Bioresource Technology 160 (2014) 3–14

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Biosorption: current perspectives on concept, definition and application

Marina Fomina [a], Geoffrey Michael Gadd [b,*]

[a] Institute of Microbiology and Virology, NASU, Zabolotnogo st. 154, Kiev 03680, Ukraine
[b] Geomicrobiology Group, College of Life Sciences, University of Dundee, Dundee DD1 5EH, Scotland, UK

HIGHLIGHTS

- Up-to-date critical review.
- Covers concept, definition and application.
- Provides directions for future research.

ARTICLE INFO

Article history:
Available online 3 January 2014

Keywords:
Biosorption
Organic pollutants
Toxic metals
Commercialization
Microorganisms

ABSTRACT

Biosorption is a physico-chemical and metabolically-independent process based on a variety of mechanisms including absorption, adsorption, ion exchange, surface complexation and precipitation. Biosorption processes are highly important in the environment and conventional biotreatment processes. As a branch of biotechnology, biosorption has been aimed at the removal or recovery of organic and inorganic substances from solution by biological material which can include living or dead microorganisms and their components, seaweeds, plant materials, industrial and agricultural wastes and natural residues. For decades biosorption has been heralded as a promising cost-effective clean-up biotechnology. Despite significant progress in our understanding of this complex phenomenon and a dramatic increase in publications in this research area, commercialization of biosorption technologies has been limited so far. This article summarizes existing knowledge on various aspects of the fundamentals and applications of biosorption and critically reviews the obstacles to commercial success and future perspectives.

1. Introduction

Anthropogenic activity and industrialization has put increasing pressure on the environment by generating large quantities of toxic aqueous effluents containing toxic metals, metalloids, radionuclides as well as various organic pollutants. Detrimental effects on ecosystems and the health hazards associated with organic and inorganic pollutants have been established beyond any doubt, making it absolutely necessary to apply ever increasing standards of pollutant detection and treatment. Industrial treatment methods aimed at preventing or limiting toxic discharges demand increasing expenditure.

Various physico-chemical and biological processes are usually employed to remove pollutants from industrial wastewaters before discharge into the environment (Gadd, 2009). Biological processes such as standard sewage and water purification treatments as well as auxiliary reed bed and wetlands approaches have been used for many years because of the remarkable capabilities of microorganisms to detoxify organic and inorganic pollutants (Gadd, 1986, 2000, 2007). Biosorption is one of the significant properties of both living and dead microorganisms (and their components) relevant for treatment of pollutants (Tsezos and Volesky, 1981; Gadd and White, 1993; Texier et al., 1999). However, practically all biological material including macroalgae (seaweeds) as well as plant and animal biomass and derived products (e.g. chitosan) is capable of biosorption. For a number of years, biosorption has been claimed as a promising biotechnology for pollutant removal and/or recovery from solution, due to its simplicity, analogous operation to conventional ion exchange technology, apparent efficiency and availability of biomass and waste bio-products (Gadd, 1986; Volesky, 1990, 2001, 2007; Gadd and White, 1993; Veglio and Beolchini, 1997; Tsezos, 2001; Wang and Chen, 2006; Mack et al., 2007).

Since the first reports on biosorption, great efforts have been made to prepare efficient, effective, and economic biomaterials and apply them for wastewater treatment. Initially being focussed on metals and related substances, biosorption research has expanded into additional areas of potential use by application to particulates and all kinds of organic substances including pharmaceuticals. However, despite the fact that biosorption phenomena have been discussed in the literature for a long time (over 13,000 scientific papers have been published to date in peer-reviewed

* Corresponding author. Tel.: +44 1382 384767.
E-mail address: g.m.gadd@dundee.ac.uk (G.M. Gadd).

0960-8524/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2013.12.102

journals) there has been little or no obvious successful exploitation in an industrial context. This article gives a critical overview of the area of biosorption research, its fundamentals, applications and problems, and attempts to clarify future perspectives and commercial feasibility.

2. Defining biosorption

The conception of "biosorption" is multidimensional and has been evolving over the past few decades. The difficulties with a sound definition of the term "biosorption" are related to the existence of many mechanisms, the biosorbent used, environmental factors and the presence or absence of metabolic processes in the case of living organisms. It is also affected by expanding areas of suggested potential applications (Volesky, 2007; Gadd, 2009; Michalak et al., 2013). The term "biosorption" has been used by different authors for a diverse range of processes including bioadsorption, bioabsorption, and biosorption by living or dead biomass, bioaccumulation, and a diverse array of substances, e.g. metals, radionuclides, and organics. However, the quality and productivity of specialist communication depends to a large extent on the quality of the terminology employed.

