

CELLULOSIC SUBSTRATES FOR REMOVAL OF POLLUTANTS FROM AQUEOUS SYSTEMS: A REVIEW. 1. METALS

Martin A. Hubbe,^{a,*} Syed Hadi Hasan,^b and Joel J. Ducoste^c

Recent years have seen explosive growth in research concerning the use of cellulosic materials, either in their as-received state or as modified products, for the removal of heavy metal ions from dilute aqueous solutions. Despite highly promising reports of progress in this area, important questions remain. For instance, it has not been clearly established whether knowledge about the composition and structure of the bioadsorbent raw material is equally important to its availability at its point of use. Various physical and chemical modifications of biomass have been shown to boost the ability of the cellulose-based material to bind various metal ions. Systems of data analysis and mechanistic models are described. There is a continuing need to explain the mechanisms of these approaches and to determine the most effective treatments. Finally, the article probes areas where more research is urgently needed. For example, life cycle analysis studies are needed, comparing the use of renewable biosorbents vs. conventional means of removing toxic metal ions from water.

Keywords: Cellulose; Remediation; Pollutants; Heavy metals; Adsorption; Biosorbents

Contact information: a: Department of Forest Biomaterials, North Carolina State University, Campus Box 8005, Raleigh, NC 27695-8005; b: Department of Applied Chemistry, Institute of Technology, Banaras Hindu University, Varanasi – 221005, U. P., India; c: Department of Civil, Construction and Environmental Engineering, Campus Box 7908, Raleigh, North Carolina 27695-7908;

* Corresponding author: hubbe@ncsu.edu

INTRODUCTION

This article reviews publications in which lignocellulosic materials have been used, either “as-received” or in modified form, to remove various heavy metals from dilute aqueous solution. There have been an impressive number of relevant publications in this field. The preparation of the present article was made easier by the existence of earlier reviews, some of which are listed in Table 1. As shown, certain reviews have dealt with the biosorption of metal ions in general, while others have focused on specific ionic species or classes of biomass. Some of the articles have reviewed chemical or thermochemical modifications of cellulosic raw materials to render them more effective for the collection and binding of various metal ions. Readers interested in certain metals, certain types of sorbents, or certain aspects of metal bioadsorption are encouraged to scan the columns of Table A (see Appendix), as well as chapters in Wase and Forster (1998). In addition, a book by Cooney (1998) describes engineering principles and strategies for implementation of absorbent-based water treatment systems. Kurniawann *et al.* (2006a) and Owlad *et al.* 2009) reviewed systems other than biosorption for removal of metals.

Table 1. Selective List of Relevant Review Articles and Chapters

Metal species considered	Cellulose-based substrates	Emphasis of the article	Citation information
Chromium	All options	Metal recovery	Agrawal <i>et al.</i> 2006
Heavy metals	Microbial & plant	Choice of sorbent	Ahluwalia & Goyal 2005b
Chromium	Agro-based	Bio-sorption	Alpana 2008
Rare earth metals	Microbial biomass	Capacities, models	Andr�s <i>et al.</i> 2003
Heavy metals	Low-cost biomass	Activated carb., <i>etc.</i>	Babel & Kurniawan 2003
Heavy metals	Low-cost biomass	Lignin, chitosan	Bailey <i>et al.</i> 1999
Heavy metals	Fungal biomass	Sustainability	Bishnoi & Garima 2005
Heavy metals	Various	Bioaccumulation	Chojnacka 2009, 2010
Heavy metals	Rice husk	Low cost	Chuah <i>et al.</i> 2005
Heavy metals, <i>etc.</i>	Polysaccharide	Polym. modification	Crini 2005
Mined metals	Various methods	Recovery of metals	Cui & Zhang 2008
Heavy metals	Brown algae	Sorbent properties	Davis <i>et al.</i> 2003
Heavy metals	Agro-based	Low concentrations	Demirbas 2008
Various pollutants	Activated carbon	Low cost biomass	Dias <i>et al.</i> 2007
Various pollutants	Various sorbents	Drinking water	Dubey <i>et al.</i> 2009
Heavy metals	Biomass	Low cost sorption	Gadd 2009
Heavy metals	Chitosan	Adsorp. capacities	G�rente <i>et al.</i> 2007
Heavy metals	Various biomass	Sorp. rate models	Ho & McKay 1999
Heavy metals	Biosorbants	Mechanisms	Ho <i>et al.</i> 2000
Heavy metals	Fungal biomass	Performance	Kapoor & Viraraghavan 1995
Heavy metals	Biopolymers	Protein-based	Kostal <i>et al.</i> 2005
Heavy metals	Agricultural prods.	Compilation	Kumar 2006
Heavy metals	Various biomass	Biomass attributes	Kurniawan <i>et al.</i> 2006
Cadmium	Biosorbants	Thermo & kinetics	Lodeiro <i>et al.</i> 2006
Mined metals	Plant, microbial	Metal recovery	Madrid & Camara 1997
Heavy metals	Algae	Wastewater	Mehta & Gaur 2005
Heavy metals	Nonliving biomass	Each metal-ion pair	Modak & Natarajan 1995
Chromium(III, VI)	Carbons, low-cost	Strategies, theories	Mohan & Pittman 2006
Arsenic	Absorbents	Strategies, options	Mohan & Pittman 2007
Heavy metals	Modified cellulose	Activated carb., <i>etc.</i>	O'Connell <i>et al.</i> 2008
Heavy metals	Activated carbons	Low-cost sources	Pollard <i>et al.</i> 1992
Trace metals	Functionalized	Preconcentration	Pyrzynska & Trojanowicz 1999
Heavy metals	Dead macrophytes	Phytoremediation	Rai 2009
Heavy metals	Algae	Statistical review	Romera <i>et al.</i> 2006
Heavy metals	Fungal biomass	Functional groups	Sag 2001
Various pollutants	Sawdust	Mechan., factors	Shukla <i>et al.</i> 2002
Heavy metals	Agricultural waste	Compilation	Sud <i>et al.</i> 2008
Various pollutants	Lignin, act. carbon	-	Suhas <i>et al.</i> 2007
Heavy metals	Biosorbents	Metals recovery	Veglio & Beolcini 1997
Various pollutants	Bacterial	Binding mechan.	Vijayaraghavan & Yun 2008
Heavy metals	Biosorbents	Selec. of biomass	Volesky 1994
Heavy metals	Biosorbents	Sorption capacities	Volesky & Holan 1995
Heavy metals	Biosorbents	Implementation	Volesky 2001
Heavy metals	Modified plants	Modification	Wan Ngah & Hanafiah 2008b
Heavy metals	Fungal biomass	Yeast	Wang & Chen 2006
Heavy metals	Biosorbents	Ads. sites, trends	Wang & Chen 2009
Heavy metals	Silvichem biomass	Methods, immobil.	Yu <i>et al.</i> 2008
Metals	Ion exchange	Introductory text	Zagorodni 2007
Arsenic	Low-cost biomass	Drinking water	Zahra 2010

Table 2 displays the main organization of the present article. An attempt was made to gather metal sorption data from many individual studies, bearing in mind that conditions of sample preparation, treatment, and testing varied greatly among the published studies. A second main goal of this review article is to provide a fairly complete overview of several mathematical formulas that have been employed to fit metal adsorption data. By using Table 2, readers can select topics of highest interest within the article.

Table 2. Organization of the Present Article

Topic	Page
Introduction	2161
Guide to the tabulation of data	2164
Criteria for success of metal removal	2164
Biomass types and important factors	2166
Modification of biosorbents	2172
Sorption mechanism and ion exchange	2177
Sorption isotherms	2181
Applying isotherms to metal sorption data	2187
Chemical factors affecting sorption	2209
Closing comments	2213

Metals in soluble form have raised increasing concerns in recent years. Toxic effects of various metals have been described in detail by Chang (1996), and more recently by Babula *et al.* (2008) for less common metals. Metal-induced neurological disorders in particular are covered in a book edited by Zatta (2003). Progress has been achieved recently in understanding the attributes of metal ions that contribute to their toxicity (Yoon *et al.* 2008). Most metal ions become harmful when their concentration exceeds a certain threshold, which depends on the sensitivity of the consuming organism. At the same time, a majority of the same metal species can be considered as essential nutrients, and serious adverse health effects would result if they were completely eliminated from an environment or from a drinking water/food supply system. The most dangerous metals are those that tend to bioaccumulate, building up in the fatty tissues of animals in a food chain (Luoma 2008; Chojnacka 2009, 2010). Chromium(VI) is of particular concern in this regard, since the chromate ion (CrO_4^{2-}) is easily transportable across cell membranes. The species is readily reduced to the Cr(III) form, which tends to form insoluble complexes that cannot easily be expelled by the affected organism (Cabtingan *et al.* 2001; Srinath *et al.* 2002; Aravindhan *et al.* 2004b; Deng *et al.* 2006). Metal speciation and the analysis of metal ion species in water have been reviewed by Ali and About-Enien (2006).

Many of the published studies considered in this review article may have been motivated by a desire to find profitable uses of specific waste streams or under-utilized materials produced during industrial operations. When considered separately, almost every such study can be considered successful. However, there has been a need to answer some practical questions, such as those that follow:

- Are cellulosic materials universally effective at removing hazardous metal ions from aqueous solutions?

- Are there rules of thumb that can lead to the selection of suitable biomass for use in sorption of metal ions from solution?
- What are the most useful mathematical expressions that can be used to fit adsorption isotherm data?
- What mechanisms governing metal uptake have been well established? Where are there opportunities for progress in useful theories?
- Can the biosorption of metal ions be improved by mechanical treatments of the cellulosic material?
- What kinds of chemical extractions, derivatizations, or grafting can greatly improve the efficiency of metal ion uptake?
- Should one attempt to regenerate or incinerate cellulose-based biosorbent materials after they have been used to remove metals from water and thereby change the material's life-cycle?

Guide to the Tabulation of Data

As a first step in attempting to answer questions such as those listed above, an extensive literature search was performed, and information reported in the various articles are collected in Table A, which due to its size is placed in the Appendix to this article. Because Table A will be mentioned frequently during subsequent discussions, a description of its organization is provided here. Columns in Table A indicate the type of biomass, the type of modification (if any), the studied metal species, the adsorption capacity (listed both on a mass basis and a molar basis per unit mass), an abbreviated summary of key findings, and the author-year information, which can be used to find the full citation in the "Literature Cited" section. Going down the table, the entries are organized according to biomass type (first column) and then alphabetically by author name within each category. An exception is made when considering studies in which the biomass was so profoundly modified that the nature of the original biomass was judged to be unimportant in comparison. Thus, the various kinds of chemical modifications, as well as production of activated carbon products from cellulose-derived resources, are given unique groups with no regard for the biomass type that was used as the starting material. Starting at the top of the table, the biomass types are organized as follows: **Wood**: (hardwood, softwood, unspecified), wood fibers, bark, foliage, cones, nut shells; **Crop residuals**: husk, stalks; **Food residuals**: sugar cane bagasse, sugar beet pulp, other, seeds, fruit stone, fruit peel, tea leaves; straw and grasses; weeds and plants; **Aquatic plants**: fresh water, seaweed, loofa; **Microbiota, etc.**: algae, bacterial biomass, yeast; **Fungal biomass**, **Lignin-related**: isolated lignin, lignite and humic matter, peat moss, sludge and biogas residuals; **Chemically modified**: alkali-treated, oxidized, with adsorbed materials, derivatized (succinylated, citric acid-treated, carboxymethylated, aminated, other), grafted; **Activated carbons**; and **Ash**.

Criteria for Success

A wide range of criteria have been considered by different authors when judging the relative success of methods to remove heavy metal ions from water. Most authors list adsorptive capacity of the biosorbent among their top concerns. It has been pointed out, however, that one of the most advantageous applications of cellulose-derived sorbents is

in the treatment of very dilute solutions and in the reduction of aqueous metal concentrations to very low levels (Gaballah and Kilbertus 1998; Gupta *et al.* 2000; Amuda *et al.* 2007; Demirbas 2008). None of the reviewed works expressed the opinion that adsorption was not rapid enough for any envisioned usage, though the speed of uptake is mentioned by many authors. Rather, much attention has been paid to modeling the kinetics of metal uptake (see, for instance Table A), and the obtained rate expressions have been used in modeling water treatment systems based on both packed-bed operations and batch treatment (Ho and McKay 1999a; Ho *et al.* 2000b).

Far less attention has been paid to a number of other criteria that might be used to judge the success of a metal remediation strategy. One such criterion is the stability of partially or fully saturated biosorbent. A question remains as to whether the bioadsorbent will continue to hold onto adsorbed metal ions during long-term storage. Another issue that has received relatively little attention is the practical handling of the biomass, including its efficient collection from an aqueous mixture for proper disposal or regeneration without discharging into a surrounding waterbody (Kapoor and Viraraghavan 1998b). Some powdered biomass tends to become soft when placed into water. Its low density and fine particle size can make it difficult to separate from treated wastewater, and fixed bed reactors filled with biomass powders have a tendency to clog (Kapoor and Viraraghavan 1998b).

Using the cellulose-derived material as a support for a primary adsorbent

Another way to define successful use of cellulose-based matter in removal of heavy metals involves the concept of “support”. In other words, the biomass may serve as a backbone structure upon which the main adsorbent material is attached. Zhu *et al.* (2009b) demonstrated such a concept in their use of zero-valent-iron (ZVI) nanoparticles supported on activated carbon. The combination was found to be effective for the removal of arsenic from water. The ZVI nanoparticles act as a strong reducing agent, having the potential to change the valence state of such metals as arsenic and chromium to less toxic forms. The cited article is a prime example of how it is possible to address such problems without needing to release a strong reducing agent directly into aqueous streams or groundwater, which would create an additional contribution to the pollutant load.

Life-cycle issues

It is important, for both environmental and economic reasons, to consider in detail what happens to an absorbent material after it has been employed to remove heavy metals from water. As evidenced by numerous entries in Table A, most cellulose-based sorbents can be “regenerated” by treatment with acid solution (see, *e.g.*, Chang *et al.* 1997), though some studies also evaluated the feasibility of using an alkaline solution or brine. In each case, the idea is to displace the metal ions back into a relatively concentrated solution, which either can be disposed of or further processed as a source of valuable metals or inorganic compounds (Cui and Zhang 2008). Another approach is to incinerate the metal-containing biomass, so that the metal content can be concentrated in the ash (Gaballah and Kilbertus 1998).

Relatively little attention has been paid by researchers to landfilling as an alternative fate for used sorbent material. Unlike the options considered in the previous paragraph, landfilling does not require the use of either chemical treatment or incineration of the contaminated sorbent. Treatments with acid or brine can have environmental consequences, even if the pH is subsequently neutralized. Energy may be required to dry sorbent material before it can be incinerated. Thus, as a potential end-of-use strategy for metal-containing biosorbent material, landfilling should be an option in future life-cycle analyses. Issues that need to be considered include the degree to which typical biosorbents will hold onto their metal content during long-term storage and the likely concentrations of metal ions in leachate from such operations. Considering the case where material in a landfill is subjected to rainfall, research results suggest that typical biosorbents will release relatively low concentrations of metals (Gaballah and Kilbertus 1998; Gupta *et al.* 2000; Amuda *et al.* 2007; Demirbas 2008). None of the cited studies, however, addressed what might happen as the biomaterial breaks down in the soil.

BIOMASS TYPES AND KEY FACTORS

Based on the reviewed literature, it appears that almost every possible category of biomass material has been evaluated for the uptake of heavy metal ions. As indicated in Table A, multiple representatives from many different classes of cellulose-derived materials have been evaluated and judged to be successful as biosorbents. Individual studies have generally tended to be narrow in scope, considering relatively few sorbents, relatively few heavy metal ions, and a limited range of aqueous conditions. Taken together, however, a voluminous collection of scientific work has been published, most of it within the last 20 years. In addition, effects of a great many chemical and thermochemical modifications of cellulosic materials have been used in an attempt to achieve higher adsorption capacities. The take-away message is that there is a large selection of suitable sorbent materials with which one can remove heavy metals from water.

Evaluation of First Hypothesis: The Type of Biomass is Important

The first question to consider is whether there are clear differences in metal uptake, depending on the type of untreated biomass support. Figures 1A and 1B display the amounts of lead and chromate ions that were taken up by unit mass of different classes of cellulose-based materials under the conditions specified in the cited works. Each plotted “X” symbol in the figure corresponds to the results of an individual study. In general, the data taken from studies considered in this review show that the adsorbed amounts varied over very wide ranges, even within each class of sorbent. For instance in the case of “Wood, sawdust” (as represented by the left-most column), the results for Cr(VI) sorption (Fig. 1B) spanned a factor of about 300). Subsequent sections of this article will describe a variety of reasons that each might account for part of these differences. Note that the rectangular “boxes” in these figures indicate the 25%, 50%, and 75% levels based on the relative frequency of articles reporting different values. The “stems” in the diagram extend upwards and downwards to the highest and lowest reported values of metal sorption in each case.

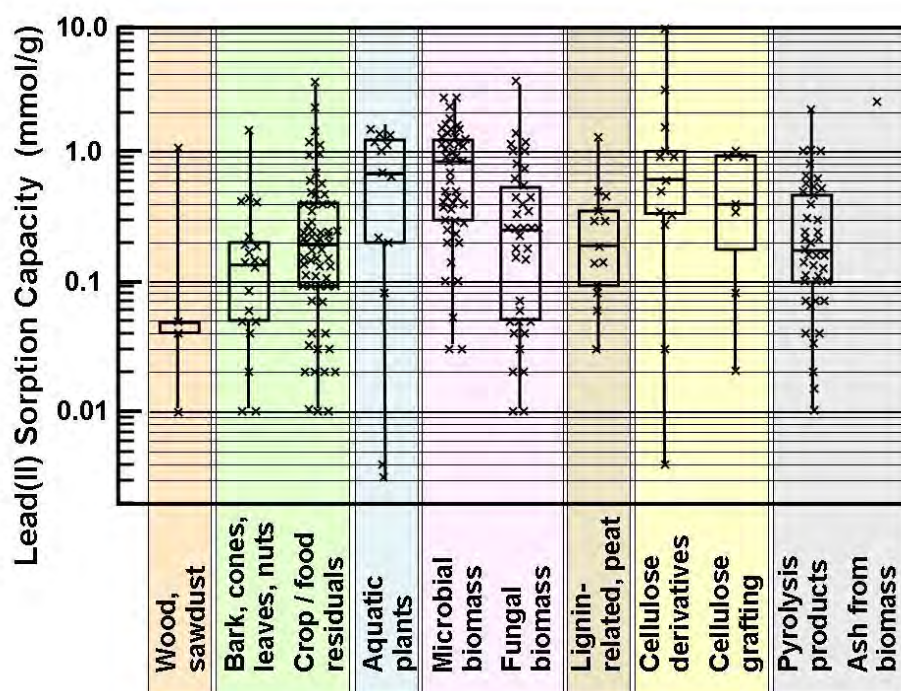


Figure 1A. Graphical summary of reported amounts of lead ion, Pb(II), adsorbed by different classes of cellulose-based matter according to the conditions specified in articles cited in Table A

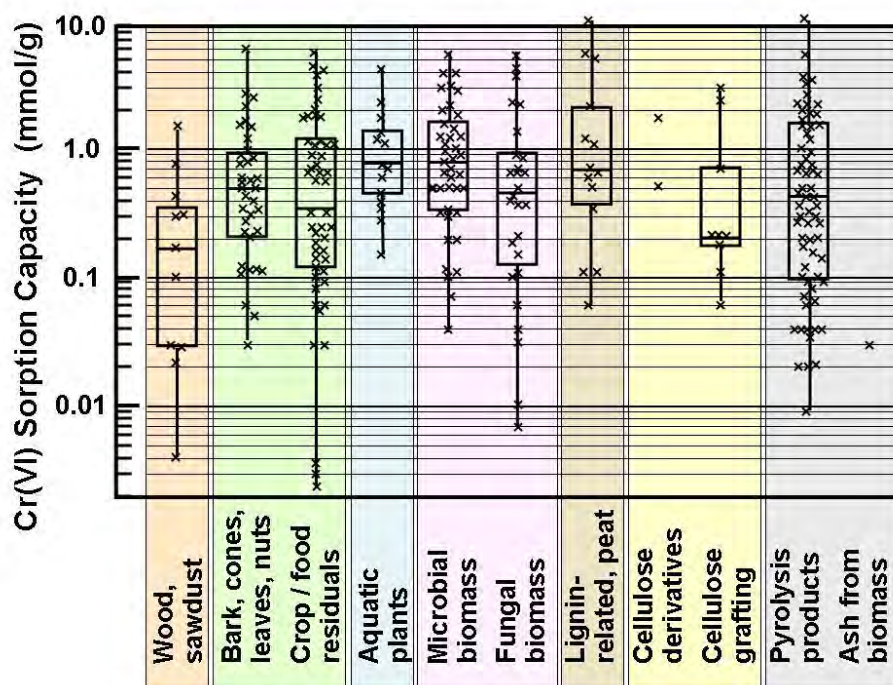


Figure 1B. Graphical summary of reported amounts of adsorbed Cr(VI) taken up by different classes of cellulose-based sorbents according to the conditions specified in articles cited in Table A. Note that Cr(VI) can be present as the CrO_4^{2-} (chromate) anion, depending on the pH.

Visual inspection of Fig. 1A and B suggests that certain biomass classes were somewhat more promising in terms of achieving relatively high levels of sorption of specific metal ions. Though there were important differences attributable to the metal species (especially when comparing adsorption of the chromate ion vs. cationic metal species), such differences appeared to be dominated by effects attributable to differences among the substrate samples, even when the nominal material was similar. As a class, average adsorptive capacities reported for “Wood” did not appear to be as high as those reported for such classes as “Bark, cones, leaves, and nuts,” “Crop/food residuals,” “Aquatic plants,” “Lignin-related,” and “Pyrolysis products.”

Figure 2 addresses a related question: How did different metal ions generally compare against each other, with respect to their tendency to be taken up by a given class of cellulosic material? To make this comparison, seven kinds of metal ions were compared with respect to their sorption by the “crop/food residuals” types of biomass. Though later sections of this article will refer to studies providing evidence of significant “metal selectivity,” such effects are not apparent when one looks at the assemblage of data plotted in Fig. 2.

One of the most fascinating aspects of these results is the finding that the chromate ion (data plotted farthest to the right) compared very well with the other ions, even though the chromate ion (CrO_4^{2-}) has a negative charge, which is the same net charge as that of typical cellulosic surfaces.

