our analysis highlights the major gaps that need to be filled in the future, and provides the tools for facilitating the decision-making processes in view of large scale applications. Fig. 1 shows a roadmap for a better orientation in this review paper.

2. Metal bioleaching: Microorganisms and mechanisms

2.1. Microbes in sediment bioleaching

The main microbes that can 'bioleach' metals from solids are acidophilic bacteria and archaea that have dissimilatory metabolism that is based on the oxidation of S^0, reduced inorganic sulphur compounds