Sorption is a physico-chemical process by which one substance becomes attached to another. Despite the 'bio' prefix that denotes the involvement of a biological entity, biosorption is a physico-chemical process that can be simply defined as the removal of substances from solution by biological material (Gadd, 2009). However "sorption" to biological material may not be as simple as might be perceived. One of the dimensions here is bioadsorption versus bioabsorption (Gadd, 2009). Sorption is a term that has been used for both absorption and adsorption. Absorption is the incorporation of a substance in one state into another of a different state (e.g. liquids being absorbed by a solid or gases being absorbed by water), i.e. into a three-dimensional matrix. Adsorption is the physical adherence or bonding of ions and molecules onto the surface of another molecule, i.e. onto a two-dimensional surface. Many researchers consider biosorption as a subcategory of adsorption, where the sorbent is a biological matrix (Michalak et al., 2013). Adsorption is the most common form of sorption involved in 'traditional' clean-up technologies but unless it is clear which process (absorption or adsorption) is operative, sorption is the preferred term, and can be used to describe any system where a sorbate (e.g. an atom, molecule, a molecular ion) interacts with a sorbent (i.e. a solid surface) resulting in an accumulation at the sorbate–sorbent interface (Borda and Sparks, 2008). If adsorption occurs and continues through the formation of a new three-dimensional surface species, this new species can be defined as a surface precipitate. A number of different systems clearly exist in the continuum from adsorption to precipitation (Gadd, 2009).

Another dimension of the term "biosorption" is related to the traditional and expanding areas of its application, primarily to the target substances to be sorbed. Traditionally, the term referred specifically to metals as biosorbates and, often, or microbial material as biosorbents. Most biosorption research still concentrates on metals and related elements and several authors have emphasized this in their definition of biosorption (Gadd, 2009). However, biosorption research and applications have been extended to removal of organics, e.g. dyes, to the recovery of high-value proteins, steroids, pharmaceuticals and drugs, and to enrichment with microelements biological feed supplements and fertilizers (Volesky, 2007; Kaushik and Malik, 2009; Michalak et al., 2013). Thus, the term biosorption can apparently describe any system where a solid surface of a biological matrix interacts with a sorbate resulting in the reduction in the solution sorbate concentration (Gadd, 2009).

A different dimension of the term "biosorption" relates to passive versus active processes. Three overlapping levels of definitions in this dimension can be recognised: (i) a narrow definition when biosorption is defined as a passive, metabolically-independent process; (ii) a wider definition including both passive and active processes in case of living biomass and often referred to as bioaccumulation and, finally, (iii) biosorption as a fundamental generalization covering all aspects of interactions of any sorbate with a biological matrix.

Biosorption has been defined by most researchers as a passive and metabolically-independent process, e.g. the passive uptake of metals by microbial biomass (Volesky, 1990; Malik, 2004; Gadd, 2009). It can be performed either by dead biomass or fragments of cells and tissues which may have some advantages for both the ease and safety of handling and preparation of the biological substrate. However, it can also be performed by live cells as passive uptake or metabolically-independent adsorption of a sorbate via surface complexation onto cell walls and/or other outer layers being the first, fast and reversible adsorption step operating within a much slower and complex overall bioaccumulation mechanism (Volesky, 1990; Malik, 2004). Both mechanisms can overlap bringing additional confusion in the use of terminology. Bioaccumulation is a function of living organisms dependent on a variety of physical, chemical and biological mechanisms including both intra- and extracellular processes where passive uptake plays only a limited and not very well-defined role (Gadd, 1993, 2010; Dhankhar and Hooda, 2011; Gadd and Fomina, 2011; Gadd et al., 2012). It should be noted that passive biosorption processes occurring in living biomass are subject to effects of changing physico-chemical conditions resulting from changes in pH, available ligands and other metabolites as a result of metabolic activity and possible stress responses caused by the toxic sorbate. This complicates adequate descriptions of the process and predictive modelling for practical use. Therefore, in this account, bioaccumulation is used to describe the process involving living cells, whereas biosorption mechanisms refer to the use of dead biomass.

The overall generality of biosorption processes as a property of living and dead biomass to bind and concentrate inorganic and organic compounds should also be noted (Kotrba, 2011). Biosorption is an important part of many processes occurring in nature including, e.g. sorption in soil, antigen–antibody immune reactions and adsorption to host cells as a first stage in virus replication, which are all subjects of different scientific disciplines. Many methodological approaches used in life sciences, biotechnology and medicine are, in fact, based on biosorption processes, e.g. staining microbial cells for electron microscopy and targeted therapies in cancer treatment. In one sense, all life phenomena are somehow related to interactions between biological surfaces and a sorbate.

3. Fundamentals of biosorption

As mentioned previously, biosorption is a physico-chemical metabolism-independent process resulting in the removal of substances from solution by biological material (Gadd, 2009). The biosorption process therefore involves a solid phase (biosorbent) and a liquid phase (solvent: normally water) containing the dissolved or suspended species to be sorbed (sorbate).

3.1. Biosorbates

A wide range of target sorbates can be removed from aqueous solution using biosorbents. As well as metals, particulates and colloids have been studied as well as organometal(loid) inorganic and organic compounds including dyes, fluoride, phthalates, and pharmaceuticals (Volesky, 2007; Gadd, 2009; Michalak et al., 2013). A