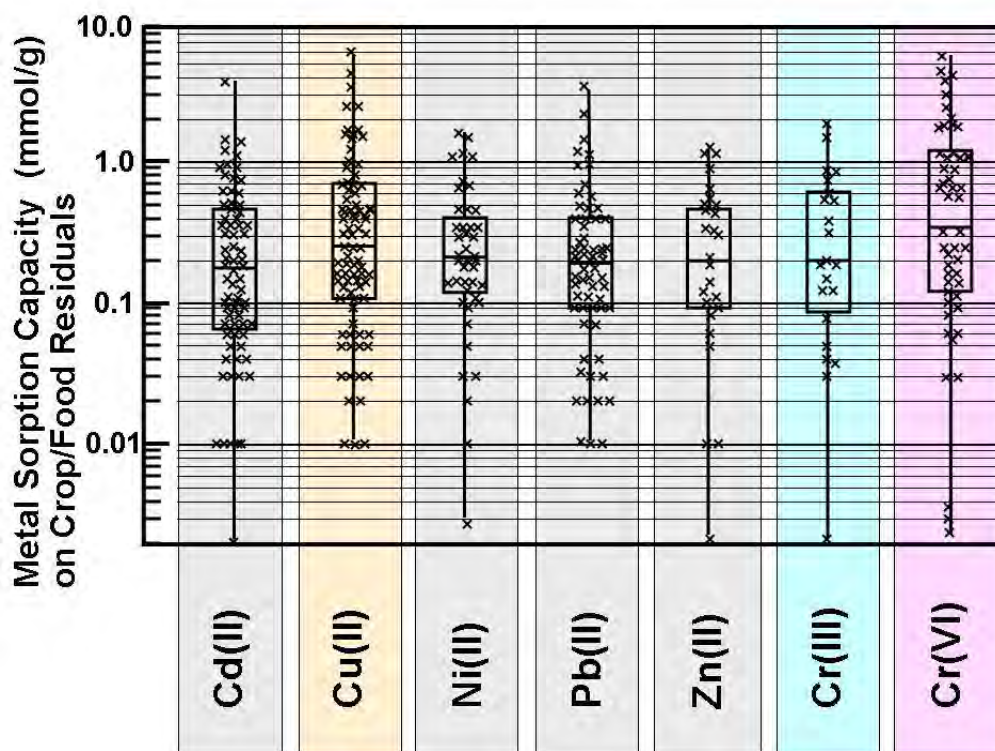


Figure 2. Graphical summary of reported amounts of seven types of metal ions taken up by one class of cellulose-based sorbents (“crop/food residuals”) according to the conditions specified in articles cited in Table A

Because the proportions of cellulose, hemicellulose, and lignins can differ to a great extent, not only among the biomass categories mentioned above, but also from species to species, it makes sense to compare the metal sorption efficiency of biomass samples showing large differences in composition. Various authors have proposed that lignin-rich samples, such as composts, would be expected to have a high affinity for metals ions due to an expected high level of carboxylation (Harman *et al.* 2007). Indeed, various studies support this hypothesis (Srivastva *et al.* 1996; Lalvani *et al.* 1997; Dizhbite 1999; Crist *et al.* 2002, 2003; Acemioğlu *et al.* 2003; Babel and Kurniawan 2003; Basso *et al.* 2004; Demirbas 2004, 2005; Sciban and Klasnja 2004a,b; Celik and Demirbas 2005; Mohan *et al.* 2006; Harman *et al.* 2007; Guo *et al.* 2008; Quintana *et al.* 2008; Wu *et al.* 2008; Harmita *et al.* 2009). By contrast, there has been a notable lack of attention paid to hemicelluloses and extractive components of biomass in this regard; this is surprising, since these components of biomass are known generally to be rich in carboxylic acid groups (Sjöström 1993).

Cost and Availability

A possible lesson that can be drawn from Table A is that almost any biomass-derived product can be used for metal ions removal from solution. It is difficult, however, to claim that any one type of source material is consistently superior to others, though large differences have been observed between different types of biosorbents. That being the case, it is worth questioning whether it is sometimes adequate to make one's selection based only on cost and local availability. For instance, if one were able to obtain peanut shells, fungal biomass, and pine sawdust from local sources, what factors other than performance ought to guide one's choice?

In principle, transportation costs and associated usage of energy can be minimized by using locally-collected biomass as the basis for a biosorbent system. But the overall cost and energy expenditure will also depend on the performance of the material. One needs to consider that a higher-performing biosorbent may achieve one's objectives for metal removal with much less biosorbent material, thus reducing labor costs and operational costs. There may be savings related to safe disposal or regeneration of the spent material.

The ideal biosorbent should be very cheap, an unwanted byproduct that currently has to be hauled away and landfilled or burnt in heaps. On the other hand, the ideal biosorbent should have a huge appetite for a broad range of metal ions, binding them quickly, tightly, and dependably. One approach is just to test various readily available materials in "as-received" form. However, as will be shown in the course of this review, other investigators have employed a more proactive option, treating the biomass in various ways to improve its performance. Though the detailed prices of various biosorbents, both in their as-received and treated forms, lie beyond the scope of the present review article, it is expected that some of the collected data will permit subsequent investigators to make judicious choices among existing biosorbents and to develop additional variations to further enhance performance of biosorbents for different applications.

Cost

The words “low cost” have been used frequently, especially in review articles, by authors summarizing the main motivations prompting the use of biosorbent technology (Scheider *et al.* 1995; Gupta *et al.* 1998; Bailey *et al.* 1999; Brown *et al.* 2000; Gérente *et al.* 2000; Kumar *et al.* 2000; Marchetti *et al.* 2000a; Wartelle and Marshall 2000; Yu *et al.* 2000; Reddad *et al.* 2002b; Babel and Kurniawan 2003; Fiol *et al.* 2003; Ulmanu *et al.* 2003; Krishnani *et al.* 2004; Chuah *et al.* 2005; Horsfall and Spiff 2005b; Karthikeyan *et al.* 2005; Agarwal *et al.* 2006; Ali and Gupta 2006; Kumar 2006; Kumar and Bandyopadhyay 2006a; Kurniawan *et al.* 2006b; Lodeiro *et al.* 2006; Mohan and Pittman 2006; Parab *et al.* 2006a; Pino *et al.* 2006; Sarin and Pant 2006; Singh *et al.* 2006; Upendra and Manas 2006; Abdel-Ghani *et al.* 2007; Dubey and Krishna 2007; Garg *et al.* 2007; Ghodbane *et al.* 2007; Nouri *et al.* 2007; Soleimani and Kghazchi 2007; Zafar *et al.* 2007; Ahmady-Asbchin *et al.* 2008; Arief *et al.* 2008; Chakravarty *et al.* 2008; Demirbas 2008; Farinella *et al.* 2008; Igwe *et al.* 2008; Sud *et al.* 2008; Anandkumar and Mandal 2009; Gadd 2009; Rai 2009; Shukla *et al.* 2009; Wang and Chen 2009; Parab *et al.* 2010; Zahra 2010). Though Gupta *et al.* (2000) claimed that the operating costs involved in the usage of biosorbents for metal removal can be low relative to various alternative pollution abatement measures, there has been insufficient attention to operating costs, including the costs of transporting the sorbent material to the point of use, as well as costs associated with transportation to a site of final disposal, regeneration, or other beneficial use.

Gadd (2009) raised the following challenge to those attempting to make distinctions, other than cost, among alternative cellulose-derived sorbents: Because the composition of biomass does not vary a great deal between different species, it would seem pointless to spend a lot of effort testing many different representatives within a given class of biomass.

As an alternative, it was suggested that researchers should focus on biomass types that have distinct chemical differences from other types. Fungal biomass was mentioned as a key example, since it contains chitin within its cell walls (Ahluwalia and Goyal 2005b). The amino groups within chitin may have the potential to bind certain metal ion species in a different way from other kinds of biomass. Details about the use of fungal biomass for metal remediation have been reviewed (Sag 2001; Bishnoi and Garima 2005).

Local availability of large quantities

When the attributes of a needed commodity include “very low cost,” and often “bulky,” it can be a great advantage to minimize transportation costs. One promising low transportation strategy is to position one’s bioremediation facility adjacent to a business that produces a suitable lignocellulosic waste stream. For example, substantial quantities of microbial biomass are produced during industrial-scale fermentation processes (Ahluwalia and Goyal 2005b). Likewise, there may be opportunities to accumulate such byproducts as bark, sawdust, carcoal, or ash adjacent to a facility that produces wood products or paper pulp as a primary product.

Performance Factors

Having already noted that cellulosic biomass is mainly composed of cellulose, hemicellulosics, lignin, and some extractives – the next challenge is to try to account for the huge ranges of metal ion adsorptive capabilities, such as those that are indicated in Fig. 1. Indeed, while certain cellulose-based sorbents represented in the figure were not very effective on a unit mass basis, others can equal or exceed the sorption capability of commercial ion exchange resins (*e.g.* Chang and Hong 1994; Ariff *et al.* 1999; ChamCarthy *et al.* 2001; Saliba *et al.* 2002b; Choi and Yun 2004; Bishnoi and Garima 2005; Cochrane *et al.* 2006; Arshad *et al.* 2007; Ziagova *et al.* 2007).

Surface area

Cellulosic materials of biological origin tend to be organized with systems of interconnecting pores, thus providing a relatively high surface area per unit mass. However in such cases, there may be questions about: (a) whether parts of that surface area are inaccessible to the metal ions in question, and (b) whether parts of that surface area are lacking in potential binding sites for the metal ions. The importance of maximizing the accessible surface area has been demonstrated by studies that considered effects of particle size of the sorbent (Bai and Abraham 2001). However, there has been a lack of detailed study to compare surface area parameters *vs.* metal uptake under well-defined conditions. Future research might use, for instance, the BET nitrogen adsorption method (Faur-Brasquet *et al.* 2002; Budinova *et al.* 2006; Demiral *et al.* 2008; Hanafiah and Ngah 2009) to quantify the surface area of sorbent materials. A solvent-replacement method and freeze-drying could be used to minimize collapse of submicroscopic pores as water is removed (Stone and Scallan 1996).

As shown in Figs. 1 and 2, the typical data for adsorption of specified metal ions on nominally similar biomass samples range over three orders of magnitude. Including all the factors to be considered in this article, such a wide spread of data would appear to be best explained by differences in accessible surface area. Indeed, the cited work of Stone and Scallan (1996) showed that the drying of cellulosic material has the potential to decrease the apparent surface area by at least a factor of 100. Stone and Scallan revealed that about half of the mesopores that collapsed during drying of cellulosic pulp failed to re-open when the same fibers were rehydrated under the conditions of testing. Future studies related to metal remediation could address this point by scrupulously avoiding inadvertent drying of fresh biomass material at any point before the start of experimentation. This approach has the potential to show whether or not “un-dried biomass,” in contrast to more typically available samples of unknown drying history, might offer substantially higher metal uptake capacity.

Agitation

Another possibility that researchers have studied is whether the uptake of metal ions may be limited by the rate of diffusion of metal ions to surfaces. Some researchers have found that the amount of metals adsorbed increased with increasing agitation during batch testing (Ahalya *et al.* 2005; Basci *et al.* 2003). Though both of the cited studies observed higher adsorbed amounts associated with higher rates of agitation, the mechanism is not completely clear. Agitation can be expected to facilitate convective

transport of metal ions to sorbent surfaces, and several studies indeed showed positive effects of agitation on the rate or extent of metal sorption (Basci *et al.* 2003; Ahalya *et al.* 2005; Shen and Duvnjak 2005b,c; Malkoc 2006; Martinez-Garcia *et al.* 2006b; Chaves *et al.* 2009; Garg *et al.* 2009). Alternatively, the associated pressure pulses acting on suspended particles in a mixture might also create a pump-like action, creating intermittent flow into and out of pore spaces within cellulosic materials in suspension. Such questions have not been adequately resolved and will require further research.

Ion exchange capacity

The issue of “binding sites,” as mentioned previously, can be addressed by considering the ion exchange capacities of candidate sorbent materials (Gadd 2009). Strictly speaking, ion exchange capacity can be measured by determining how much of one type of ion desorbs from a unit mass of a given sorbent when the system is saturated with a specified metal ion. The desorbed ion is usually either the proton, sodium, or an alkaline earth ion, such as calcium. The term “ion exchange” usually implies that the researchers are considering non-specific, electrostatic mechanisms of metal binding. Though such approaches often can be used as a first approximation, later sections of this article will consider alternative approaches that can help to explain deviations from an anticipated 1:1 stoichiometry between the ion exchange capacity of a sorbent and the adsorption capacities of different metal ions, even those having the same valence.

The major proportion of the ion exchange capacity of a biosorbent material usually can be attributed to surface-bound carboxylic acid groups. In principle, the content of carboxylic acid groups can be estimated by titrating a mixture of the sorbent material in water between two levels of pH, such as 3 and 9, and comparing the result with a blank determination (Gill 1989; Herrington and Petzold 1992; TAPPI 1993; Lindgren *et al.* 2002). An alternative method is required if one needs to determine carboxylic acid groups in the presence of other sources of acidity (*e.g.*, Chai *et al.* 2003). The importance of carboxyl groups in sorbing metal ions has been demonstrated in many studies (Maranon and Sastre 1992b; Gloaguen and Morvan 1997; Jia and Thomas 2000; Kadirvelu *et al.* 2000; Merdy *et al.* 2002; Tiemann *et al.* 2002; Chubar *et al.* 2003; Davis *et al.* 2003; Pagnanellil *et al.* 2003; Karunasagar *et al.* 2005; Leyva-Ramos *et al.* 2005; Southichak *et al.* 2009b; Gurgel *et al.* 2008; Lodeiro *et al.* 2008; Bakir *et al.* 2009; Iqbal *et al.* 2009b; Jaramillo *et al.* 2009; Martin-Lara *et al.* 2008, 2009).

MODIFICATION OF BIOSORBENTS

Once a decision has been made to use a certain type of biosorbent, perhaps due to favorable performance of the as-received material, the next decision may involve whether and how to modify that material to improve its efficiency. The following discussion will start with gross mechanical and thermal treatments, then proceed to chemical treatments. Of the latter, relatively superficial “rinsing” strategies will be considered first, then more pervasive treatments such as oxidation, polymer adsorption, and formation of chemical derivatives or graft polymers at the surface of cellulosic materials. Activated carbon, which is often prepared from cellulosic biomass, will be considered last.

Size Reduction

In principle, a more finely ground sample of a given cellulose-based material is expected to adsorb more metal ions from solution, under specified conditions, compared to coarser particles. Indeed, this statement has been proven in a few studies (Ajmal *et al.* 1998; Blazquez *et al.* 2005). A further question is whether the effort and expense of size reduction can be justified. Here the answer is less clear. The study by Ajmal *et al.* (1998) observed an increase in metal sorption capacity by only a factor of about 2 when the particle size of sawdust was decreased from 500 μm to 100 μm . In addition to the high energy requirements, especially if one aims to achieve particles much smaller than 1 mm, one can anticipate increased problems with the handling of very fine material, including greater difficulties in later separation from the water phase, clogging of filters, and even dust and fire hazards if and when the material is dried. Sawdust actually represents a favorable case, since the energy to reduce the particle size has already been expended, perhaps in the production of lumber. Unfortunately, there have been few studies dealing systematically to determine under what circumstances one can justify the energy and time needed to reduce the particle size of a selected biomass sample in preparation for its use as a metal sorbent.

Living vs. Dead Biomass

One of the likely consequences of mechanically or chemically treating a biomass sample (see next sections) is its conversion from living organisms into dead biomass. Several investigators have investigated whether a change from living to dead has a significant effect on the ability of the material to adsorb metals ions (Kapoor *et al.* 1999; Srinath *et al.* 2002; Chen *et al.* 2005; Mehta and Guar 2005; Yan and Viraraghavan 2003). Mehta and Guar (2005) reviewed relevant studies and concluded that dead biomass samples typically outperform living biomass for the uptake of heavy metals. Only in some cases did the investigators find substantially higher uptake when utilizing live cells (Yan and Viraraghavan 2003; Chen *et al.* 2005). The ability of some cells to accumulate metals internally by active biological processes has been suggested (Chen *et al.* 2005), and interest in the use of living cells for biosorption has been predicted to increase (Wang and Chen 2009). Other researchers have found cases where metal sorption was actually increased after such processes as autoclaving (Kapoor *et al.* 1999; Srinath *et al.* 2002; Deepa *et al.* 2006). The explanation for the latter findings may be that killing the cells opens internal surfaces, making the material more accessible. Kapoor and Viraraghavan (1998a) found mixed results; pretreatment of live *Aspergillus niger* biomass with various reagents yielded the best results for uptake of lead, cadmium, and copper, but the best uptake of nickel ions was observed with dead cells.

As noted by Ahluwalia and Goyal (2005b), non-living biosorbents have many potential advantages, including insensitivity to growth conditions or toxins, easier handling, easier storage, and easier disposal. Also, as noted by Ozdemir *et al.* (2004) and Hasan *et al.* (2007), the growth of living cells may be inhibited in the presence of significant concentrations of the specific metal that one would like to remove from an aqueous system. Kurek and Majewska (2004) found that autoclaving of different strains of fungal biomass tended to minimize differences among them in terms of metal sorbency.

Heat Treatment

Rocha *et al.* (2006) observed that the drying conditions used to prepare algal biomass may impact its sorptive capacity. In general, drying tended to shrink the material and resulted in the closing of pores. Various authors have reported increases in metal sorption capacity in the case of heat-inactivated biomass samples (Kacar *et al.* 2002; Bayramoglu *et al.* 2003; Gurisik *et al.* 2004; Arica *et al.* 2005; Tunalı *et al.* 2005).

Drying of biomass also has been reported by many researchers as having a positive effect on metal uptake (Rocha *et al.* 2006), and many of the articles cited in this work specified the use of dried biomass. However, there has been almost no systematic study of this important issue.

Alkaline Treatment

Treatment with alkaline solution has been shown to enhance metal uptake in a few cases (Azab and Peterson 1989; Luef *et al.* 1991; Fourest and Roux 1992; Addour *et al.* 1999; Kapoor *et al.* 1999; Mameri *et al.* 1999; Kumar *et al.* 2000; Reddad *et al.* 2002d; Spanelova *et al.* 2003; Min *et al.* 2004; Tuanli *et al.* 2005; Sciban *et al.* 2006b; Southichak *et al.* 2006a; Afkhami *et al.* 2007; Nasir *et al.* 2007; Gupta and Rastogi 2008b; Argun *et al.* 2009). The mechanism has not been confirmed in detail. It seems likely that saponification of various ester groups may be involved, increasing the number of carboxylate groups on the treated surfaces (Reddad *et al.* 2002e; Xuan *et al.* 2006; Li *et al.* 2007, 2008).

Oxidation

One kind of treatment that has been consistently shown to increase the ability of cellulose-derived substrates to adsorb cationic metal species is oxidation (Maekawa and Koshihima 1984; Jia and Thomas 2000; Rangel-Mendez and Streat 2002; Chen and Zeng 2003; El-Hendawy 2003; Park *et al.* 2003; Park and Kim 2004; Babel and Kurniawan 2004; Saito and Isogai 2005; de Mesquita *et al.* 2006; Kikuchi *et al.* 2006; Argun *et al.* 2008a; Chavez-Guerrero *et al.* 2008; Baccar *et al.* 2009; Berenquer *et al.* 2009; El-Hendawy 2009; Foglarova *et al.* 2009; Han *et al.* 2009; Jamillo *et al.* 2009; Klasson *et al.* 2009; Shukla *et al.* 2009). As already has been noted, oxidation of cellulose-derived material may result in increased numbers of carboxyl groups, which can dissociate to their negatively charged carboxylate form as the pH is increased in a range of 3 to 6.

In contrast to oxidation, chemical reduction may be useful for metal ion uptake, but only in isolated circumstances. Harry *et al.* (2008) observed enhanced adsorption on carbon cloth following electrochemical reduction, especially in the case of Cr(VI). Reduction would be expected to render the biomass-derived surfaces less negative in charge, thus favoring the adsorption of a negative species. Consistent with this finding, Aggarwal *et al.* (1999) found that oxidation of activated carbon samples suppressed the adsorption of the Cr(VI) chromate anion, though it favored the adsorption of the Cr(III) cation. However, other authors observed higher adsorption onto substrates that had been oxidized, even for the adsorption of Cr(VI) (Babel and Kurniawan 2004). Redox interactions during the adsorption of Cr(VI) and certain arsenic and mercury ions will be discussed in a later section.

Polymer Adsorption

Although polymer adsorption can be considered as a gentle treatment in the sense that no covalent reactions need to take place with the substrate, the effects on metal adsorption capacity can be profound. There has been a notable lack of research attention paid to adsorption of carboxyl-containing species onto biosorbents, for purposes of enhancing metal uptake.

Surprisingly, increases in adsorption of metal cations have been observed when using positively charged polyelectrolytes such as polyamines (Deng and Ting 2005b,c). Such systems are especially effective for adsorption of the chromate anion (Deng et al. 2006; Fang *et al.* 2007). Analogously, a cationic surfactant has been used to enhance the uptake of chromate ions onto fungal biomass (Mungasavalli *et al.* 2007). Chitosan, a positively charged polymer of natural origin, was likewise found to be effective for adsorption of Cr(VI) (Nomanbhay and Palanisamy 2005). The chitosan was loaded onto a charcoal support in the cited work. Tschabalala *et al.* (2004) observed, similarly, that a cationized cellulosic support was effective for removing phosphate, a negatively charged material, from aqueous solution. Gérente *et al.* (2007) have provided context from some of these findings in their review of research related to the use of chitosan for removal of heavy metals from aqueous solution.

Chemical Derivatization

Chemical derivatization of cellulosic material can be defined as the covalent attachment of various functional groups. This approach makes it possible for technologists to select chemical functionalities that may be expected to enhance metal uptake. From a scientific standpoint, derivatization also can be considered as a way to evaluate different hypotheses regarding which chemical groups, some of which may be present naturally, are likely to contribute to observed metal-binding effects.

Carboxylic acid derivatives

Earlier it was noted that carboxylic acid groups contribute directly to the ion exchange capacity of sorbent materials. Accordingly, many authors have reported favorable effects on metal uptake when using biosorbents that have been derivatized to increase their carboxylic acid content. Xie *et al.* (1996) describe the use of chloroacetic acid for this purpose. Other authors have achieved similar effects by reacting the cellulosic material with succinic anhydride (Marchetti *et al.* 2000a; Nada and Hassan 2006; Karnitz *et al.* 2007; Gurgel *et al.* 2008; Parab *et al.* 2008; Belhafaoui *et al.* 2009; Chandlia *et al.* 2009; Garg *et al.* 2009). In general, such approaches have been shown to increase the adsorption capacity of a biosorbent for the target metal(s).

Multifunctional carboxylic acid derivative

Esterification of a cellulose-based polymer with 1,2,3-propanetricarboxylic acid was found to yield strong binding of a wide range of heavy metals (Sugur and Babaoglu 2005). By such a reaction, there is potential to create adjacent carboxylic acid sites at the sorbent surface. Ideally, if one were to use just the right monomer, there is a theoretical possibility to approach the strong metal binding capabilities of a chelating agent. However, one needs to keep in mind that the most effective chelating agents require three

to six carboxylic acid groups in a specific arrangement that is best suited for coordinating with a given type of metal ion (Lawrance 2010).

Phosphate derivative

Alternatively, it has been shown that a phosphate group can be attached to the surface of activated carbon (Nada *et al.* 2002a; Puziy *et al.* 2002). The product was found to be stable and offering a good ion-exchange capability and ability to bind heavy metal ions.

Sulfur-containing derivatives

When the goal is to adsorb such metals as Hg, Ag, and As, it may make sense to prepare sulfur-containing derivatives. Such an approach has been demonstrated in several cases (Tashihiro and Shimura 1982; Igwe *et al.* 2008). Thus, Aoki *et al.* (1999a) derivatized cellulose with a variety of groups, including isothiuronium and mercapto groups and achieved higher adsorption of Ag(I) and Hg(II). Macias-Garcia *et al.* (2004) and Marshall *et al.* (2007) introduced sulfur groups – presumably sulfonate – by use of SO₂ gas during preparation of activated carbon. Kim *et al.* (1999) observed a three-fold increase in the adsorption of lead after derivatizing algal biomass with xanthate groups.

Grafting

The term “grafting” will be used to represent a polymeric or oligomeric group that is attached to the cellulosic surface, usually by a covalent reaction involving the hydroxyl groups. Researchers have demonstrated the potential to create high-performing biosorbents by such treatments (Kubota and Shigehisa 1995; Yu *et al.* 2007), and the field has been reviewed by O’Connell *et al.* (2008). In particular, researchers have attached acrylamide-related chains to cellulosic surfaces (Aoki *et al.* 1996b; Raji and Anirudhan 1998; Bicak *et al.* 1999; Marchetti *et al.* 2000b; Shibi and Anirudhan 2002, 2005, 2006; Guclu *et al.* 2003; Choi *et al.* 2004; Unnithan *et al.* 2004; Chauhan *et al.* 2005a,b, 2006; Deng and Ting 2005a; Hashem 2006; Hashem *et al.* 2006a; Nada and El-Wakil 2006; Nada *et al.* 2007a; Sharma and Chauhan 2009; Sokker *et al.* 2009). The major increases in metal-binding capability that have been observed by many of these authors are consistent with the chelating effects that can be achieved by multifunctional carboxylic acids, as in the case of substrates that have been grafted with acrylic acid chains. In principle, grafting technologies enable the technologist to attach a wide range of highly specific functional groups to the substrate surface. As such, the approach can be compared to the use of the underlying biomaterial as a kind of support, rather than necessarily being a significant individual contributor to metal uptake.

Pyrolyzing to Produce Activated Carbon Products

Very strong heating in the relative absence of oxygen is known to convert cellulosic materials into carbon. Careful control of the pyrolysis conditions, including the temperature and the composition of the surrounding gases, make it possible to achieve a very high accessible surface area per unit mass, in addition to providing significant control regarding the chemical sites at the carbon surface (Dias *et al.* 2007; Chen *et al.* 2008). For instance, the pore structure often can be enhanced by the use of steam during

preparation of the activated carbon (Budinova *et al.* 2006). Many authors have demonstrated the potential to remove metal ions from aqueous systems by the use of such products, and these are listed in the appropriate section of Table A. Because of the generally hydrophobic nature of many activated carbon products, some authors regard such products as being especially suitable for removal of organic pollutants from aqueous systems, whereas removal of metal ions might be considered as a secondary benefit (O'Connell *et al.* 2008).

Numerous strategies have been used to render activated carbon products more effective in the uptake of one or more kinds of metal ions, and these are likewise indicated in Table A (see the "Activated Carbon" section indicated in the first column, near to the back of the table, and see the "Modifications" as indicated in the second column). Many of these treatments have already been discussed in preceding paragraphs. In general, these modifications can be achieved by the following strategies: First, the gaseous conditions can be adjusted, *e.g.* by the addition of steam, controlled amounts of oxygen, and by controlling the temperature, *etc.* Second, the mixture fed into the pyrolysis operation can be treated, for instance, with such materials as phosphoric acid to achieve a higher proportion of carboxylic acid groups or phosphorous-containing groups on the resulting carbon surface. Finally, the resulting powder can be post-treated, *e.g.* with nitric acid, to oxidize the surface, thus increasing the number of carboxyl groups (see, *e.g.* Lyubchik *et al.* 2004).

Ash

Ash often is available as an under-utilized waste product of the combustion of lignocellulosic materials. Though the properties of the ash itself are seldom a prime consideration in its genesis, it still makes sense to consider its possible beneficial applications. Chonjacka and Michalak (2009) found, for instance, that ash from wood was three times as effective for the removal of metal ions, compared to bone ash. Other studies that have considered the use of ash for metal removal can be cited (Rao *et al.* 2002; Banarjee *et al.* 2004; Chaves *et al.* 2009; Chu and Hashim 2002; Gupta *et al.* 1998, 1999, 2003; Gupta and Ali 2000, 2004; Pehlivan *et al.* 2006; Srivastava *et al.* 2006a,b,c, 2007, 2008a, 2009a,b).

MECHANISMS OF INTERACTIONS WITH METAL SPECIES

Ion-Exchange

"Ion exchange" refers to a class of mechanisms in which adsorbing metal ions take the place of other species already associated with the sorbent surface. For instance, these entities may be metal ions such as Na^+ , Ca^{2+} , or the proton, *etc.* Let's suppose that a given biosorbent material has been prepared by equilibration in either NaOH solution or NaCl brine. In such cases, it's reasonable to expect that acidic sites on the substrate will be mainly associated with Na ions. If the Cu^{2+} ion, for instance, is then introduced to the system, it may have a higher affinity for acidic sites in comparison to a monovalent cation. The resulting competition will lead to a net desorption of Na^+ from surface sites and a net uptake of Cu^{2+} .

Recent studies reviewed by Sag (2001) with fungal biomass in general and seaweed in particular have indicated a dominant role of ion exchange in metal binding. The classical ion-exchange concept, based on exchange-equilibrium constants and separation factors, can be applied. For a generalized ion-exchange reaction for dissolved species A being exchanged for a bound species B, with the underlined character representing the bound species,



where the equilibrium constant K_{AB} and the separation factor γ_{AB} are given as follows, for the case of ideal behaviour of the exchanging species (1:1 ion exchange, activity = 1) in both of the phases:

$$K_{AB} = \frac{q_A^b C_{Bf}^a}{C_{Af}^b q_B^a} = \left(\frac{y_A^b x_B^a}{x_A^b y_B^a} \right) \frac{C_o^{b-a}}{Q^{a-b}} \quad (2)$$

$$\gamma_{AB} = \frac{y_A x_B}{x_A y_B} \quad (3)$$

For a binary ion-exchange system, the value of the equilibrium constant K_{AB} can be determined from the slope of the plot of q_A/q_B versus C_A/C_B . Biosorbents can also be prepared in different ionic forms, and the sorption analysis is often reduced to considering a series of simple binary ion-exchange systems. By eliminating q_B through substitutions, the following expression is obtained:

$$\frac{q_A}{Q} = \frac{1}{1 + \frac{C_B}{K_{AB} C_A}} \quad (4)$$

As q_A / Q represents the fraction of the binding sites occupied by A, this equation may be used to evaluate the decrease of the equilibrium uptake of the species A by the biosorbent caused by the presence of species B. Using simple dimensionless concentration fractions as variables, Eq. (4) can be re-written as follows:

$$y_A = \frac{1}{1 + \frac{x_B}{K_{AB} x_A}} \quad (5)$$

This equation is the most generalized description of the ion-exchange sorption equilibrium for binary systems (Kratochvil and Volesky 1998). Modeling multi-metal ion exchange in biosorption has been applied to the brown alga *Sargassum fluitans*, which contains the carboxyl groups of alginate and the sulfate groups of fucoidan. An ion-exchange-based two-site model has been developed (Schiewer and Volesky 1995) and

extended to describe multi-site and multi-ion system behavior (Schiewer and Volesky 1996).

Substantial published evidence supports the validity of the concept as just described, when it is applied to cellulosic-derived substrates. Desorption of displaced ionic species has been demonstrated during the uptake of a charge-equivalent amount of the heavy metal of interest. For instance calcium or magnesium ions may be released, depending on how the sorbent material has been prepared (Akthar *et al.* 1995; Diniz and Volesky 2005).

As an example, alkali-treated *A. niger* biomass was used to sequester silver ions from dilute as well as concentrated solutions (Akthar *et al.* 1995). The bound Ag^+ was fully desorbed by dilute HNO_3 , and the biosorbent was regenerated by washing with $\text{Ca}^{2+}/\text{Mg}^{2+}$ solution. The binding of Ag^+ was attended by a stoichiometric release of Ca^{2+} and Mg^{2+} ions together (the sum of the two released being equal to Ag^+ bound in molar terms, as expected on the basis of the univalency of the Ag^+ ion). This equivalence established the mechanism of Ag^+ sorption as being quantitatively due to exchange with $(\text{Ca}^{2+} + \text{Mg}^{2+})$ ions of the biosorbent.

Biosorption of the lanthanides, lanthanum (La^{3+}), europium (Eu^{3+}), and ytterbium (Yb^{3+}) from single component and multi-component batch systems using *Sargassum polycystum* Ca-loaded biomass was studied (Diniz and Volesky 2005). The ion exchange sorption mechanism was confirmed by the release of calcium ions from the biomass that matched the total number of metal and protons removed from the solution.

In other cases, the adsorption of metal ions is accompanied by dissociation of a stoichiometrically equivalent amount of protons. Metal (Pb, Cu, Zn, Cd, Ca) uptake by kraft lignin was also found to occur by displacement of protons or bound metals (Crist *et al.* 2002), as shown by the following equations, where X stands for a mono-valent bonding site on the substrate. Square brackets indicate concentrations in solution, while terms in parentheses represent the sorbate on the sorbent after ion exchange.



$$K_{\text{ex}} = [\text{Ca}^{2+}](\text{MX}_2)/[M^{2+}](\text{CaX}_2) \quad (7)$$



$$K_{\text{ex}}^{\text{H}} = [\text{H}^+]^2(\text{MX}_2)/[M^{2+}](\text{HX})^2 \quad (9)$$

Crist *et al.* (2003) also conducted a detailed study with a kraft pine lignin powder. This material has acid functions that can act as ion exchange sites, which showed that uptake of divalent toxic metals was accompanied by a release of protons or existing metals from the lignin. A demonstrated stoichiometry of one mole Ca displaced for one mole of metal (Sr or Cd) sorbed was fully consistent with a chemical reaction of ion exchange and difficult to explain by frequently used adsorption models.

Adsorption of Hg(II), Cr(III), Cu(II), Cd(II), Ni(II), Ca(II), Sr(II), Zn(II), Co(II), Mn(II), Mg(II), K(I), and Na(I) by activated carbon made from pecan shells (Dastgheib and Rockstraw 2002a), showed that the Slips and Freundlich equations (see later) were satisfactory for explaining the experimental data. The ratio of equivalent metal ions adsorbed to protons released was calculated for the studied metal ions over a range of concentrations. In most cases, particularly at low concentrations, this ratio approached one, confirming that ion exchange of one proton with one equivalent metal ion was the dominant reaction mechanism.

Other studies have shown correlations between the number of weak-acid sites on the substrate in comparison to the amount of metal ions that can be adsorbed. The concept of ion exchange is also supported by the fact that a sufficiently high concentration of salt, acid, or base can cause a reversal of the process; this type of phenomenon will be discussed later in this article with respect to the regeneration of sorptive materials that have been used at least once in the sorption of heavy metals.

Figure 3 contrasts the ion exchange concept, as just described, with a site-specific concept. Ion exchange is mainly concerned with the stoichiometry of displacement of bound ions by dissolved ions, as displayed in the left-hand frame of the figure. For instance, adsorption of a trivalent metal ion is shown to occur from the displacement of three mono-valent species. By contrast, a complexation model (see later discussion) focuses on the underlying interactions of ions with surface sites. Thus, the right frame of Fig. 1 envisions the adsorption of a hydrated divalent ion, the simultaneous release of some of the waters of hydration, and the formation of a bi-dentate complex having moderate stability. Concepts related to such complexation are considered near the end of this article.

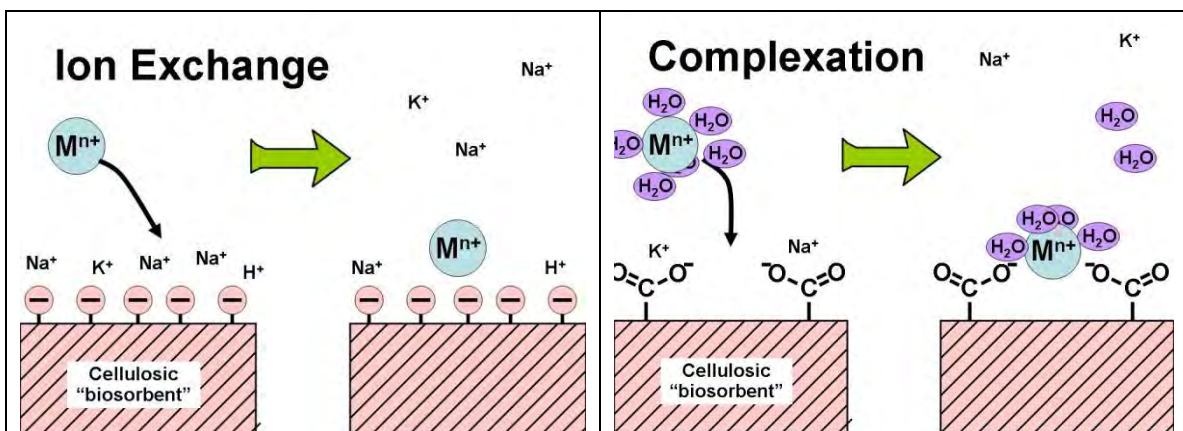


Fig. 3. Pictorial comparison of ion exchange concept (left frame) vs. metal adsorption involving chemical complexation (right frame)

To further understand implications of the foregoing observations, the next sections deal with mathematical, as well as theoretical fits between adsorption characteristics and solution concentrations, *i.e.* sorption isotherms.

SORPTION ISOTHERMS

When any sorption system reaches a state of equilibrium, there is a defined distribution of sorbate molecules at the solid-liquid interface and also in the bulk at a particular temperature. This provides an idea of the capacity of the sorbent for the sorbate. The maximum possible accumulation of the sorbate at the solid surface is a function of its concentration at a constant temperature, and it can be expressed by the following generalized relationship,

$$q_e = f(C_e) \quad (10)$$

where q_e is the amount of sorbate sorbed at equilibrium (mg/g), C_e is the equilibrium concentration of the sorbate (mg/L), and “f” can be equated to the phrase “is a function of”. This type of relation is termed a ‘sorption isotherm’, which represents equilibrium between the concentration of a solute in solution and its concentration on the sorbent, at a given temperature. For assessing the maximum sorption capacity of a given biosorbent, the derivation of sorption isotherms is the most appropriate method. Further, the study of sorption isotherms is useful not only to evaluate to what extent a sorption system can be improved, but also to help predict conditions for working in open reactors and estimate optimal operating conditions.

The mathematical modeling of sorption is a very powerful tool for understanding the sorption process and essential for process design and optimization (Esposito *et al.* 2002). Several equilibrium-based models have been used to describe the metal transfer between the solution and solid phase during the sorption process (Vijayaraghavan *et al.* 2006a).

Langmuir Sorption Isotherm

The Langmuir model, which is one of the most widely used (see Table A), was initially proposed for the adsorption of a gas on the surface of a solid. Nevertheless, it has been extended to include the sorption of solute at a solid-liquid interface. The Langmuir model suggests that the sorption occurs on the surface of the solid that is made up of elementary sites, each of which can adsorb one sorbate molecule, *i.e.* monolayer sorption. It was also assumed that every sorption site is equivalent and the ability of sorbate to get bound there is independent of whether or not the neighbouring sites are occupied (Langmuir 1918).

The Langmuir model is given as follows (Langmuir 1918):

$$q_e = \frac{Q^o b C_e}{1 + b C_e} \quad (11)$$

Equation (11) can be linearized as follows:

$$C_e / q_e = 1 / Q^o b + C_e / Q^o \quad (12)$$

where q_e (mg/g) and C_e (mg/L) are the sorbed metal ions on the sorbent and the metal ion

concentration in the solution at equilibrium, respectively, b (L/mg) is the constant related to the affinity of binding sites, *i.e.* the affinity of sorbent for the sorbed species. Q^o (mg/g) is known as the Langmuir constant, which represents the monolayer sorption capacity, *i.e.* a practical limiting sorption capacity when the surface is fully covered with metal ions. Q^o assists in the comparison of sorption performances. In general, for good sorbents, high values of Q^o and low values of b are required (Kratochvil and Volesky 1998). Equation 11 also can be linearized to other forms. The final linearized form will be a function of the data distribution.

The affinity between adsorbate and adsorbent can be predicted using the Langmuir parameter b from the dimensionless separation factor R_L ,

$$R_L = 1 / (1 + bC_o) \quad (13)$$

where C_o is the initial metal ion concentration and b is the Langmuir isotherm constant. The adsorption process as a function of R_L may be described as follows: When R_L is greater than one, then the sorption reaction is unfavourable, and it is linear when R_L is equal to one. When R_L is between zero and one, the reaction is favourable, while the reaction is supposed to be irreversible when R_L is equal to zero. This can be summarized as follows:

$$\begin{aligned} R_L > 1 & \text{ unfavorable} \\ R_L = 1 & \text{ linear} \\ 0 < R_L < 1 & \text{ favorable} \\ R_L = 0 & \text{ irreversible} \end{aligned}$$

Freundlich Sorption Isotherm

The Freundlich isotherm model, which is also very widely used, describes the sorption of solute from liquid to solid surface and assumes that the stronger binding sites are occupied first and that the binding strength decreases with an increasing degree of site occupation. The Freundlich model proposes a monolayer sorption with a heterogeneous energetic distribution of active sites, and/or interactions between sorbed species, *i.e.* multilayer sorption (Freundlich 1907).

The Freundlich model can be expressed by the following empirical equation:

$$q_e = K_F C_e^n \quad (14)$$

Equation (14) can be expressed in logarithmic terms to obtain the following form,

$$\log q_e = \log K_F + n \log C_e \quad (15)$$

where K_F ($\text{mg}^{1-n}/\text{g L}^n$) and n (dimensionless) represent the Freundlich constants characteristic of the system. K_F is indicative of the relative sorption capacity, whereas n is the measure of the nature and strength of the sorption process and the distribution of active sites. If $(n) < 1$, then the bond energies increase with the surface density. If $(n) > 1$, the bond energies decreases with the surface density. When $n = 1$, all surface sites are equivalent. Alternatively, it has been shown using mathematical calculation that n values

between 1 and 10 represent beneficial sorption. These parameters are empirical constants, and they depend on several factors (Bajpai *et al.* 2004; Febrianto *et al.* 2009).

Dubinin-Radushkevich (D-R) Sorption Isotherm

The Dubinin–Radushkevich isotherm model (Dubinin and Radushkevich 1947) is postulated within a sorption space close to the sorbent surface to evaluate the sorption free energy and to help determine the nature of bonding, *i.e.* either physisorption or chemisorption.

The D–R isotherm can be presented as follows,

$$\ln q_m = \ln X_m - K_{DR} F^2 \quad (16)$$

where q_m is the amount of sorbate sorbed (mmol/g), X_m is the maximum sorption capacity of the sorbate retained (mmol/g), K_{DR} is the activity coefficient constant related to the sorption free energy of the transfer of the solute from the bulk solution to the solid sorbent ($\text{mol}^2 \text{kJ}^2$), and F is the Polanyi potential, which is given by the equation,

$$F = RT \ln\left(1 + \frac{1}{C_e}\right) \quad (17)$$

where R is the universal gas constant (0.0834 kJ/mol/K) and T is the absolute temperature in Kelvin. C_e was defined earlier.

Assuming that the surface of the sorbent is heterogeneous and when choosing an approximation to a Langmuir isotherm model as a local isotherm for all sites that are energetically equivalent, the quantity K_{DR} , which is related to the mean free energy (E) of the transfer of 1 mol of solute from infinity to the surface of the sorbent, can be expressed by the equation:

$$E = \frac{1}{\sqrt{-2K_{DR}}} \quad (18)$$

If the magnitude of E is between 8 and 16 kJ/mol, then the sorption process is supposed to proceed via chemisorption, while for values of $E < 8$ kJ/mol, the sorption process is of physical nature (Basar 2006; Hasany and Chaudhary 2001; Saeed *et al.* 1996; Tunalı *et al.* 2006; Vijayaraghavan *et al.* 2006a).

Temkin Isotherm

The Temkin isotherm equation (Temkin and Pyzhev 1940) contains a factor that explicitly takes into account adsorbing species–adsorbate interactions. It assumes that the heat of adsorption of all the molecules in the layer decreases linearly with coverage due to adsorbate–adsorbate repulsions and that adsorption involves a uniform distribution of maximum binding energy. In addition, it assumes that the fall in the heat of sorption is linear rather than logarithmic, as implied in the Freundlich equation. The Temkin isotherm has commonly been written in the following form,

$$q = \frac{RT}{b_{Te}} \ln(a_{Te} C_e) \quad (19)$$

Equation 19 can also be represented as follows:

$$q = \frac{RT}{b_{Te}} \ln a_{Te} + \frac{RT}{b_{Te}} \ln C_e \quad (20)$$

where, T is the absolute temperature in Kelvin, and R is the universal gas constant, 8.314 J/mol/K. The constant b_{Te} is related to the heat of adsorption (J/mol), and a_{Te} is the equilibrium binding constant (L/g) corresponding to the maximum binding energy.

Flory-Huggins Isotherm

Another two-parameter isotherm is the Flory-Huggins model, which can be represented as follows (Padmesh *et al.* 2006):

$$\log \frac{\theta}{C_o} = \log K_{FH} + n_{FH} \log(1 - \theta) \quad (21)$$

The equilibrium constant, K_{FH} has been used to compute the Gibbs free energy (ΔG):

$$\Delta G = -RT \ln K_{FH} \quad (22)$$

where $\theta = (1 - C_f/C_o)$ is the degree of surface coverage, K_{FH} is the Flory-Huggins equilibrium constant, and n_{FH} is the Flory-Huggins exponent.

Redlich–Peterson Isotherm

The R–P isotherm can be described as follows (Padmesh *et al.* 2006),

$$q_e = \frac{K_{RP} C_e}{1 + a_{RP} C_e^\beta} \quad (23)$$

where K_{RP} is a first R–P isotherm constant (l/g), a_{RP} is a second R–P isotherm constant (L/mg), β is an exponent, the value of which lies between 0 and 1, and C_e is the equilibrium liquid phase concentration (mg/L).

If $\beta = 1$, then the Langmuir will be the preferable isotherm, while if $\beta = 0$, the Freundlich isotherm will be preferred. Although the two parameters in the Langmuir and Freundlich equations can be graphically determined, Redlich–Peterson constants are not computed by graphing, because there are three unknown parameters. However, the values of the three parameters in the equation can be obtained using non-linear regression analysis.

Toth Isotherm

The Toth isotherm is derived from the potential theory, and it is applicable for heterogeneous adsorption (Toth 1971). This model assumes a quasi-Gaussian energy distribution, where most sites have adsorption energies lower than the peak or maximum adsorption energy. The Toth isotherm is represented as follows (Padmesh *et al.* 2006),

$$q = \frac{q_{\max} b_T C_f}{[1 + (b_T C_f)^{1/n_T}]^{n_T}} \quad (24)$$

where q_{\max} is the maximum dye sorption (mg dye/g biomass), b_T is the Toth model constant, and n_T is the Toth model exponent.

Determining Isotherm Parameters

By linearization

The simplest approach to determining isotherm constants for two-parameter isotherms is to transform the isotherm variables so that the equation is converted to a linear form and then to apply linear regression (Ho *et al.* 2002). Although a linear analysis is not possible for a three-parameter isotherm, a trial and error procedure has previously been applied to a pseudo-linear form of the Redlich-Peterson isotherm to obtain values for the isotherm constants (McKay *et al.* 1984), and this involves varying the isotherm parameter, K_{RP} , to obtain the maximum value of the correlation coefficient for the regression.

By non-linear regression

Due to the inherent bias resulting from linearization, alternative isotherm parameter sets can be determined by non-linear regression (Ho *et al.* 2002). This provides a mathematically rigorous method for determining isotherm parameters using the original form of the isotherm equation (Seidel and Gelbin 1988; Seidel-Morgenstern and Guiochon 1993; Malek and Farooq 1996; Khan *et al.* 1996). Most commonly, algorithms based on the Levenberg-Marquardt or Gauss-Newton methods (Edgar and Himmelblau 1989; Hanna and Sandall 1995) are used.

The optimization procedure requires the selection of an error function in order to evaluate the fit of the isotherm to the experimental equilibrium data. The choice of error function can affect the parameters derived. Error functions based primarily on absolute deviation bias the fit towards high concentration data, and this weighting increases when the square of the deviation is used to penalize extreme errors.

This bias can be offset partly by dividing the deviation by the measured value in order to emphasize the significance of fractional deviations. In the cited study (Ho *et al.* 2002), five non-linear error functions were examined and in each case a set of isotherm parameters were determined by minimizing the respective error function across the concentration range studied. The error functions employed were as follows:

1. The Sum of the Squares of the Errors (ERRSQ):

$$\sum_{i=1}^P (q_{e,meas} - q_{e,calc})^2_i \quad (25)$$

2. A Composite Fractional Error Function (HYBRD):

$$\sum_{i=1}^P \left[\frac{(q_{e,meas} - q_{e,calc})^2}{q_{e,meas}} \right]_i \quad (26)$$

3. A Derivative of Marquardt's Percent Standard Deviation (MPSD):

$$\sum_{i=1}^P \left(\frac{q_{e,meas} - q_{e,calc}}{q_{e,meas}} \right)^2_i \quad (27)$$

4. The Average Relative Error (ARE):

$$\sum_{i=1}^P \left| \frac{q_{e,meas} - q_{e,calc}}{q_{e,meas}} \right|_i \quad (28)$$

5. The Sum of the Absolute Errors (EABS):

$$\sum_{i=1}^P |q_{e,meas} - q_{e,calc}|_i \quad (29)$$

As each of the error criteria is likely to produce a different set of isotherm parameters, an overall optimum parameter set is difficult to identify directly. Hence, in order to try to make a meaningful comparison between the parameter sets, a procedure of normalizing and combining the error results was adopted, producing a so-called 'sum of the normalized errors' for each parameter set for each isotherm.

The calculation method for the 'sum of the normalized errors' was as follows:

- (a) select one isotherm and one error function and determine the isotherm parameters that minimize that error function for that isotherm to produce the isotherm parameter set for that error function;
- (b) determine the values for all the other error functions for that isotherm parameter set;
- (c) calculate all other parameter sets and all their associated error function values for that isotherm;
- (d) select each error measure in turn and ratio the value of that error measure for a given parameter set to the largest value of that error from all the parameter sets for that isotherm; and
- (e) sum all these normalised errors for each parameter set.

The parameter set thus providing the smallest normalised error sum can be considered to be optimal for that isotherm, provided that:

- There is no bias in the data sampling – *i.e.* the experimental data are evenly distributed, providing an approximately equal number of points in each concentration range; and
- There is no bias in the type of error methods selected.

APPLYING ISOTHERM EQUATIONS TO METAL SORPTION DATA

The following subsections describe a number of cases in which authors have provided justification for different types of isotherm models for the analysis of metal sorption onto cellulosic materials under different experimental conditions.

Langmuir Isotherm

As has been noted, the use of the Langmuir adsorption isotherm implies an assumption of uniform, non-interacting adsorption sites. When one considers the impure nature of typical biomass-derived sorbents, it is remarkable how large a proportion of the publications considered in this review reported that good fits were achieved by means of the Langmuir equation (see Table A). Possible ways to explain the goodness of fit, in so many of the listed cases, are as follows:

- Many studies tend to be dominated by effects due to one kind of chemical group, *e.g.* a certain kind of carboxylate group present on that type of modified biomass.
- In addition, it is likely that in many cases the adsorption experiments were performed at sufficiently high ionic strength such that the adsorption of a metal ion at one site did not have an appreciable influence on the adsorption of the next metal ion at an adjacent site. The likely range of influence can be roughly estimated based on the Debye-Hückel reciprocal length parameter (Hiemenz and Rajagopalan 1997).

Multifunctional Langmuir Adsorption Models

Aksu *et al.* (1997, 1999) studied adsorption onto *Chlorella vulgaris* for Fe(III), Cr(VI) and Cu(II) as single-component systems, as well as Fe(III)–Cr(VI) and Cu(II)–Cr(VI) binaries. They concluded that single-component isotherms could be modeled by either the Freundlich or Langmuir isotherms. The binary Freundlich equation proposed by Fritz and Schlönder was appropriate for fitting the data of both binary systems, while the extended Langmuir equation was used successfully for only the Fe(III)–Cr(VI) system.

The simultaneous biosorption of copper(II) and chromium(VI) to *C. vulgaris* from binary metal mixtures was investigated by Aksu *et al.* (1999) in a single-staged batch reactor as a function of V_o/X_o ratio (volume of wastewater containing heavy metal mixture/quantity of biosorbent) at different orders of second metal ion addition and at pH values of 2.0 and 4.0 chosen as the optimum biosorption pH values for chromium(VI) and copper(II), respectively. The sorption phenomenon was expressed by a competitive, multi-component Freundlich adsorption isotherm, which was then used for calculating each residual or adsorbed metal ion concentration at equilibrium ($C_{eq,i}$ or $C_{ad,eq,i}$) at a constant V_o/X_o ratio for a given combination of heavy metals in a single-staged batch reactor. In the cited study, the non-competitive Freundlich isotherm model (Eq. 14) was used for describing the short-term and mono-component adsorption of heavy metal ions by algal cells. However, for binary mixtures, an empirical extension of the Freundlich model has been proposed where the coefficients relating to isotherms could be determined from mono-component isotherm data, except for the biosorption competition coefficients, which had to be determined experimentally. The Freundlich models for the

first and the second components restricted to binary mixtures are given by Eqs. (30) and (31),

$$q_{eqI} = \frac{K_{FI} C_{eqI}^{nI+xI}}{C_{eqI}^{nI} + y_I C_{eqII}^{zI}} \quad (30)$$

$$q_{eqII} = \frac{K_{FII} C_{eqII}^{nII+xII}}{C_{eqII}^{nII} + y_{II} C_{eqI}^{zII}} \quad (31)$$

where K_{FI} , K_{FII} , n_I , and n_{II} are derived from the corresponding individual Freundlich isotherm equations and the six other parameters (noting that x_I , y_I , z_I , x_{II} , y_{II} , and z_{II} are the competitive Freundlich adsorption constants of the first and second metal ions, respectively, for the binary system) are the competition coefficients for two metal ion species.

The biosorption of heavy metal ion mixtures by the biomass in a batch reactor can be considered as a single-staged equilibrium operation. Consideration of the single-stage equilibrium operation would depend on two basic constraints, that of equilibrium (shown in Eqs. (30) and (31)) and that of a mass balance. The mass balance for the first component in the mixture is given by,

$$V_0 C_{0I} + X_0 q_{0I} = V_0 C_{eqI} + X_0 C_{eqI} \quad (32)$$

$$V_0 (C_{0I} - C_{eqI}) = X_0 q_{0I} + X_0 q_{eqI} \quad (33)$$

$$-\frac{V_0}{X_0} (C_{eqI} - C_{0I}) = (q_{eqI} - q_{0I}) \quad (34)$$

where C_{0I} is the initial concentration of the first component (mg L^{-1}); C_{eqI} is the residual concentration of the first component at equilibrium (mg L^{-1}); q_{0I} is the amount of the first component adsorbed per unit weight of algae at the beginning (mg g^{-1}); q_{eqI} is the amount of the first component adsorbed per unit weight of algae at equilibrium (mg g^{-1}); V_0 is the volume of solution containing heavy metal ion mixture in the batch reactor (l); and X_0 is the amount of biosorbent in the batch reactor (g)

Equation (34) belongs to a straight line for the first metal ion, and the line passes through points (C_{0I}, q_{0I}) and (C_{eqI}, q_{eqI}) with $(-V_0/X_0)$ slope. This is the operating line for this stage at a known concentration of the second metal ion. As q_{eqI} and C_{eqI} values are known from experimental data for the first metal ion in the mixture, the single-staged batch operation can be shown in a figure on the same coordinates by drawing the operation line and equilibrium curve for the first metal ion at a known combination and pH value. V_0/X_0 for a desired purification or C_{eqI} and q_{eqI} values at a given V_0/X_0 and a second metal ion concentration can be determined. The initial metal ion concentration of the first metal ion must be equal to,

$$C_{0I} = C_{eqI} + C_{ad,eqI} \quad (35)$$

where $C_{ad,eqI}$ is the adsorbed concentration of the first component at equilibrium (mg L^{-1}). The value of $C_{ad,eqI}$ can be calculated easily from Eq. (35). If a calculation is required, then Eq. (34) can be rearranged as:

$$-\frac{V_0}{X_0}(C_{eqI} - C_{0I}) = \frac{K_{FI} C_{eqI}^{nI+xI}}{C_{eqII}^{xI}} - q_{0I} \quad (36)$$

The amount of the first metal adsorbed per unit weight of biomass at the beginning of the biosorption (q_{0I}) is equal to 0.0, so Eq. (36) can be rewritten:

$$-\frac{V_0}{X_0} = \frac{K_{FI} C_{eqI}^{nI+xI}}{(C_{eqI} - C_{0I})(C_{eqI}^{xI} + y_I C_{eqII}^{zI})} \quad (37)$$

As K_{FI} , n_I , K_{FII} , and n_{II} can be found from experimental data, Eq. (37) also provides the $V_0:X_0$ ratio for desired purification or C_{eqI} and C_{eqII} (or indirectly $C_{ad,eqI}$ and $C_{ad,eqII}$) at a given $V_0:X_0$ ratio for a given heavy metal mixture at a known combination. Equation (37) can also be rewritten for the second metal ion in the same manner.

Thus the copper(II)-chromium(VI) multi-ion system was defined with the multi-component Freundlich adsorption isotherm and used to model the adsorption of a binary system to *C. vulgaris* in a single-staged batch reactor as a function of $V_0:X_0$ ratio and second metal ion concentration at pH 2.0 and 4.0. The pH of the biosorption medium, the order of addition of the metal ions, and the amount of biosorbent ($V_0:X_0$ ratio) strongly affected the equilibrium uptake of the first metal ion by the algae. The individual Freundlich constants evaluated from the non-competitive isotherms were used to find the competitive Freundlich constants in a competitive Freundlich model describing multicomponent adsorption equilibrium. These constants were used in Eq. (37) to calculate the residual concentration of the first metal ion at a known second metal ion concentration and the $V_0:X_0$ ratio in a single-staged equilibrium operation.

The equilibrium isotherms for the first metal ion at the known second metal ion concentrations with the operation line with $V_0:X_0$ slope were also developed to predict the residual concentrations of the first metal ion. It was considered that these two methods may be used successfully to estimate the residual concentrations of the first and second metal ions in a mixture at equilibrium. *C. vulgaris* biomass offers a practical approach for removing mixtures of copper(II) and chromium(VI) ions from waste waters containing mainly these two components. Using low $V_0:X_0$ ratios, high purification yields can be obtained for the first metal ion at its optimum pH value and at low second metal ion concentrations or for desired purifications of the first metal ion, $V_0:X_0$ ratios, pH, and second metal ion concentrations. Parameters can be chosen according to Eq. (37) by using individual and competitive Freundlich constants in a single-staged batch reactor up to 150 mg/L initial metal ion concentration for each metal ion. Multi-staged reactors can

also be designed and operated by estimating a sufficient amount of algae for a known volume of waste water (choosing $V_0:X_0$) with a known heavy metal ions combination, especially if required purification cannot be provided in a one-staged reactor when studying higher metal ion concentrations.

In the work of Leyva *et al.* (2001), single and simultaneous Cd(II) and Zn(II) adsorption isotherms from aqueous solution onto activated carbon were determined experimentally. Single isotherms for these ions were fitted to Langmuir isotherms, while the simultaneous adsorption isotherms was fitted to the bisolute Langmuir isotherm modified with an interaction factor. Experimental data for single adsorption isotherms for Zn(II) and Cd(II) onto C (carbon) were fitted to the Langmuir isotherm (Eq. 11).

The constants for this isotherm were obtained by a least-squares method based on the optimization algorithm of Rosenbrock-Newton. The average percent deviation was calculated, and a reasonable fit to the experimental data was obtained based on application of the Langmuir isotherm. The Freundlich isotherm (Eq. 15) was also tested, but produced a weaker goodness of fit compared to the Langmuir isotherm. The maximum molar uptake of Zn(II) averaged 1.6 times that of Cd(II). This result was explained by the author as probably being related to the electrostatic attraction between the very heterogeneous surface of the activated carbon and the metal ions in solution. Another possible explanation for the relatively high Zn(II) selectivity was related to the ability of both Cd(II) and Zn(II) to be adsorbed at one class of surface sites, while Zn(II) was exclusively adsorbed on other class of surface sites. Thus the single adsorption isotherm of Zn(II) can be represented by a dual-site Langmuir isotherm, known as the bi-Langmuir isotherm. However, a Scatchard plot (q/C vs. q , presented in the paper) of the single solute adsorption data of Zn(II) did not suggest that Zn(II) was adsorbed on two kinds of sites. Thus, it was said that the single-site Langmuir isotherm was appropriate to represent the single adsorption of both metal ions (Leyva *et al.* 2001).

The simultaneous adsorption of Cd(II) and Zn(II) was also studied, as these ions usually occur together in industrial wastewaters. In multicomponent systems, the adsorption isotherm of a certain solute also depends on the concentration and characteristics of the other solutes in the aqueous solution. The solute of interest may be in competition with other solutes for the same active adsorption sites. The experimental data for simultaneous Cd(II) and Zn(II) adsorption were interpreted with the bisolute Langmuir isotherm. The competitive Langmuir isotherms for Cd(II) and Zn(II) are represented as follows:

$$q_{Cd} = \frac{q_{m,Cd} K_{Cd} C_{Cd}}{1 + K_{Cd} C_{Cd} + K_{Zn} C_{Zn}} \quad (38)$$

$$q_{Zn} = \frac{q_{m,Zn} K_{Zn} C_{Zn}}{1 + K_{Cd} C_{Cd} + K_{Zn} C_{Zn}} \quad (39)$$

The constants of these two isotherms are from the single-solute Langmuir isotherms. The experimental molar uptake values of Cd(II) and Zn(II) were compared to the molar uptake values of Cd(II) and Zn(II) predicted with the bisolute Langmuir

isotherm, and it was found that the bisolute Langmuir isotherm overestimated the molar uptake of Zn(II) with an average percent deviation of 94.0%. However, it underestimated the molar uptake of Cd(II), and the average percent deviation was 33.36%. Thus, the binary adsorption data were not properly described with the bisolute Langmuir isotherm. The literature reports that the bisolute Langmuir model provides a reasonable fit to the multicomponent adsorption data when the $q_{m,i}$ values for each metal evaluated from single-solute Langmuir isotherm are similar to each other. As previously noted in this study, $q_{m,Zn}$ is approximately 1.6 times greater than $q_{m,Cd}$. Jain and Snoeyink (1973) assumed that some adsorption occurs without competition, because not all sites were available to all solutes. Consequently, the bisolute Langmuir isotherm was modified for systems in which the $q_{m,i}$ values of components were different, proposing the following isotherm for the solute with the higher $q_{m,i}$, which in the cited study was Zn(II):

$$q_{Zn} = \frac{(q_{m,Zn} - q_{m,Cd})K_{Zn}C_{Zn}}{1 + K_{Zn}C_{Zn}} + \frac{q_{m,Cd}K_{Zn}C_{Zn}}{1 + K_{Cd}C_{Cd} + K_{Zn}C_{Zn}} \quad (40)$$

The isotherm for the solute with the lower $q_{m,i}$ is the same as that represented in Eq. (38), and the constants are from the single-solute Langmuir isotherms. In Eq. (40), the difference between the maximum molar uptakes is the number of sites with noncompetitive adsorption. The modified bisolute Langmuir model was applied to the experimental data for simultaneous Cd(II) and Zn(II) adsorption and it overpredicted the molar uptake of Zn(II), with an average deviation of 112.7%. Thus the modified bisolute Langmuir isotherm failed to predict the molar uptake of Zn(II), and its prediction had a higher average percent deviation than that obtained with the bisolute Langmuir isotherm.

Ho and McKay (1999b) modified the bisolute Langmuir isotherm with an interaction factor, η , and obtained an excellent fit of the adsorption data of Cu(II) and Ni(II) onto peat. The model proposed by these authors can be represented as follows,

$$q_{Cd} = \frac{q_{m,Cd}K_{Cd}\left(\frac{C_{Cd}}{\eta_{Cd,Cd}}\right)}{1 + K_{Cd}\left(\frac{C_{Cd}}{\eta_{Cd,Cd}}\right) + K_{Zn}\left(\frac{C_{Zn}}{\eta_{Zn,Cd}}\right)} \quad (41)$$

$$q_{Zn} = \frac{q_{m,Zn}K_{Zn}\left(\frac{C_{Zn}}{\eta_{Zn,Zn}}\right)}{1 + K_{Cd}\left(\frac{C_{Cd}}{\eta_{Cd,Zn}}\right) + K_{Zn}\left(\frac{C_{Zn}}{\eta_{Zn,Zn}}\right)} \quad (42)$$

where η_{ij} is the interaction factor of metal i for the adsorption of metal j . This interaction factor is specific to each metal ion in a given system and depends upon the other metal ions present. In the cited study, the best interaction factor was obtained by fitting the

isotherm models to the experimental data with a least-squares method that employs an optimization algorithm.

The values of the interaction factors were calculated and found to be as follows: $\eta_{Cd,Cd} = 1.02$; $\eta_{Zn,Cd} = 3.29$; $\eta_{Cd,Zn} = 0.089$; and $\eta_{Zn,Zn} = 1.26$. The experimental molar uptake and the molar uptake predicted with the bisolute Langmuir isotherm that had been modified with the interaction factor were compared, and it was found that the bisolute Langmuir isotherm interpreted the experimental data for both ions reasonably well. The average percent deviation was 18.8% for Cd(II) and 31.0% for Zn(II), which are the lowest values for all the models tested in the cited work. Thus, the experimental data for simultaneous Cd(II) and Zn(II) adsorption onto carbon correlated well with the bisolute Langmuir isotherm modified with an interaction factor. The simultaneous adsorption isotherms for Cd(II) and Zn(II) were always reduced compared to the single adsorption isotherms for these ions. The Zn(II) adsorption isotherm was affected more by the presence of the other ion than Cd(II). The adsorption isotherm for a given ion is always reduced by the presence of the other because the two ions compete for some of the same active sites.

The adsorption behavior of Cu(II) and Mn (II) cations in the presence of other metal ions that display strong or intermediate affinities for adsorption sites was systematically investigated, taking into consideration the following factors: (1) metal ion site competition; (2) charge accumulation near the carbon surface; and (3) speciation of the metal ions. Two multicomponent adsorption models were proposed, and the results were then compared to two models presented in the literature (Dastgheib and Rockstraw 2002b).

For modeling multicomponent systems comprised of species whose single-solute isotherms obey the Freundlich Isotherm, a multicomponent Freundlich equation was used. The first equation of this type was proposed for binary systems by Fritz and Schlünder (1974, 1981), as provided in Eq. (43),

$$q_1 = \frac{K_1 C_1^{n_1 + \beta_{11}}}{C_1^{\beta_{11}} + \alpha_{12} C_2^{\beta_{12}}} \quad (43)$$

where q_1 and C_1 are the concentrations of solute 1 in the solid and liquid phases, respectively; C_2 is the concentration of the solute 2 in liquid phase; K_1 and n_1 are Freundlich equation constants in the single solute 1 system; and β_{11} , α_{12} and β_{21} are constants that are determined from the least squares analysis of the binary data.

The second multicomponent Freundlich equation, which was proposed by Sheindorf *et al.* (1981), was derived under the assumption that: (1) each component in a single system obeys the Freundlich model and (2) for each component in multicomponent system, the adsorption energies of different sites are distributed exponentially, with the distribution function being identical to that for the single-component system. The proposed binary system equation is shown in Eq. (44),

$$q_1 = K_1 C_1 (C_1 + \eta_{12} C_2)^{n_1 - 1} \quad (44)$$

where η_{12} is the interaction parameter (with other parameters are defined in the same manner as Eq. (43)).

Thus the proposed equation, written for solute 1 in a binary system of solutes 1 and 2, can be shown as,

$$q_1 = \left[\frac{K_1 C_1^{n_1}}{K_1 C_1^{n_1} + a_{12} K_2 C_2^{n_2} + b_{12} C_2^{n_{12}}} \right] K_1 C_1^{n_1} \quad (45)$$

where q_1 and C_1 are the concentrations of solute 1 in the solid and liquid phases, respectively; C_2 is the concentration of solute 2 in the liquid phase; K_1 , n_1 , K_2 , and n_2 are the single component Freundlich constants, and a_{12} , b_{12} , and n_{12} are interaction constants obtained from a least squares analysis of the binary data. The term inside the bracket on the right hand side of Eq. (45) represents the overall competition and interaction factor, and has a value of less than or equal to unity (when $C_2 \rightarrow 0$, this term is equal to 1). The term $a_{12} K_2$ can be condensed to a single term, and was considered as one constant.

It was found in most cases that the value of 0.5 for n_{12} in Eq. (45) gave acceptable results. Using this assumption, Eq. (45) was reduced to a form that has only two interaction constants, as shown by Eq. (46),

$$q_1 = \frac{(K_1 C_1^{n_1})^2}{K_1 C_1^{n_1} + a_{12} K_2 C_2^{n_2} + b_{12} C_2^{0.5}} \quad (46)$$

The general case of the proposed multicomponent Freundlich model is Eq. (47),

$$q_i = \frac{(K_i C_i^{n_i})^2}{K_i C_i^{n_i} + \sum_{j=1}^m a_{ij} K_j C_j^{n_j} + b_{ij} C_j^{n_{ij}}} \quad (47)$$

where q_i and C_i represent concentrations of solute i in the solid and liquid phases, respectively; C_j represents the concentration of other solutes in liquid phase; K_i , n_i , K_j , and n_j are the single-component Freundlich constants; a_{ij} , b_{ij} , and n_{ij} are binary interaction constants obtained from $a_{ii} = b_{ii} = 0$; and m is the number of solutes.

Least squares analysis was used to find the constants of Eqs. (43 through 46). In each case, the objective function, as defined in Eq. (48), was minimized

$$\phi = \sum_{i=1}^m \left(\frac{q_{\text{exp},i} - q_{\text{cal},i}}{q_{\text{exp},i}} \right)^2 \quad (48)$$

In Eq. (48), $q_{\text{exp},i}$ is the experimental value of the metal ion uptake in binary system at data point i , $q_{\text{cal},i}$ is the calculated value of metal ion uptake (from the selected model), and m is the number of data points.

To evaluate and compare the performance of each model, average relative error (ARE%) and root mean squares error (RMSE%) were calculated for each binary system. The large calculated values of RMSE% corresponding to Eq. (44) demonstrated that this model did not predict the metal ion adsorption isotherms in binary systems particularly well. Equation (43) and the proposed model in Eq. (45) were both found to be good models for predicting adsorption isotherms of metal ions in binary systems, as demonstrated by low RMSE% of different binaries.

Samples of dead biomass from the marine brown algae *Fucus ceranoides*, *Fucus vesiculosus*, and *Fucus serratus* were studied for their ability to remove cadmium from aqueous solutions by Herrero *et al.* (2006). A non-ideal competitive adsorption isotherm model (NICCA) (Kinniburgh *et al.* 1999), which described very well the competition between protons and metal ions, in contrast to a simpler discrete competitive Langmuir model, was applied. This model is a semi-empirical, thermodynamically consistent model, which implicitly accounts for a variable degree of heterogeneity of the sorbent. The basic NICCA equation for the overall binding of species *i* in the competitive situation is,

$$\theta_i = \frac{(K_i c_i)^{n_i}}{\sum_i (K_i c_i)^{n_i}} \frac{\left[\sum_i K_i c_i^{n_i} \right]^p}{1 + \left[\sum_i K_i c_i^{n_i} \right]^p} \quad (49)$$

where θ_i is the coverage fraction of the species *i*, K_i is the median value of the affinity distribution for species *i*, p is the width of the distribution (usually interpreted as a generic or intrinsic heterogeneity seen by all ions), and n_i is an ion-specific non-ideality term. Strictly speaking, c_i should be the local concentration of species *i* at the binding site, *i.e.*, the bulk concentration (or activity) corrected for the double layer effect (for instance, the concentrations in the Donnan phase). In this work, the bulk concentrations was used instead, and therefore, the metal binding constants calculated were conditional parameters (referred to 0.05 M ionic strength). The following normalization condition was used to calculate the amount of species *i* bound, q_i ,

$$q_i - \theta_i = (n_i / n_H) q_{\max, H} \quad (50)$$

where $q_{\max, H}$ is the maximum binding capacity for protons, which can be calculated from the equivalence point of the acid-base titrations in absence of heavy metal. The ratio n_i/n_H was interpreted by Kinniburgh *et al.* (1999) in terms of stoichiometry and cooperativity. When this ratio is less than one, then the maximum binding of species *i* is lower than the total amount of sites (defined as the amount of titratable protons), which would be a consequence of some degree of multi-dentism. On the other hand, a value of n_i/n_H greater than one would reflect some degree of cooperativity. Finally, if $n_i/n_H=1$, it can be demonstrated that the maximum proton/metal exchange ratio is one, and the NICCA

isotherm reduces to the generalized (multicomponent) Langmuir-Freundlich isotherm (GLF):

$$\theta_i = \frac{(K_i c_i)}{\sum_i (K_i c_i)} \frac{\left[\sum_i (K_i c_i) \right]^p}{1 + \left[\sum_i (K_i c_i) \right]^p} \quad (51)$$

If only the proton binding is considered (*i.e.*, absence of competing ions) in Eqs. (50) and (51), then the LF isotherm is recovered,

$$q_H = q_{\max, H} \frac{(K_H c_H)^{m_H}}{1 + (K_H c_H)^{m_H}} \quad (52)$$

where now the heterogeneity parameter m_H describes the combined effect of n_H and p ($m_H = n_H p$). In the case of a homogeneous system (no chemical heterogeneity), $m_H = 1$, and then the Langmuir isotherm is obtained. For instance, the ideal Langmuir competitive isotherm for the binding of Cd^{2+} (assuming a 1:1 stoichiometry) would be,

$$\theta_{Cd} = \frac{K_{Cd} C_{Cd}}{1 + K_H c_H + K_{Cd} C_{Cd}} \quad (53)$$

with $q_{Cd} = \theta_{Cd} q_{\max, H}$.

It was found that the fit of the NICCA model to the cadmium binding data (discarding the data at pH 6 and lower metal concentrations) was satisfactory.

Other Models

In addition to the relatively well known isotherm approaches summarized on previous pages, one of the goals of the present review is to provide some guidance on alternative equations that have been demonstrated in at least one study involving metal removal but not widely used as those discussed earlier. Such approaches may have potential to become more widely used in the future.

Incorporation of Donnan relationships

Schiewer and Volesky (1997a) used biomass of the brown alga *Sargassum* for the biosorption of Cd^{2+} ions. This work provided a mathematical model for predicting the equilibrium of proton and metal ion binding as a function of metal ion concentration, pH, and ionic strength. Since the presence of sodium significantly influenced Cd binding, it is recommended to use models that incorporate ionic strength effects. Although swelling of the biomass particle was observed, a simple Donnan model that assumed a rigid particle already yielded a good prediction of the experimental data. A combined Donnan-Biosorption Isotherm equation was derived that allowed for direct calculation of cation

binding without interactions. Three versions of the Donnan model were considered: one that assumes a rigid particle (DORI), one (DOSWa) that accounts for swelling by a linear correlation (Eq 54), and one (DOSWb) that accounts for swelling by a more complex relation (Eq 55).

Since the swelling of sorbent increased with the number of free sites C , the following simple linear relationship between the specific particle volume and C was assumed,

$$V_m = Y_v C \text{ (L/g)} \quad (54)$$

where Y_v is a constant that has to be determined from the experimental data. For C approaching zero (*i.e.*, all sites are occupied), electrostatic effects and therefore the volume are irrelevant (*i.e.*, it does not matter that the value calculated for V_m approaches zero). Equation 54 expresses that the charge density per volume is constant, independent of the degree of site occupation.

Since, the swelling not only increased significantly with C but, additionally, it decreased with $^M q$ (the metal ion binding (mequiv/g)), the following swelling correlation was considered:

$$V_m = 1 + 0.5(C^2 - ^M q) \text{ L/g} \quad (55)$$

Schiewer and Wong (2000) investigated the binding of protons and metal ions by three brown seaweeds *Sargassum hemiphyllum*, *Colpomenia sinuosa*, and *Petalonia fascia* as well as the marine green alga *Ulva fascia* as a function of metal concentration, pH, and ionic strength. Differences in overall biosorption behavior were explained as a result of different numbers of binding sites, affinities for metal complexation, and charge density. These relationships were predicted using the Donnan model combined with an ion exchange biosorption isotherm for covalent binding of metals (Cu and Ni) and protons.

The concentration factor $[H]_p/[H]$ was modeled according to the Donnan equilibrium, whereby the concentration of any ion was assumed to be homogeneous throughout the biomass particle, and the negative charge of the biomass was balanced by counter-ions such as protons (H), sodium (Na), or divalent metal ions (M), whose concentration factor was determined by:

$$\lambda = [H]_p/[H] = [Na]_p/[Na] = ([M^{2+}]_p/[M^{2+}])^{0.5} \quad (56)$$

One main factor determining K is the ionic strength. K decreases with increasing ionic strength, approaching a value 1.0.

A pH-sensitive isotherm equation was derived, which allows for the calculation of the amount of metal and protons bound covalently.

$$CH = C_i (K_H [H]_p) / (1 + K_H [H]_p + (K_M [M]_p)^{0.5}) \text{ (mequiv/g)} \quad (57)$$

$$CM_{0.5} = C_t (K_M [M]_p)^{0.5} / (1 + K_H [H]_p + (K_M [M]_p)^{0.5}) \quad (\text{mequiv/g}) \quad (58)$$

The Donnan model with particle swelling (DOSW) was represented by the following equation:

$$V_m = Y_V C \quad (\text{L/g}) \quad (59)$$

where Y_V is a fitting parameter and C is the number of free carboxyl groups (i.e., assumed not covalently bind to any cation). The following equations were derived by combining the Donnan model Eq. (56) with the isotherm equations (60) and (61):

$$q_H = C_t (K_H [H] + [H] Y_V (1 - 1/\lambda)) / ((1/\lambda) + K_H [H] + (K_M [M])^{0.5}) \quad (\text{mequiv/g}) \quad (60)$$

$$q_M = C_t ((K_M [M])^{0.5} + 2[M] Y_V (\lambda - 1/\lambda)) / ((1/\lambda) + K_H [H] + (K_M [M])^{0.5}) \quad (\text{mequiv/g}) \quad (61)$$

The Donnan model was successfully used to account for the ionic strength effects in pH titrations and in metal binding. In metal binding experiments at high ionic strength swelling of the biomass particles was observed. The model fit improved when compared to the Donnan model for rigid particles when particle swelling proportional to the number of free binding sites was assumed.

Sundman *et al.* (2008) characterized the interactions between Ca^{2+} , Cu^{2+} , and two different fibre materials—a fully bleached softwood kraft pulp, and a chemically modified fully bleached softwood kraft fibre material—aiming for a better understanding of the interactions between water suspended cellulose fibres and metal ions. The study was conducted as a function of pH (2 to 7), both in the absence and presence of an excess of Na^+ ions (0 to 100 mM NaCl). For both fibre materials, adsorption data collected in the absence of Na^+ were fully explained by the non-specific Donnan ion-exchange model. However, in the presence of an excess of NaCl, the data clearly indicated that higher amounts of divalent metal ions adsorbed in comparison to the prediction of the Donnan model. Therefore, to model these data, specific metal ion–fibre surface complexes were assumed to form, in addition to the Donnan ion-exchange. It was found that the Donnan ion exchange model satisfactorily described Ca^{2+} and Cu^{2+} ion adsorption by both fibre materials when no excess of Na^+ ions was present in the fibre suspensions. On the other hand, in an excess of ionic medium, the Donnan model underestimated the Ca^{2+} - and Cu^{2+} -ion uptake in all experiments. The deviation was greatest for the native low-charged fibre material and at the highest ionic medium.

Lumped parameter isotherm model

Schiewer and Wong (1999) used a lumped parameter isotherm model, where they emphasized the need to incorporate pH effects into the isotherm model. Since pH is one of the key parameters in biosorption, it is desirable to use isotherm equations that can accommodate pH as one model variable. Their model also incorporates ion exchange

constants, reflecting that the biosorbent is initially saturated with some ions that have to be released when the metal ion is consumed. Ion exchange constants do not, however, take into account that the degree of binding site occupation may change. Therefore, multicomponent isotherm models have to be proposed that can account for ion exchange and pH effects. The model needs to be based on a 1:2 binding stoichiometry, whereby one divalent metal ion M binds to two binding sites B. Two different approaches have been proposed, *i.e.*, to use ion exchange constants that assume the formation of B₂M complexes or a multicomponent isotherm assuming the formation of BM_{0.5} complexes.

These isotherm models can be represented as:

$$q_M / q_H = BM / BH = K_x [M] / [H] \text{ for } B + M = BM \quad (62)$$

$$q_M^2 / q_H^2 = BM_{0.5}^2 / BM^2 = K_x [M] / [H]^2 \text{ for } 2B + M = 2BM_{0.5} \quad (63)$$

$$q_M / q_H^2 = 2B_2M / BH^2 = 2K_x [M] / [H]^2 \text{ for } 2B + M \rightleftharpoons B_2M \quad (64)$$

The main advantage of the BM_{0.5} and B₂M models is that they adequately represent the possible occurrence of divalent metals occupying two binding sites. Therefore, these stoichiometric assumptions are better suited to model the exchange between metals and protons. The BM_{0.5} and B₂M models yield slightly lower deviations from the experimental data in comparison to the BM_b model, but all have similar magnitudes. The cited authors found that for Cu binding, the B₂M model was better than the BM_{0.5} stoichiometry, while the reverse was true for Ni. This improved performance for BM_{0.5} for Ni was due to different isotherm shapes, whereby the BM_{0.5} model showed rather gradual changes of ion binding with metal concentration. In either case, the stoichiometric assumption that yielded the better fit displayed a slope in the exchange plot much closer to 1.0 compared to the other model. It can be concluded that the slope in the log/log plot for metal proton ion exchange is the best indicator of the appropriateness of the stoichiometric assumptions.

The B₂M model can be advantageous at very low metal concentrations, where the BM_{0.5} model sometimes tends to overpredict the metal binding. Since however both stoichiometric assumptions typically fit equally well and since the BM_{0.5} model offers the additional advantage of being much simpler to use (no iterations are required), it is recommended to use the BM_{0.5} model. An exception is when utilizing the assumption that binding sites must be a suitable distance from each other in order to form a stable complex. Thus, the lesser affinity in *Ulva* in the cited work may be caused by a lack of suitably spaced sites (*i.e.*, the individual carboxyl sites may be too far apart to allow bidentate binding).

Other multicomponent fits

Srivastava *et al.* (2006) studied the competitive adsorption of Cd(II) and Zn(II) ions onto bagasse fly ash (BFA) from binary systems and used different isotherm models to study the equilibrium of systems.

Various monocomponent isotherm equations such as those of Freundlich (Eq. 14), Langmuir (Eq. 11), and Redlich–Peterson (R–P) (Eq. 23) were used to describe the equilibrium characteristics of adsorption; the Redlich–Peterson (R–P) and the Freundlich models represented the single ion equilibrium adsorption data better than the Langmuir model. Equilibrium isotherms for the binary adsorption of Cd(II) and Zn(II) ions on BFA had been analyzed by non-modified Langmuir, modified Langmuir, extended-Langmuir, Sheindorf–Rebuhn–Sheintuch (SRS), non-modified R–P, and modified R–P adsorption models. These multicomponent isotherm equations that have been used are presented as follows:

Non-modified competitive Langmuir model

The extension of the basic Langmuir model for component i in a N -component system to competitive adsorption can be formulated as follows:

$$q_{e,i} = \frac{q_{m,i} K_{L,i} C_{e,i}}{1 + \sum_{j=1}^N K_{L,j} C_{e,j}} \quad (65)$$

where $q_{m,i}$ and $K_{L,i}$ are derived from the corresponding individual Langmuir isotherm equations.

Modified competitive Langmuir isotherm

Individual adsorption constants may not define exactly the multi-component adsorption behavior of metal ion mixtures. For that reason, better accuracy may be achieved by using modified isotherms related to the individual isotherm parameters and the correction factors. An interaction term, $\eta_{L,i}$, which is a characteristic of each species and depends on the concentrations of the other components, has been added in the competitive Langmuir model. The modified competitive Langmuir isotherm is given as,

$$q_{e,i} = \frac{q_{m,i} K_{L,i} (C_{e,i} / \eta_{L,i})}{1 + \sum_{j=1}^N K_{L,j} (C_{e,j} / \eta_{L,i})} \quad (66)$$

where $q_{m,i}$ and $K_{L,i}$ are derived from the corresponding individual Langmuir isotherm equations, and $\eta_{L,i}$ values are estimated from competitive adsorption data. For binary mixtures, this equation can be rewritten as the first and the second component, respectively, and the two equations can be solved simultaneously to obtain the multicomponent Langmuir adsorption constants for each component.

Extended Langmuir isotherm

Assuming that the surface sites are uniform, and that all the adsorbate molecules (ions) in the solution compete for the same surface sites, the extended Langmuir equation for multicomponent systems can be written as

$$q_{e,i} = \frac{q_{\max} K_i C_{e,i}}{1 + \sum_{j=1}^N K_j C_{e,j}} \quad (67)$$

Sheindorf–Rebuhn–Sheintuch (SRS) model

A Freundlich-type multi-component adsorption isotherm known as the Sheindorf–Rebuhn–Sheintuch (SRS) equation was derived by Sheindorf *et al.* (1981), to represent experimental data. A general SRS equation for the adsorption isotherm for component *i* in a *N*-component system is given as:

$$q_{e,i} = K_{F,i} C_{e,i} \left(\sum_{j=1}^N a_{ij} C_{e,j} \right)^{n_i-1} \quad (68)$$

The pre-exponential coefficient $K_{F,i}$ and the exponent n_i are determined from the mono-component systems. The competition coefficients a_{ij} describe the inhibition to the adsorption of component *i* by component *j*, and can be determined from the thermodynamic data, or more likely, from the experimental data of multicomponent systems. The SRS equation assumes that (I) each component individually obeys the Freundlich isotherm; (II) that for each component in a multicomponent adsorption system, there exists an exponential distribution of site adsorption energies,

$$N_i(Q) = \alpha_i \exp(-\beta_i Q / RT) \quad (69)$$

where a_i and b_i are constants; and (III) the coverage by each adsorbate molecule (or ion) at each energy level Q is given by the multicomponent Langmuir isotherm equation:

$$\theta_i(q) = \frac{K_i C_{e,i}}{1 + \sum_{j=1}^N K_j C_{e,j}} \quad (70)$$

where,

$$K_j = K_{0j} \exp\left(\frac{q}{RT}\right)$$

Integration of $N_i(Q)\theta_i(Q)$ over energy levels in the range of $-\infty$ to $+\infty$ yields Eq. (71), and the competition coefficients are defined as $a_{ij} = K_{0j}/K_{0i}$ and thus $a_{ji} = 1/a_{ij}$. The SRS equation was successfully applied to a multicomponent equilibrium adsorption of different types of contaminants,

$$\theta_i = \frac{\alpha_i RT b_{0i}}{n_i} C_i (\sum_{j=1}^k b_{0j} C_j)^{n_i-1} = A_i C_i (\sum_{j=1}^k a_{ij} C_j)^{n_i-1} \quad (71)$$

where

$$A_i = \frac{\alpha_i RT b_{0i}^{n_i}}{n_i} \quad \text{and} \quad a_{ij} = b_{0j} / b_{0i}$$

Non-modified competitive Redlich–Peterson model

The competitive non-modified R–P model related to the individual isotherm parameters only is given as follows,

$$q_{e,i} = \frac{K_{R,i} C_{e,i}}{1 + \sum_{j=1}^N a_{R,j} C_{e,j}^{\beta,j}} \quad (72)$$

where $K_{R,i}$, $a_{R,i}$, and β_i are the R–P parameters derived from the corresponding individual R–P isotherm equations. The competitive non-modified R–P model is rearranged to the following modified competitive R–P Model to take the characteristics of each species into account,

$$q_{e,i} = \frac{K_{R,i} (C_{e,i} / \eta_{R,i})}{1 + \sum_{j=1}^N a_{R,j} (C_{e,j} / \eta_{R,j})^{\beta,j}} \quad (73)$$

where values of $\eta_{R,i}$ are estimated from competitive adsorption data.

Marquardt's percent standard deviation (MPSD) was used to test the adequacy and accuracy of various isotherm model fits with the experimental data. Based on a linearly regression analysis, Srivastava *et al.* (2006) showed that R^2 was closer to unity for the R–P and the Freundlich models compared to the Langmuir model. Thus it was concluded that equilibrium adsorption data of single component adsorption, *i.e.* Cd(II) and Zn(II) ion, could be represented more appropriately by the R–P and the Freundlich models in the studied concentration range and at lower concentrations, since the Langmuir isotherm did not adequately represent the equilibrium sorption. The single-component Langmuir constants are Q^o (monolayer saturation at equilibrium) and b (corresponding to the concentration where the amount of metal ion bound to adsorbent is equal to $Q^o/2$ and which indicates the affinity of the metal ions to bind with adsorbent). The results of this study showed that the amount of Zn(II) ions per unit weight of BFA for the complete monolayer surface coverage was higher than that of Cd(II), and a large value of b implied strong bonding of Zn(II) ions to BFA. K_F and n , the single-component Freundlich constants (indicating the adsorption capacity and adsorption intensity, respectively) were also calculated, and the BFA displayed greater heterogeneity for Cd(II) than for Zn(II) ions. The value of n was found to be 1, which implied that both the Cd(II) and Zn(II) ions were favorably adsorbed by BFA at pH 6.0. The magnitude of K_F also showed higher uptake of Zn(II) than Cd(II) ions by BFA at pH 6.0. It was noted that the Redlich–Peterson constant b normally lies between 0 and 1, indicating a favorable adsorption. The experimental and predicted equilibrium uptake (q_e) evaluated from the single-component Langmuir, Freundlich, and Redlich–Peterson models for the individual adsorption of Cd(II) and Zn(II) onto BFA at pH 6.0 were also compared, and the MPSD values were calculated. Based on the lower MPSD values, the R–P and Freundlich models displayed better fit to the experimental adsorption data than the Langmuir model.

Studies comparing alternative multi-component models to fit data

The simultaneous adsorption data of Cd(II) and Zn(II) on the BFA was also fitted to multi-component isotherm models (Srivastava *et al.* 2006). The multi-component non-modified Langmuir model displayed a poor fit to the experimental data (MPSD = 101.6). All the modified Langmuir coefficients ($\eta_{L,i}$) estimated were much greater than 1.0, indicating that the non-modified multi-component Langmuir model related to the individual isotherm parameters could not be used to predict the binary-system adsorption. However, the use of the interaction term, $\eta_{L,i}$, in the modified Langmuir model (MPSD = 28.3) improved the fit of the non-modified Langmuir model. The use of the multi-component extended-Langmuir model in the cited study showed its inadequacy to represent the experimental data (MPSD values were large). The K_i values, reflecting the affinity between the adsorbent and the metals in the binary systems by using the BFA were found to be 0.04 L/mg for both Cd(II) and Zn(II). The overall total metal ions uptake (q_{max}) by BFA is 7.24 mg/g. These values were found to be considerably lower than the sum of the maximum total capacities of Cd(II) and Zn(II) ions resulting from the single component adsorption systems. For that reason, it was concluded that the adsorption sites of Cd(II), and Zn(II) in binary systems onto BFA may likely be partially overlapped. These lower metal ion uptake results also implied that there may be a variety of binding sites on the adsorbents showing partial specificity to the individual metal ions. The information obtained from the maximum capacities seems to violate the basic assumptions of the Langmuir model, *i.e.* that the entire adsorbent surface is homogeneous and that there is no lateral interaction between the adsorbate molecules. Consequently, the affinity of each binding site for the adsorbate molecules should be uniform. The use of interaction terms, $\eta_{R,i}$, for the modified R-P model (MPSD = 24.1) improved the fit of the non-modified R-P model (MPSD = 52.0); however, the SRS model (MPSD = 15.4) provided the best-fit to the binary adsorption data of Cd(II) and Zn(II) onto BFA. Thus, the SRS isotherm was found to best represent the binary system adsorption. This improved SRS performance was expected, as BFA has a heterogeneous surface, and the adsorption of the single metal ions had also been well represented by the Freundlich isotherm equation. It was evident that the modification of the Freundlich equation, as given by the SRS model, took into account the interactive effects of individual metal adsorbate ions between and among themselves and the adsorbent reasonably well. Therefore, the binary adsorption of metal ions onto BFA can be represented satisfactorily and adequately by the SRS model. The multicomponent SRS model is applicable to those systems where each component individually obeys the single-component Freundlich isotherm.

The isotherm coefficients can be determined from the mono-component isotherm except for the adsorption competition coefficients, a_{ij} , which have to be determined experimentally. The competition coefficients, a_{ij} , describe the inhibition to the adsorption of component *i* by component *j*. The two components for the cited study were found to obey the single-component Freundlich model individually. The competition coefficients a_{ij} and a_{ji} were estimated from the competitive adsorption data for Cd(II), Ni(II), and Zn(II) ions by using the MS EXCEL 2002 program. A comparison of the competition coefficients in the adsorption isotherm equation shows that the uptake of the strongly adsorbed Zn(II) was significantly inhibited by the presence of Cd(II) ($a_{21} = 2.70$).

Similarly, the uptake of Cd(II) by BFA was suppressed in the presence of Zn(II) ion in the solution ($a_{12} = 2.15$).

Three-dimensional (3-D) adsorption isotherm surfaces were used to evaluate the performance of the binary metal ions adsorption system. It was found that the SRS model predictions for the simultaneous adsorption of Cd(II) and Zn(II) ions by BFA from aqueous solution were very satisfactory.

Srivastava *et al.* (2009a) analyzed the competitive adsorption of Cd(II), Ni(II), and Zn(II) ions onto rice husk ash (RHA) from ternary metal ion mixtures. Various isotherm equations such as those of Freundlich (Eq. 6), Langmuir (Eq. 2), and R-P (Eq. 14) were used to describe the monocomponent equilibrium characteristics of adsorption of individual ions onto RHA. The MPSD error values were the lowest for the Freundlich model, followed by the R-P and Langmuir models. Therefore, the equilibrium adsorption data of Cd(II), Ni(II), and Zn(II) ion adsorption on RHA could be represented appropriately by the Freundlich model within the studied concentration range. RHA has a heterogeneous surface. It is, therefore, expected that the Freundlich and R-P isotherm equations can better represent the equilibrium sorption data than the Langmuir isotherm model. The simultaneous sorption data of Cd(II), Ni(II), and Zn(II) from the ternary mixture onto RHA was fitted to the multicomponent isotherm models, *viz.*, nonmodified, modified, and extended Langmuir models (Eq. 2); nonmodified and modified R-P models (Eq. 14); and the SRS model. On the basis of the MPSD error function, it was found that the simultaneous sorption phenomena of Cd(II), Ni(II), and Zn(II) ions on the RHA could be adequately represented by the SRS model.

The sorption of heavy metals (lead, copper, and cadmium) by a marine algal biomass *Sargassum sp.* was studied in single and multiple metal-ion systems (Sheng *et al.* 2007). The equilibrium data for the single metal ion system was studied with the help of the Langmuir adsorption isotherm model (Eq. 11). The effect of the presence of multiple metal ions on the biosorption performance was investigated, and the results were evaluated using the modified competitive Langmuir model and modified Jain-Snoeyink model.

The extension of the basic Langmuir model to account for competitive adsorption in multiple-metal systems can be formulated as follows,

$$q_{e,i} = \frac{q_{\max,i} b_i C_{e,i}}{1 + \sum_{i=1}^n b_i C_{e,i}} \quad (74)$$

where the terms $q_{\max,i}$ (monolayer sorption capacity) and b_i (affinity of sorbent for the sorbed species) are derived from the corresponding individual Langmuir isotherm equations; $q_{e,i}$ and $C_{e,i}$ are, respectively, the uptake and final concentration when adsorption equilibrium is reached, and n is the number of metal ions in solutions. The Langmuir model assumes that each component is adsorbed onto the surface according to ideal solute behaviors, where there is no interaction or competition between molecules involved under homogeneous conditions. To account for nonideal systems using the Langmuir theory, Jain and Snoeyink introduced an additional term into Eq. 74 for binary metal systems,

$$q_{e,1} = \frac{(q_{\max,1} - q_{\max,2})b_1C_{e,1}}{1 + b_1C_{e,1}} + \frac{q_{\max,2}b_1C_{e,1}}{1 + b_1C_{e,1} + b_2C_{e,2}} \quad (75)$$

where $q_{\max,1} > q_{\max,2}$. The additional term on the right-hand side of Eq. 75 (proportional to the quantity $q_{\max,1} - q_{\max,2}$) is the Langmuir expression for the amount of solute 1 adsorbed on to the surface without competition. The second term on the right hand side represents the amount of solute 1 adsorbed onto the surface in competition with solute 2. The amount of solute 2 adsorbed onto the sorbent surface can be calculated from Eq 74.

All the model parameters in these competitive isotherms for multiple-metal systems may be derived from single-component isotherms. Indeed, better accuracy may be achieved by extracting additional coefficients from the multiple-metal isotherms. For instance, an interaction term η , which is a characteristic of each species and is dependent on the sorption properties of the sorbents, has been defined in the modified competitive isotherms.

The modified competitive Langmuir model takes the form

$$q_{e,i} = \frac{q_{\max,i}b_i(C_{e,i}/\eta_i)}{1 + \sum_{i=1}^n b_i(C_{e,i}/\eta_i)} \quad (76)$$

For a binary system, the modified Jain-Snoeyink model becomes

$$q_{e,1} = \frac{(q_{\max,1} - q_{\max,2})b_1(C_{e,1}/\eta_1)}{1 + b_1(C_{e,1}/\eta_1)} + \frac{q_{\max,2}b_1(C_{e,1}/\eta_1)}{1 + b_1(C_{e,1}/\eta_1) + b_2(C_{e,2}/\eta_2)} \quad (77)$$

The root-mean-square error (RMSE) was used to check the adequacy of the model. The sorption data for single metal system at different pH values were well-modeled by the Langmuir isotherm. However, in case of binary and tertiary metal systems, the original competitive Langmuir model and the Jain-Snoeyink model failed to fit the experimental data adequately, with all the R^2 values being less than 0.70. Experimental data fitted both the modified competitive Langmuir model and the modified Jain-Snoeyink model well. It was evident that the modified models, with the introduction of the interaction coefficient (η), considerably improved the accuracy of the modeling. Furthermore, it was also shown that the interaction coefficient η derived from the binary metal system could be successfully applied to the ternary metal system, thus indicating the possibility of predicting biosorption performance of such complex systems, based on the modeling parameters obtained from simpler experiments.

The lead (II) biosorption potential of *Aspergillus parasiticus* fungal biomass was investigated in a batch system (Akar *et al.* 2007b). Freundlich (Eq. 14), Langmuir (Eq. 11), and Dubinin–Radushkevich (D–R) isotherms (Eq. 16) were used for the biosorption isotherm modelling. Results indicated that the Langmuir, Freundlich, and D–R isotherm models are suitable for describing the lead (II) biosorption equilibrium by *A. parasiticus*

in the studied concentration range with the regression coefficient (R^2) values more than 0.97. The R_L (affinity between sorbent and sorbate using Langmuir constants) value for this study was 1.73×10^{-2} , indicating that the biosorption of lead (II) was favorable. The Freundlich constants K_F and n indicate the biosorption capacity of the biosorbent and a measure of the deviation from linearity of the biosorption, respectively. The adequate description of the experimental results with all of the isotherm models investigated in this study implied that the biosorption of lead (II) ions onto *A. parasiticus* biomass was complex, involving more than one mechanism. The biosorption process could be described by ion exchange as the dominant mechanism, in addition to complexation with groups at the surface of this biosorbent. The ion exchange mechanism was confirmed by the E value obtained from D-R isotherm model as well.

The biosorption of chromium(VI) from saline solutions onto dried *Rhizopus arrhizus* was studied as a function of pH, initial chromium(VI), and salt (NaCl) concentrations in a batch system by Aksu and Balibek (2007). The equilibrium sorption data were analysed by using Freundlich (Eq. 14), Langmuir (Eq. 11), Redlich–Peterson (Eq. 23), and Langmuir–Freundlich (Sips) models. The two- and three-parameter adsorption models, using non-linear regression technique and isotherm constants, were evaluated depending on salt concentration.

The Langmuir–Freundlich (Sips) model used in the cited study is another three-parameter empirical model for the representing equilibrium biosorption data (Eq. 78). This model suggests that the equilibrium data follow Freundlich isotherm at lower solute concentration, and thus, do not obey Henry's law, but that they follow a Langmuir pattern at higher solute concentration,

$$q_{eq} = \frac{AC_{eq}^m}{1 + BC_{eq}^m} \quad (78)$$

where A , B , and m are the Langmuir–Freundlich parameters. Values for $m \gg 1$ indicate heterogeneous adsorbents, while values closer to or even equal to 1.0 indicate a material with relatively homogenous binding sites. In this case, the Sips model is reduced to the Langmuir equation.

Thus the equilibrium data were fitted to these isotherm models, and the values of average percentage errors and linear regression coefficients were the criteria for the selection of the most suitable isotherm model. On the basis of lower average percentage errors (in the range 0.8 to 2.4) and higher linear regression coefficients (in the range 0.998 to 1.000), the three-parameter Langmuir–Freundlich (Sips) model best described the chromium(VI) sorption isotherm data compared to other models examined, which suggested the monolayer, homogeneous sorption in single as well as salt-added binary-systems. The relatively lower percentage errors also indicated that both the two-parameter Langmuir and three-parameter Redlich–Peterson models were also very suitable for describing the biosorption equilibrium of chromium(VI) by the fungal cells in all cases. The other two-parameter model of Freundlich exhibited a poor fit to the biosorption data of chromium(VI) with an average percentage error more than 8.3.

The value of n (Freundlich constant), which was significantly higher than unity, indicated that chromium(VI) ions were favorably adsorbed under all the experimental

conditions examined. The values of n at different salt concentrations also indicated that decreased chromium(VI) biosorption intensity was affected by salt addition into biosorption medium. The magnitude of the constant K_F (Freundlich constant) showed a relatively easy uptake of chromium(VI) ions from aqueous solution, with high adsorptive capacity of biomass for chromium(VI) in both single and binary systems. The presence of salt at any initial concentration was found to reduce the K_F constant significantly. The salt added at different levels also affected the Langmuir constants (Q^0 and b). Dried *R. arrhizus* exhibited the maximum biosorption capacity (Q^0) for single chromium(VI) biosorption. The addition of salt decreased the Q^0 value of chromium(VI) biosorption to an insignificant extent. A high value of the other Langmuir parameter, b , indicated a high affinity of the biosorbent for the sorbate. The highest b value obtained for monometal conditions also decreased with the addition of salt, indicating its negative effect on chromium(VI) biosorption. Related biosorption parameters were also calculated according to the three-parameter isotherm of Redlich–Peterson using a non-linear regression method for chromium(VI) biosorption at different salt levels. The Redlich–Peterson constant, K_{RP} , indicated that the adsorption capacity of biosorbent also diminished with increasing salt concentration. It is noted that β normally lies between 0 and 1, indicating favorable biosorption. In the case considered, the value of β was 1.0 for 50 g/L salt containing medium and tended to unity for other salt concentrations studied, suggesting that the isotherms approached the Langmuir form. The corresponding Langmuir–Freundlich parameters of A , B , and m for different salt concentrations were also calculated. Constant A , indicating the biosorption capacity and affinity of biosorbent to chromium(VI) ions, also decreased with salt addition. The value of m , an indicator of heterogeneity index, which was calculated to be about 1.0 for all levels of salt, showed that the chromium(VI) sorption data obtained in the cited study tended towards the Langmuir form rather than the Freundlich form, and thus, the fungus had a homogeneous surface. The results showed that three-parameter models represented the biosorption isotherm data much better than two-parameter models for all cases, with low percentage error values.

Again all these parameters changed with respect to the level of salt, and the results could be used to predict the adsorption behavior of chromium(VI) in an aqueous solution at a specific salt concentration. When isotherm constants were plotted against the salt concentration, the functional relationship between isotherm constants and salt concentration were not linear for the entire range of salt concentration. The results showed that the Freundlich and Langmuir parameters decreased following a second-order polynomial function of salt concentration with high linear regression coefficients. An exponential relationship between the Redlich–Peterson parameters (a_{RP} and K_{RP}) of chromium(VI) and salt concentration was obtained (β is assumed as 1 for all cases) with the correlation coefficients of 0.935 and 0.981, respectively. The relationship between the Langmuir–Freundlich model constants of A and B of chromium(VI) and salt concentration also followed an exponential equation with a high linear regression coefficient, while other Langmuir–Freundlich parameter, m , varied linearly with salt concentration.

The sorption of hexavalent chromium by marine brown algae *Cystoseira indica*, which was chemically-modified by cross-linking with epichlorohydrin (CB1, CB2),

oxidized by potassium permanganate (CB3), or only washed by distilled water (RB), was studied with variations in the parameters: contact time, pH, initial metal ion concentration, and solid/liquid ratio (Basha *et al.* 2008). Langmuir (Eq. 11), Freundlich (Eq. 14), and Dubinin–Radushkevich models (Eq. 16) were used to describe the equilibrium between the Cr(VI) sorbed on the four pretreated biomasses of *C. indica* (q) and Cr(VI) ions in the solution. It was found that the Dubinin–Radushkevich isotherm model was in good agreement with all the experimental data as compared to the Langmuir and Freundlich isotherm models. The magnitude of E (mean free energy, kJ/mol), as obtained in the cited work, was useful for estimating the type of sorption reaction. The E values obtained were around 15 kJ/mol, which is in the energy range of an ion-exchange reaction, *i.e.*, 8 to 16 kJ/mol. This E value suggests that biosorption of Cr(VI) by *C. indica* may be classed as an ion exchange reaction.

Chakravarty *et al.* (2008) used newspaper pulp as an adsorbent for the removal of copper from aqueous medium. The experimental data were analyzed using Freundlich (Eq. 14), Langmuir (Eq. 11), Dubinin–Radushkevich (D–R) (Eq. 16), and Redlich–Peterson (R–P) (Eq. 23) isotherm models. Their results showed that adsorption data fit reasonably well to the Langmuir, Freundlich, and R–P isotherms, as was reflected by the high correlation coefficients (R^2). The Freundlich constant n increased with increasing initial Cu concentration. The D–R isotherm showed a definite trend for the K_{DR} value. However, the R^2 in D–R isotherm decreased with increasing initial concentration of Cu. No definite trend was observed for the Langmuir constants b and Q^o . The calculated R_L value (affinity) for adsorption of Cu(II) on the newspaper pulp adsorbent were found to be in the range of 0 to 1 at all initial Cu(II) concentrations, which confirms the favorable uptake of Cu(II) in the sorption process.

El Nemir *et al.* (2008) used a new activated carbon developed from date palm seed wastes, generated in the jam industry, for removing toxic chromium from an aqueous solution. The equilibrium data were tested using several isotherm models, including the Langmuir (Eq. 11), Freundlich (Eq. 14), Redlich–Peterson (Eq. 23), Temkin (Eq. 19), Dubinin–Radushkevich (Eq. 16), Koble–Corrigan (79), and generalized isotherm (80) equations.

The Koble–Corrigan equation used in the cited study is another isotherm model that depends on the combination of the Langmuir and Freundlich equations in one non-linear equation for representing the equilibrium adsorption data. It is represented as follows,

$$q_e = \frac{aC_e^n}{1 + bC_e^n} \quad (79)$$

where a , b , and n are the Koble–Corrigan parameters, which were obtained by solving Eq. (79) using SPSS version 10.0 computer program.

The generalized isotherm equation was also tested for correlation of the equilibrium data. The linear form of the generalized isotherm is given by,

$$\log \left[\frac{Q^o}{q_e} - 1 \right] = \log K_G - N_b \log C_e \quad (80)$$

where K_G is the saturation constant (mg L^{-1}); N_b the cooperative binding constant; Q^o the maximum adsorption capacity of the adsorbent (mg g^{-1}) (obtained from the Langmuir isotherm model); and q_e (mg g^{-1}) and C_e (mg L^{-1}) are the equilibrium chromium concentrations in the solid and liquid phases, respectively.

In the cited study, four different linear forms of Langmuir isotherm were used, which are presented as follows (El Nemir *et al.* 2008):

<i>Form</i>	<i>Linear equation</i>	
Langmuir-1	$\frac{C_e}{q_e} = \frac{1}{bQ^o} + \frac{1}{Q^o} XC_e$	(81)

Langmuir-2	$\frac{1}{q_e} = \left(\frac{1}{bQ^o} \right) + \frac{1}{C_e} \frac{1}{Q^o}$	(82)
------------	---	------

Langmuir-3	$q_e = Q^o - \left(\frac{1}{b} \right) \frac{q_e}{C_e}$	(83)
------------	--	------

Langmuir-4	$\frac{q_e}{C_e} = bQ^o - bq_e$	(84)
------------	---------------------------------	------

Parameters related to each isotherm were determined by using linear regression analysis, and R^2 was calculated. Their results showed that the linear forms 1 and 2 of the Langmuir isotherm were best fitted for the equilibrium data in comparison to 3 and 4. The experimental data were also found to fit well to the Freundlich model, with $n_F > 1$, indicating that adsorption of Cr^{6+} onto DSC is a favorable physical process. The Koble-Corrigan equation also displayed high R^2 values, which indicates that the Koble-Corrigan equation had a strong goodness of fit to the experimental data. The values of b were 0.01 and 0.02, indicating the combination between heterogeneous and homogeneous adsorption of Cr^{6+} on DSC. The three isotherm constants (A , B , and g) of the Redlich-Peterson isotherm model were also calculated using non-linear regression analysis. The correlation coefficients obtained were comparable to the Langmuir and Freundlich equations, indicating that the Redlich-Peterson isotherm can be representative of the data obtained from the adsorption of Cr^{6+} on DSC. According to the R^2 values, the Temkin isotherm can also characterize the equilibrium adsorption data. However, this isotherm appeared to be less suitable than both the Koble-Corrigan and Redlich-Peterson isotherm models. The results using the D-R isotherm indicated that the D-R model had a poorer fit to the experimental data compared to the Langmuir, Freundlich, Koble-Corrigan, and Temkin isotherm models. The values of E (mean free energy) were also calculated and were found to be in the range of ion-exchange mechanisms, indicating that the adsorption process of Cr^{6+} ion onto DSC was physisorption. The results also showed that the generalized adsorption isotherm represented the equilibrium data reasonably well. The results showed that most of the tested isotherm models fitted well to the experimental

data obtained for the adsorption of Cr^{6+} on DSC. Only the Dubinin-Radushkevich isotherm showed less agreement with the experimental data obtained.

The removal of poisonous Pb (II) from wastewater by different low-cost abundant adsorbents, e.g. rice husks, maize cobs, and sawdust was investigated, and the equilibrium adsorption capacity of adsorbents used for lead were measured and extrapolated using linear Freundlich, Langmuir, and Temkin isotherms (Abdel-Ghani *et al.* 2007). The experimental data were found to best fit the Temkin isotherm model.

Biosorption of chromium using suspended and immobilized cells of *Rhizopus arrhizus* was studied by evaluating the physicochemical parameters of the solution such as initial chromium ion concentration in both batch and packed bed reactor. The Langmuir, Freundlich, and Redlich-Peterson adsorption isotherm models were used in the equilibrium modeling. The Freundlich and Redlich-Peterson adsorption isotherm models were found to fit accurately with the experimental data (Preetha and Viruthagiri 2007b).

A need for further comparative evaluation of different isotherm models

Based on the discussion in the foregoing section, it is clear that data from metal sorption studies can be well fitted to a large number of different isotherm models. These models consider various aspects of the problem, including surface characteristics of the sorbent, affinity between sorbate and sorbent, potentiality of the sorbent, and the nature of the sorption process. However, two of the earliest models, those of Langmuir and Freundlich, continue to dominate the attention of the majority of researchers. This situation suggests that there may be important opportunities for researchers to compare the goodness of fit of existing or newly generated data to a wider variety of the available isotherm models, as outlined in this article. A goal of such efforts can be to determine which of the more recently developed models offers sufficient benefits in terms of fitting accuracy and mechanistic insights to justify their more frequent usage, with some emphasis placed on making the methods available to engineers in a user-friendly format.

CHEMICAL FACTORS AFFECTING SORPTION

Chemical Complexation

The concept of chemical complexation presupposes that there will be a site-specific interaction between particular kinds of metal ions and functional groups at the sorbate surface (Fourest and Volesky 1996; Kim *et al.* 1998; Merdy *et al.* 2002; Vijayaraghavan and Yun 2008; Lawrance 2010). Based on such concepts, some authors (Paagnanelli *et al.* 2005b; Zhang *et al.* 2005; Lodiero *et al.* 2006; Valex *et al.* 2006) have advocated an approach in which chemical complexation, rather than ion exchange, is used to account for adsorbed amounts as a function of solution concentrations.

Metal specificity

Some of the most cogent evidence in support of a chemical complexation concept of metal ion sorption consists of a dependency of molar adsorption capacities on the identity of the tested metal ion. Such differences have been widely reported, and the following citations are representative (Qadeer *et al.* 1996; Puranik and Paknikar 1999;

Schiewer and Wong 1999; Kogej and Pavko 2001; Iqbal *et al.* 2002; Pardo *et al.* 2003; Chauhan *et al.* 2005b; Kobya *et al.* 2005; Saito and Isogai 2005; Romera *et al.* 2006; Zhang and Banks 2006; Afkhami *et al.* 2007; Arslan and Pehlivan 2008; Chen and Wang 2008b; Krishnani *et al.* 2008b). According to theories of chemical complexation (Lawrance 2010), differences in the ability of a surface site to bind different metals are often attributed to matching the radius of the metal ion, as well as the symmetry (octahedral, *etc.*) of its valence electron orbitals, to the positions of the surface-bound atoms (*e.g.* carboxylate groups) at the site of adsorption.

Hard and soft ions

The concept of hard and soft ions (Pearson 1963) has been used effectively to explain why certain metal ions tend to have greater affinity for certain types of sorbent surfaces (Avery and Tobin 1993; Brady and Tobin 1995; Chen and Wang 2007b,c, 2010; Gadd 2009). To summarize, ions that are called “soft” are those that have relatively loosely held, polarizable outer electrons, so that greater contributions of covalent character can be expected in their interaction with surface sites. Examples include lead and mercury. By contrast, “hard” ions have more closely held, less polarizable outer electrons, so that their interactions are more simply dominated by electrostatic factors. Nickel is a prime example. In some cases the molar amounts of adsorbed ions have been shown to be related to the ionic radius of the metal (Chen and Wang 2007b,c). Avery and Tobin (1993) observed that soft ions can be expected to favor sites containing S and N atoms, whereas hard ions can be expected to favor sites with oxygen atoms.

Demonstration of Metal Ion Interaction with Functional Groups

A large number of studies have provided evidence in support of metal ions interaction with specific functional groups at the substrate surface. Many authors have used shifts in the maxima of infrared light adsorption as evidence for specific interactions (Ashkenazy *et al.* 1997; Guibaud *et al.* 2003; Ahluwalia and Goyal 2005a; Deng and Ting 2005a; Ahalya *et al.* 2006, 2007; Chen and Yang 2006; Murphy *et al.* 2007; Arief *et al.* 2008; Li *et al.* 2008; Bakir *et al.* 2009; Garcia-Reyes *et al.* 2009; Iqbal *et al.* 2009a; O’Connell *et al.* 2010). NMR spectra also have been used to substantiate the involvement of specific chemical sites in the binding of metal ions (Araujo *et al.* 2007). One question that has not been completely resolved by these investigations is whether the observed shifts in IR absorbance maxima might be an effect, rather than indicating a cause of metal ion binding. This lack of certainty regarding cause/effect is because anything that changes the electron density significantly near a functional group can be expected to have an impact on the energy content of the associated covalent bonds. It follows that the presence of a metal ion in a fixed position on a substrate surface will change the IR spectra associated with adjacent functional groups, whether or not they each have a positive effect on the bonding mechanism.

In particular, IR evidence has supported the participation of carboxylate groups in metal ion binding (Ahluwalia and Goyal 2005a; Gardea-Torresdey *et al.* 2002). Several studies have supported such a conclusion by selectively converting the existing carboxylic acid groups to another form and displaying a substantial decrease in metal uptake (Beveridge and Murray 1980; Fourest and Volesky 1996; Ashkenazy *et al.* 1997;

Kapoor and Viraraghavan 1997; Tiemann *et al.* 1999; Romero-Gonzalez *et al.* 2001; Bai and Abraham 2002; Tiemann *et al.* 2002; Chubar *et al.* 2003; Meunier *et al.* 2003b; Sheng *et al.* 2004b; Southichak *et al.* 2006b; Suksabye *et al.* 2007; Iqbal *et al.* 2009b; Murphy *et al.* 2009a). Chen and Wang (2008a) and Park *et al.* (2008d) used X-ray methods to display evidence of oxygen atom participation in the binding of zinc to yeast cell biomass. Other authors have used the pH-dependency of adsorption as contributing evidence to support the importance of carboxylic acid groups in metal ion binding (Tiemann *et al.* 2000; Malik *et al.* 2002; Guo *et al.* 2008). A related approach, involving immersion calorimetry and shifts in pH, has been pioneered by Lopez-Ramon *et al.* (1999).

Effects of pH on Metal Ion Sorption

Although a great deal of attention has been paid to dissociation constants associated with different kinds of acidic groups at sorbent surfaces, inadequate attention has been paid to the simultaneous effects of pH on the ionic species of metal ions that are present in the bulk solution.

Close inspection of the next to last column in Table A indicates a common theme for the effects of pH on adsorption of metal cations. Authors of several studies have indicated that adsorption is favored by “increasing pH,” but only up to a certain limit. The trend with increasing pH (i.e., 3 to 6) is generally explained by increasing dissociation of carboxylic acid groups on the cellulosic substrate, which results in an increasing ion exchange capacity of the material. The climactic upper end of a typical curve of adsorptive capacity vs. pH is generally understood to entail an equilibrium between the soluble hydrated metal ion and a corresponding insoluble neutral hydroxide species (Chang *et al.* 1997; Leyva-Ramos *et al.* 1997; Schneider *et al.* 2001; Dastgheib and Rockstraw 2002a; Mohan and Pittman 2006; Sciban *et al.* 2006b; Sheng *et al.* 2007; Demirbas 2008). In addition, certain ions tend to form polynuclear species as they progressively interact with OH⁻ ions in solution (O’Connell *et al.* 2010).

Essentially the opposite pH dependency is often observed when evaluating the adsorption of Cr(VI) species onto biosorbent surfaces. As shown by many entries in Table A, the highest sorption of Cr from Cr(VI)-containing solutions is generally found within a pH range of about zero to 2 (see, for instance Gupta *et al.* 1999). Under such conditions the cellulosic carboxyl groups are expected to be fully protonated, thus minimizing any electrostatic barrier to sorption of negative chromate ions.

Redox Effects

Changes in the valence state of the metal

During the past decade significant progress has been achieved in understanding the adsorption of metal ions that are prone to changes in their oxidation state. Though chromium has received the greatest attention, valence changes also can play a role in the removal of platinum (Chen *et al.* 2007), mercury (Lloyd-Jones *et al.* 2004; El-Shafey 2010); copper (Chandran *et al.* 2002), gold, silver, and palladium (Cox *et al.* 2005) from aqueous solution. The following researchers have reported evidence for Cr(VI) reduction to Cr(III) accompanying its adsorption (Raji and Anirudhan 1997; Selomulya *et al.* 1999; Han *et al.* 2000; El-Shavey and Canepa 2003; Deng and Ting 2005c; Deng *et al.* 2006;

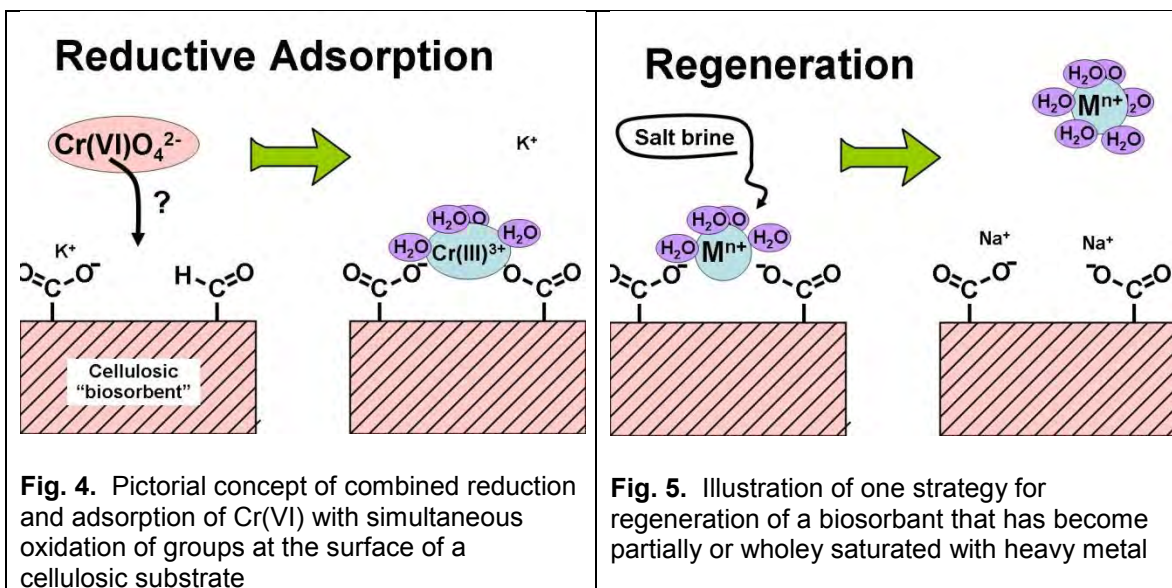
El-Shafey 2005; Gao *et al.* 2005; Park *et al.* 2004b, 2005b,c, 2006a, 2007a,b, 2008d; Murphy *et al.* 2009b; Suksabye *et al.* 2007, 2009). In certain cases, reduction from Cr(VI) to Cr(V) was observed (Suksabye *et al.* 2009). The reduction of Cr(VI) to Cr(III) has been found to proceed under highly acidic conditions (*i.e.*, pH between 1 and 3) (Candela *et al.* 1995). The reduction of metal ions by microbes has also been demonstrated as a mechanism of metal removal from water (Chandran *et al.* 2002).

Changes in the valence state of the substrate

Research has confirmed an expected balance between reduction and oxidation whenever there is a valence change of a metal during the course of its adsorption. In other words, if the metal is reduced, something else in the system must be oxidized. Several researchers have observed oxidation of surface groups of a cellulose-based sorbent material when reductively adsorbing various precious metals or hexavalent chromium (Cox *et al.* 2005; Park *et al.* 2005a,b, 2006c, 2007b, 2008b; Elangovan *et al.* 2008a; Murphy *et al.* 2009b). Oxidation of the substrate as part of the adsorption mechanism is consistent also with the form of the rate expression that governs the uptake of chromium (Park *et al.* 2005c). Further support for this type of mechanism was provided by Praghakran *et al.* (2009), who showed that the rate of reductive sorption of Cr(VI) was highly dependent on the nature of the substrate, with superior results being achieved using coffee dust. Studies involving the blocking of specific sites showed that both carboxyl groups and amino groups can participate in the reductive adsorption process of Cr(VI) (Park *et al.* 2005d). In the case of chromium (VI) adsorption, it can be considered highly fortuitous that oxidation of the surface often increases the number of carboxylate groups, which are well suited to the bonding of the positively charged Cr(III) ions that result from the process.

Figure 4 provides a schematic of some of the concepts just described. The question mark at the left of the figure represents an initial challenge in accounting for the adsorption of a negative ion onto a predominantly negative cellulose-based material. The rightward arrow represents a combined process in which (a) groups at the substrate surface (or in the bulk phase) are oxidized, (b) the chromium(VI) is reduced to Cr(III), and (c) the positively charged Cr(III) ion is simultaneously or sequentially bound to negative sites at the substrate surface.

A worthy question for future research is to explore whether intentional changes to the state of oxidation of a substrate can be used in order to induce subsequent changes in valence of metal ions, thus facilitating their collection. Such a proposal is consistent with work reported by Berenquer *et al.* (2009) who applied galvanic reduction and oxidation to activated carbon. Changes in the surface groups were observed, similar to what can be achieved by treatment with reducing agents or oxidizing agents. However, it is not yet known whether related approaches could facilitate the conversion of, say, Cr(VI) to the less toxic and more adsorbable Cr(III) form. Such observations raise questions as to whether surface sites also could be manipulated by selecting anaerobic vs. aerobic conditions of digestion (Joseph *et al.* 2009).



Reversibility of Metal Binding

In order to optimize conditions of regeneration or disposal, it is important to understand what circumstances can lead to the reversal of metal sorption onto cellulose-dried surfaces. The most straightforward way to encourage metal ions to go back into solution is to replace those ions with a large excess of something else. Hydrochloric acid is the most commonly specified reagent, as indicated by the many entries in the next to last column of Table A. Regeneration, however, also has been achieved by strong base, or less commonly by a concentrated salt solution. Many studies have demonstrated restoration of a majority of the original sorption capacity after the restorative treatment. Increases in adsorption capacity, relative to the original capacity, have been observed in some cases (Chang *et al.* 1997).

Figure 5 illustrates one way that an ion-exchange material can be regenerated. The left-hand part of the figure depicts a metal ion bound in bi-dentate fashion to a pair of carboxylate groups at a surface. Addition of salt brine (or acid, NaOH, *etc.*) causes the target metal(s) to be released into the brine, while sodium ions are left weakly associated with the carboxylate groups on the sorbate.

CLOSING COMMENTS

Any review of such an active and multifaceted field as biosorption of metals is bound to leave out information or to oversimplify critical details. Fortunately, as noted in the Introduction, subtopics of the field have already been reviewed, often with a particular focus that may be of interest to readers (see Table 1).

The explosive growth in publications in this area, with expected faster pace of technological developments to come, may still be difficult to grasp. Combinations of biomass types, chemical or thermal modification, and target metals are often being studied in relative isolation and often without a strong theoretical justification for the combinations of factors that are compared. Some studies appear to just apply well-

known methods to different species of biomass or different metal ions. The scene sometimes can be compared to a wild frontier, in which the first researcher to generate, say, a Langmuir isotherm, can lay claim to having found something new.

The field of study will hopefully continue to mature during the coming decades, and in our opinion two kinds of studies would be very valuable to lead the way into the future. On the one hand, there is a need for mechanistic studies that deal more cogently with the molecular mechanisms, including such issues as binding sites, valence states, coordination chemistry, and the speciation of metals in solution. On the other hand, there need to be a life cycle analysis, considering the wasteproducts of metal remediation operations.

A Need for Studies Related to Proteinacious Binding Sites

One apparent gap in research that can be expected to attract increasing attention during the coming decade concerns the use of engineered proteins for advanced adsorption technologies. A study by Kostal *et al.* (2005) points the way in this direction, showing how biotechnological and nanotechnological principles can be applied. A study by Vinopal *et al.* (2007) showed that certain peptide sequences have highly specific affinity for certain metal ions. In principle, the sorptive properties of enzymatic materials could be optimized by genetic manipulation. Once the optimized biomaterial has been created, the genes could be inserted into a suitable organism to produce suitable quantities for the needed application. It is possible that such proteinaceous biosorbent products could be supported on cellulosic scaffolds, facilitating their use in either batch-type or column-type treatment schemes.

A Need for Application of Nanotechnology Concepts

Given the major attention to nanotechnology during the past decade, there has been a notable lack of consideration of related concepts in the case of biosorption. In particular, the concept of self-assembly (Ninham and Lo Nostro 2010) should be considered relative to the manner in which adjacent hydrated metal cations arrange themselves in various instantaneous configurations at a substrate surface. Attention also should be focused on the nucleation of colloidal precipitates of metal hydroxides as the pH is raised in the neighborhood of a solubility limit (Chang *et al.* 1997; Leyva-Ramos *et al.* 1997; Schneider *et al.* 2001; Sciban *et al.* 2006b; Demirbas 2008). Presumably such precipitated metal hydroxides could either remain as a colloidal suspension or it may be adsorbed onto the biosorbent material. In the latter case, the mechanisms of adsorption may be entirely different from those governing adsorption of the cationic forms of the same metals.

Another aspect of nanotechnology involves accessibility. Metal-binding sites at the surfaces of biomass samples can be effective only if the metal ions are able to reach them. Mesopores in the biomass may have closed up irreversibly at some point due to an uncertain history of the drying of the material (Stone and Scallan 1966). Such effects have the potential to explain the huge ranges (typically three orders of magnitude or more) that have been reported by different researchers for the metal-uptake capacities of nominally similar biomass samples. Future studies need to address these issues science at the nanoscale level.

A Need for Life Cycle Analysis Research

An article by Chojnacka (2010) has helped to define the scope of some needed research related to the life cycle of bioremediation. For a healthy ecosystem it is necessary to account not only for biosorption (which mainly involves dead biomass), but also for bioaccumulation, which involves ingestion and retention within living organisms. The two phenomena can be expected to interact in complex ways, keeping in mind that some metals are prone to building up over time to toxic levels in living tissues.

As was noted in the introduction, there has been inadequate research towards the merits of landfilling or land application as an alternative strategy for dealing with spent cellulose-based sorbent material. Though it is reasonable to be concerned with leachate that contains metals, research is needed to determine whether the metal-binding capacity of the cellulosic material is sufficient such that the resulting concentrations of soluble species remain in a generally safe or beneficial range, especially in the case of metals that can be considered as essential minerals when they are present at low levels. By contrast, the most widely used regeneration schemes require major shifts in pH, leading to the requirement that the pH be adjusted prior to discharge of the water, which will then have a higher level of salinity. Another potentially beneficial strategy that deserves exploration is the incineration of spent biosorbent, making it possible to concentrate the collected metals in the resulting ash. Though there is potential to make use of biosorption as a fuel source, there is need to be concerned about the energy requirement for evaporation of water, as well as measures to reduce airborne particulates.

While there is clear evidence that bio-sorption could be a viable alternative for the remediation of contaminated aquifers, there are several decision factors that companies must consider when selecting an appropriate treatment technology. These factors include but are not limited to treatment cost, volume of contaminated material to be treated, treatment time, site location, the complexity of the target pollutant, and the surrounding water quality. Technologies that merely change the form of toxic wastes, such as in adsorption processes without proper removal, may lead to future problems and costs. Therefore, effective remediation treatment technologies must consider the entire fate of wastes over a longer period. It would be easy to say that these factors are independent. However, it's more likely that the decision complexity is increased due to the interdependency of these factors. Further, companies that would like to select in-situ soil remediation options must weigh that approach against dig-and-haul operators, who remove contaminated soil to landfill sites at a possibly cheaper cost. Consequently, the decision to utilize bio-sorption processes, regardless of whether it is a proven technology, is a complex decision.

A Need for Non-Selective Sorption

The mining industry has provided early stimulus for research into metal removal technology. Perhaps as a consequence, many of the studies cited in this review dealing with simultaneous adsorption of more than one type of metal contain the implicit assumption that highly specific adsorption of certain classes of metal may be advantageous. However, it would appear that the multi-component nature of typical biomass samples renders them more suitable, in principle, for a significantly different application, the removal of a wide range of pollutants simultaneously. Biosorbents have

the potential for use during polishing treatments of both freshwater and wastewater. One can expect that the public will become increasingly aware, of the importance of metal ion control in both tap water and in water discharged to the environment. By contrast, in cases where highly selective sorption of certain metal ions is required, perhaps as a preliminary step in the isolation of pure metals or compounds, it would make sense to employ relatively pure chelating agents. As one option, chelating functional groups can optionally be bound to cellulosic supports, depending on the needs of the process.

Another area that requires research attention is the use of cellulosic materials to remove not only heavy metals, but also organic toxins. It is reasonable to expect that various industrial outfalls and municipal wastewater streams may contain both heavy metals and organic contaminants. The subject of biosorption of organic materials such as dyes will be addressed in Part 2 of this series.

REFERENCES CITED

- Abdel-Aal, S. E., Gad, Y. H., and Dessouki, A. M. (2006). "The use of wood pulp and radiation modified starch in wastewater treatment," *Journal of Applied Polymer Science* 99(5), 2460-2469.
- Abdel-Ghani, N. T., Hefny, M., and El-Chagbaby, G. A. F. (2007). "Removal of lead from aqueous solution using low cost abundantly available adsorbents," *Int. J. Environ. Sci. Tech.* 4(1), 67-73.
- Abdel-Ghani, N. T., Hefny, M. M., and El-Chaghaby, G. A. (2008). "Removal of metal ions from synthetic wastewater by adsorption onto *Eucalyptus camaldulensis* tree leaves," *J. Chilean Chem. Soc.* 53(3), 1585-1587.
- Abia, A. A., Horsfall, M., and Didi, O. (2003). "The use of chemically modified and unmodified cassava waste for the removal of Cd, Cu and Zn ions from aqueous solution," *Bioresour. Technol.* 90, 345-348.
- Abia, A. A., and Igwe, J. C. (2005). "Sorption kinetics and intraparticulate diffusivities of Cd, Pb and Zn ions on maize cob," *Afr. J. Biotech.* 4(6), 509-512.
- Acar, F. N., and Malkoc, E. (2004). "Removal of chromium (VI) from aqueous solution by *Fagus orientalis*," *Bioresour. Technol.* 94, 13-15.
- Acemioğlu, B., Samil, A., Alma, M. H., and Gundogan, R. (2003). "Copper(II) removal from aqueous solution by organosolv lignin and its recovery," *J. Appl. Polym. Sci.* 89(6), 1537-1541.
- Acharya, J., Sahu, J. N., Mohanty, C. R., and Meikap, B. C. (2009). "Removal of lead(II) from wastewater by activated carbon developed from Tamarind wood by zinc chloride activation," *Chem. Eng. J.* 149(1-3), 249-262.
- Addour, L., Belhocine, D., Boudries, N., Comeau, Y., Pauss, A., and Mameri, N. (1999). "Zinc uptake by *Streptomyces rimosus* biomass using a packed-bed column," *J. Chem. Technol. Biotechnol.* 74(11), 1089-1095.
- Aderhold, D., Williams, C. J., and Edyvean, R. G. J. (1996). "The removal of heavy-metal ions by seaweeds and their derivatives," *Bioresource Technology* 58(1), 1-6.
- Afkhami, A., Madrakian, T., Karimi, Z., and Amini, A. (2007). "Effect of treatment of carbon cloth with sodium hydroxide solution on its adsorption capacity for the

- adsorption of some cations,” *Colloids Surf. A – Physicochem. Eng. Aspects* 304(1-3), 36-40.
- Agarwal, G. S., Bhuptawat, H. K., and Chaudhari, S. (2006). “Biosorption of aqueous chromium (VI) by *Tamarindus indica* seeds,” *Bioresour. Technol.* 97, 949-956.
- Aggarwal, D., Goyal, M., and Bansal, R. C. (1999). “Adsorption of chromium by activated carbon from aqueous solution,” *Carbon* 37, 1989-1997.
- Agrawal, A., Kumar, V., and Pandey, B. D. (2006). “Remediation options for the treatment of electroplating and leather tanning effluent containing chromium - A review,” *Mineral Processing Extrac. Metall. Rev.* 27(2), 99-130.
- Agrawal, A., Sahu, K. K., and Pandey, B. D. (2004). “Removal of zinc from aqueous solutions using sea nodule residue,” *Colloids Surf. A* 237, 133-140.
- Ahalya N., Kanamadi R. D., and Ramachandra, T. V. (2005). “Biosorption of chromium (VI) from aqueous solutions by the husk of Bengal gram (*Cicer arietinum*),” *Electron. J. Biotechnol.* 8, 258-264.
- Ahalya, N., Kanamadi, R. D., and Ramachandra, T. V. (2006). “Biosorption of iron(III) from aqueous solutions using the husk of *Cicer arietinum*,” *Indian J. Chem. Technol.* 13(2), 122-127.
- Ahalya, N., Kanamadi, R. D., and Ramachandra, T. V. (2007). “Cr(VI) and Fe(III) removal using *Cajanus cajan* husk,” *J. Environ. Biol.* 28(4), 765-769.
- Ahluwalia, S. S., and Goyal, D. (2005a). “Removal of heavy metals from waste tea leaves from aqueous solution,” *Eng. Life Sci.* 5, 158-162.
- Ahluwalia, S. S., and Goyal, D. (2005b). “Microbial and plant derived biomass for removal of heavy metals from waste water,” *Bioresour. Technol.* 98, 2243-2257.
- Ahmady-Asbchin, S., Andres, Y., Gerente, C., and Le Cloirec, P. (2008). “Biosorption of Cu(II) from aqueous solution by *Fucus serratus*: Surface characterization and sorption mechanisms,” *Bioresour. Technol.* 99(14), 6150-6155.
- Ajmal, M., Khan, A. H., Ahmad, S., and Ahmad, A. (1998). “Role of sawdust in the removal of copper(II) from industrial wastes,” *Water Res.* 32(10), 3085-3091.
- Ajmal, M., Rao, R. A. K., Ahmad, R., and Ahmad, J. (2000). “Adsorption studies on *Citrus reticulata* (fruit peel of orange): Removal and recovery of Ni(II) from electroplating wastewater,” *Journal of Hazardous Materials* 79(1-2), 117-131.
- Ajmal, M., Rao, R. A. K., Ahmad, R., and Khan, M. A. (2006). “Adsorption studies on parthenium hysterophorus weed: Removal and recovery of Cd (II) from wastewater,” *J. Hazard. Mater.* B135, 242-248.
- Ajmal, M., Rao, R. A. K., Anwar, S., Ahmad, J., and Ahmad, R. (2003). “Adsorption studies on rice husk: Removal and recovery of Cd(II) from wastewater,” *Bioresour. Technol.* 86(2), 147-149.
- Ajmal, M., Rao, R. A. K., and Khan, M. A. (2005). “Adsorption of Cu from aqueous solution on *Brassica cumpestris* (mustard oil cake),” *J. Hazard. Mater.* B122, 177-183.
- Akar, T., and Tunali, S. (2006). “Biosorption characteristics of *Aspergillus flavus* biomass for removal of Pb(II) and Cu(II) ions from aqueous solutions,” *Bioresour. Technol.* 97, 1780-1787.
- Akar, T., Tunali, S., and Cabuk, A. (2007b). “Study on the characterization of lead (II) biosorption by fungus *Aspergillus parasiticus*,” *Appl. Biochem. Biotech.* 136(3), 389-

405.

- Akhtar, N., Iqbal, J., and Iqbal, M. (2004). "Removal and recovery of nickel (II) from aqueous solution by loofa sponge-immobilized biomass of *Chlorella sorokiniana*: Characterization studies," *J. Hazard. Mater.* B108, 85-94.
- Aksakal, O., Uzun, H., and Kaya, Y. (2008). "Removal of nickel from aqueous solutions by Nordmann fir (*Abies nordmanniana* (Stev.) Spach subsp. *nordmanniana*) cones," *Environ. Eng. Manag. J.* 7(4), 359-363.
- Aksu, Z. (2001). "Equilibrium and kinetic modeling of cadmium(II) biosorption by *C. vulgaris* in a batch system: Effect of temperature," *Separation and Purification Technology* 21, 285-294.
- Aksu, Z., and Açikel, U. (1999). "A single-staged bioseparation process for simultaneous removal of copper(II) and chromium(VI) by using *C. vulgaris*," *Process Biochem.* 34(6-7), 589-599.
- Aksu, Z., and Açikel, U. (2000). "Modeling of a single-staged bioseparation process for simultaneous removal of iron(III) and chromium(VI) by using *Chlorella vulgaris*," *Biochem. Eng. J.* 4(3), 229-238.
- Aksu, Z., Açikel, U., Kabasakal, E., and Tezer, S. (2002b). "Equilibrium modeling of individual and simultaneous biosorption of chromium(VI) and nickel(II) onto dried activated sludge," *Water Res.* 36(12), 3063-3073.
- Aksu, Z., Acikel, U., and Kutsal, T. (1997). "Application of multicomponent adsorption isotherms to simultaneous biosorption of iron(III) and chromium(VI) on *C. vulgaris*," *J. Chem. Technol. Biotechnol.* 70(4), 368-378.
- Aksu, Z., Acikel, U., and Kutsal, T. (1999). "Investigation of simultaneous biosorption of copper (II) and chromium (VI) on dried *Chlorella vulgaris* from binary metal mixtures: Application of multicomponent adsorption isotherms," *Sep. Sci. Technol.* 34(3), 501-524.
- Aksu, Z., and Akpınar, D. (2001). "Competitive biosorption of phenol and chromium(VI) from binary mixtures onto dried anaerobic activated sludge," *Biochem. Eng. J.* 7(3), 183-193.
- Aksu, Z., and Balibek, E. (2007). "Chromium(VI) biosorption by dried *Rhizopus arrhizus*: Effect of salt (NaCl) concentration on equilibrium and kinetic parameters," *J. Hazardous Mater.* 145(1-2), 210-220.
- Aksu, Z., and Donmez, G. (2006). "Binary biosorption of cadmium(II) and nickel(II) onto dried *Chlorella vulgaris*: Co-ion effect on mono-component isotherm parameters," *Process Biochem.* 41(4), 860-868.
- Aksu, Z., Gönen, F., and Demircan, Z. (2002a). "Biosorption of chromium(VI) ions by Mowital (R) B30H resin immobilized activated sludge in a packed bed: Comparison with granular activated carbon," *Process Biochem.* 38(2), 175-186.
- Aksu, Z., and Isoglu, I. A. (2005). "Removal of copper(II) ions from aqueous solution by biosorption onto agricultural waste sugar beet pulp," *Process Biochem.* 40(9), 3031-3044.
- Aksu, Z., Sag, Y., and Kutsal, T. (1992). "The biosorption of Copper(II) by *C. vulgaris* and *Z. ramigera*," *Environ. Technol.* 13, 579-586.
- Akhtar, N., Sastry, S., and Mohan, M. (1995). "Biosorption of silver ions by processed *Aspergillus niger* biomass," *Biotechnol. Lett.* 17, 551-556.

- Akthar, M., Sastry, K., and Mohan, P. (1996). "Mechanism of metal ion biosorption by fungal biomass," *Biometals* 9, 21-28.
- Alaerts, G. J., Jitjaturunt, V., and Kelderman, P. (1989). "Use of coconut shell-based activated carbon for chromium(VI) removal," *Water Sci. Technol.* 21, 1701-1704.
- Al-Asheh, S., and Duvnjak, Z. (1998). "Binary metal sorption by pine bark: Study of equilibria and mechanisms," *Sep. Sci. Technol.* 33, 1303-1329.
- Aldor, I., Fourest, E., and Volesky, B. (1995). "Desorption of cadmium from algal biosorbent," *Can. J. Chem. Eng.* 73(4), 516-522.
- Ali, I., and About-Enein, H. Y. (2006). *Instrumental Methods in Metal Ion Speciation*, CRC, Taylor & Francis Group, New York, Chromatographic Science Ser. Vol. 96,
- Ali, I., and Gupta, V. K. (2006). "Advances in water treatment by adsorption technology," *Nature Protocols* 1(6), 2661-2667.
- Aloysius, R., Karim, M. I. A., and Ariff, A.B. (1999). "Cadmium biosorption by free and immobilized live biomass of *Rhizopus oligosporus*," *Pakistan Journal of Biological Sciences* 2, 74-79.
- Alpana, S. (2008). "Chromium adsorption on agro based waste materials: A review," *Res. J. Biotech.* 207-209.
- Altun, T., and Pehlivan, E. (2007). "Removal of copper(II) ions from aqueous solutions by walnut-, hazelnut- and almond-shells," *Clean – Soil Air Water* 35(6), 601-606.
- Altundogan, H. S. (2005). "Cr(VI) removal from aqueous solution by iron(III) hydroxide-loaded sugar beat pulp," *Process Biochem.* 40, 1443-1452.
- Altundogan, H. S., Arslan, N. E., and Tumen, F. (2007). "Copper removal from aqueous solutions by sugar beet pulp treated by NaOH and citric acid," *J. Hazard. Mater.* 149(2), 432-439.
- Alves Gurgel, L. V., and Gil, L. F. (2009). "Adsorption of Cu(II), Cd(II) and Pb(II) from aqueous single metal solutions by succinylated twice-mercerized sugarcane bagasse functionalized with triethylenetetramine," *Water Res.* 43(18), 4479-4488.
- Amin, M. N., Kaneco, S., Kitagawa, T., Begum, A., Katsumata, H., Suzuki, T., and Ohta, K. (2006). "Removal of arsenic in aqueous solutions by adsorption onto waste rice husk," *Indus. Eng. Chem. Res.* 45(24), 8105-8110.
- Amuda, O. S., Giwa, A. A., and Bello, I. A. (2007). "Removal of heavy metal from industrial wastewater using modified activated coconut shell carbon," *Biochem. Eng. J.* 36(2), 174-181.
- Anandkumar, J., and Mandal, B. (2009). "Removal of Cr(VI) from aqueous solution using Bael fruit (*Aegle marmelos* correa) shell as an adsorbent," *J. Hazard. Mater.* 168(2-3), 633-640.
- Anayurt, R. A., Sari, A., and Tuzen, M. (2009). "Equilibrium, thermodynamic and kinetic studies on biosorption of Pb(II) and Cd(II) from aqueous solution by macrofungus (*Lactarius scrobiculatus*) biomass," *Chem. Eng. J.* 151(1-3), 255-261.
- Andrès, Y., Texier, A.C., and Le Cloirec, P. (2003). "Rare earth elements removal by microbial biosorption: A review," *Environ. Technol.* 24, 1367-1375.
- Anirudhan, T. S., Rijith, S., and Suchithra, P. S. (2010). "Preparation and characterization of iron(iii) complex of an amino-functionalized polyacrylamide-grafted lignocellulose and its application as adsorbent for chromium(VI) removal from aqueous media," *J. Appl. Polymer Sci.* 115(4), 2069-2083.

- Annadurai, G., Juang, R. S., and Lee, D. L. (2003). "Adsorption of heavy metals from water using banana and orange peels," *Water Sci. Technol.* 47(1), 185-190.
- Anoop Krishnan, K., and Anirudhan, T. S. (2003). "Removal of cadmium (II) from aqueous solutions by steam-activated sulphurized carbon prepared from sugar-cane bagasse pith: Kinetics and equilibrium studies," *Water SA* 29, 147-156.
- Aoki, N., Fukushima, K., Kurakata, H., Sakamoto, M., and Furuhashi, K. (1999a). "6-deoxy-6-mercaptocellulose and its S-substituted derivatives as sorbents for metal ions," *Reactive and Functional Polymers* 42(3), 223-233.
- Aoki, Y., Tanaka, K., Sakamoto, M., and Furuhashi, K. (1999b). "Sorption of metal ions by bead cellulose grafted with amidoximated polyacrylonitrile," *Sen'i Gakkaishi* 55(12), 569-575.
- Aoyama, M. (2003). "Removal of Cr(VI) from aqueous solution by London plane leaves," *J. Chem. Technol. Biotechnol.* 78, 601-604.
- Aoyama, M., Honma, S., Kasai, A., Iseda, Y., Nakajima, A., and Sakaguchi, T. (1991). "Uranium uptake by conifer leaves," *Holzforschung* 45(1), 75-77.
- Aoyama, M., Kishino, M., and Jo, T.-S. (2004). "Biosorption of Cr(VI) on Japanese cedar bark," *Sep. Sci. Technol.* 35(5), 1149-1162.
- Aoyama, M., Sugiyama, T., Doi, S., Cho, N.-S., and Kim, H.-E. (1999). "Removal of hexavalent chromium from dilute aqueous solution by coniferous leaves," *Holzforschung* 53, 365-368.
- Aoyama, M., and Tsuda, M. (2001). "Removal of Cr(VI) from aqueous solutions by larch bark," *Wood Sci. Technol.* 35(5), 425-432.
- Apiratikul, R., and Pavasant, P. (2006). "Sorption isotherm model for binary component sorption of copper, cadmium, and lead ions using dried green macroalga, *Caulerpa lentillifera*," *Chem. Eng. J.* 119(2-3), 135-145.
- Araujo, G. C. L., Lemos, S. G., Ferreira, A. G., Freitas, H., and Nogueira, A. R. A. (2007). "Effect of pre-treatment and supporting media on Ni(II), Cu(II), Al(III) and Fe(III) sorption by plant root material," *Chemosphere* 68(3), 537-545.
- Aravindhan, R., Madhan, B., Rao J. R., and Nair, B. U. (2004a). "Recovery and reuse of chromium from tannery wastewaters using *Turbinaria ornata* seaweed," *J. Chem. Technol. Biotechnol.* 79(11), 1251-1258.
- Aravindhan, R., Madhan, B., Rao J. R., Nair, B. U., and Ramasami, T. (2004b). "Bioaccumulation of chromium from tannery wastewater: An approach for chrome recovery and reuse," *Environ. Sci. Technol.* 38(1), 300-306.
- Argun, M. E., and Dursun, S. (2008a). "A new approach to modification of natural adsorbent for heavy metal adsorption," *Bioresour. Technol.* 99, 2516-2527.
- Argun, M. E., and Dursun, S. (2008b). "Cadmium removal using activated pine bark," *J. Int. Environ. Appl. Sci.* 3, 37-42.
- Argun, M. E., Dursun, S., Gur, K., Ozdemir, C., Karatas, M., and Dogan, S. (2005a). "Adsorption of copper on modified wood (pine) materials," *Cellulose Chem. Technol.* 39(5-6), 581-591.
- Argun, M. E., Dursun, S., Gur, K., Ozdemir, C., Karatas, M., and Dogan, S. (2005b). "Nickel adsorption on the modified pine tree materials," *Environ. Technol.* 26(5), 479-487.

- Argun, M. E., Dursun, S., and Karatas, M. (2009). "Removal of Cd(II), Pb(II), Cu(II) and Ni(II) from water using modified pine bark," *Desalination* 249(2), 519-527.
- Argun, M. E., Dursun, S., Karatas, M., and Guru, M. (2008). "Activation of pine cone using Fenton oxidation for Cd(II) and Pb(II) removal," *Bioresour. Technol.* 99(18), 8691-8698.
- Argun, M. E., Dursun, Ş., Özdemir, C., and Karatas, M. (2007). "Heavy metal adsorption by oak sawdust: Thermodynamics and kinetics," *J. Hazard. Mater.* 141(1), 77-85.
- Arief, V. O., Trilestari, K., Sunarso, J., Indraswati, N., and Ismadji, S. (2008). "Recent progress on biosorption of heavy metals from liquids using low cost biosorbents: Characterization, biosorption parameters and mechanism studies," *Clean – Soil Air Water* 36(12), 937-962.
- Arica, M. Y., and Bayramoğlu, G. (2005). "Cr(VI) biosorption from aqueous solutions using free and immobilized biomass of *Lentinus sajor-caju*: Preparation and kinetic considerations," *Colloids Surf. A* 253(1-3), 203-221.
- Arica, M. Y., Tuzun, I., Yalcin, E., Ince, O., and Bayramoglu, G. (2005). "Utilization of native, heat and acid-treated microalgae *Chlamydomonas reinhardtii* preparations for biosorption of Cr(VI) ions," *Process Biochem.* 40(7), 2351-2358.
- Ariff, A. B., Mel, M., Hasan, M. A., and Karim, M. I. A. (1999). "The kinetics and mechanisms of lead(II) biosorption by powderized *Rhizopus oligosporus*," *World Journal of Microbiology Biotechnology* 15, 291-298.
- Arshad, M., Zafar, M. N., Younis, S., and Nadeem, R. (2008). "The use of neem biomass for the biosorption of zinc from aqueous solutions," *J. Hazard. Mater.* 157, 534-540.
- Arslan, G., and Pehlivan, E. (2008). "Uptake of Cr³⁺ from aqueous solution by lignite-based humic acids," *Bioresour. Technol.* 99(16), 7597-7605.
- Arulanantham, A., Balasubramanian, N., and Ramakrishna, T. V. (1989). "Coconut shell carbon for treatment of cadmium and lead containing wastewater," *Metal Finishing* 87, 51-55.
- Ash, B., Satapathy, D., Mukherjee, P. S., Nanda, B., Gumaste, J. L., and Mishra, B. K. (2006). "Characterization and application of activated carbon prepared from waste coir pith," *J. Sci. Indus. Res.* 65(12), 1008-1012.
- Ashkenazy, R., Gottlieb, L., and Yannai, S. (1997). Characterization of acetone-washed yeast biomass functional groups involved in lead biosorption, *Biotechnol. Bioeng.* 55, 1-10.
- Atkinson, B. W., Bux, F., and Kasan, H. C. (1998). "Considerations for application of biosorption technology to remediate metal-contaminated industrial effluents," *Water SA* 24, 129-135.
- Avery, S. V., and Tobin, J. M. (1993). "Mechanism of adsorption of hard and soft metal ions to *Saccharomyces cerevisiae* and influence of hard and soft anions," *Applied and Environmental Microbiology* 59, 2851-2856.
- Azab, M. S., and Peterson, P. J. (1989). "The removal of Cd from wastewater by the use of biological sorbents," *Water Sci. Technol.* 21(12), 1705-1706.
- Aziz, A., Ouali, M. S., Elandalousi, E. H., De Ménorval, L. C., and Lindheimer, M. (2009). "Chemically modified olive stone: A low-cost sorbent for heavy metals and basic dyes removal from aqueous solutions," *J. Hazard. Mater.* 163, 441-447.
- Babel, S., and Kurniawan, T. A. (2003). "Low-cost adsorbents for heavy metals uptake

- from contaminated water: A review,” *J. Hazardous Mater.* 97(1-3), 219-243.
- Babel, S., and Kurniawan, T. A. (2004). “Cr(VI) removal from synthetic wastewater using coconut shell charcoal and commercial activated carbon modified with oxidizing agent and/or chitosan,” *Chemosphere* 54(7), 951-967.
- Babula, P., Adam, V., Opatrilova, R., Zehnalek, J., Havel, L., and Kizek, R. (2008). “Uncommon heavy metals, metalloids and their plant toxicity: A review,” *Environ. Chem. Lett.* 6(4), 189-213.
- Baccar, R., Bouzid, J., Feki, M., and Montiel, A. (2009). “Preparation of activated carbon from Tunisian olive-waste cakes and its application for adsorption of heavy metal ions,” *J. Hazard. Mater.* 162(2-3), 1522-1529.
- Bai, R. S., and Abraham, T. E. (1998). “Studies on biosorption of chromium(VI) by dead fungal biomass,” *J. Sci. Ind. Res.* 57(10-11), 821-824.
- Bai, R. S., and Abraham, T. E. (2001). “Biosorption of Cr(VI) from aqueous solution by *Rhizopus nigricans*,” *Bioresour. Technol.* 79, 73-81.
- Bai, R. S., and Abraham, T. E. (2002). “Studies on enhancement of Cr(VI) biosorption by chemically modified biomass of *Rhizopus nigricans*,” *Water Res.* 36(5), 1224-1236.
- Bai, R. S., and Abraham, T. E. (2003). “Studies on chromium(VI) adsorption-desorption using immobilized fungal biomass,” *Bioresour. Technol.* 87(1) 17-26.
- Baillet, F., Magnin, J.-P., Cheruy, A., and Ozil, P. (1998). “Chromium precipitation by the acidophilic bacterium *Thiobacillus ferrooxidans*,” *Biotechnology Letters* 20(1), 95-99.
- Bailey, S. E., Olin, T. J., Bricka, R. M., and Adrian, D. D. (1999). “A review of potentially low-cost sorbents for heavy metals,” *Wat. Res.* 33(11), 2469-2479.
- Bakhti, M. Z., Selatnia, A., and Junter, G. A. (2008). “Biosorption of Ag^+ from aqueous solution by *Streptomyces rimosus* biomass,” *Intl. J. Environ. Pollution* 34(1-4), 297-307.
- Bakir, A., McLoughlin, P., Tofail, S. A. M., and Fitzgerald, E. (2009). “Competitive sorption of antimony with zinc, nickel, and aluminum in a seaweed based fixed-bed sorption column,” *Clean – Soil Air Water* 37(9), 712-719.
- Bakkaloglu, I., Butter, T. J., Evison, L. M., Holland, F. S., and Hancock, I. C. (1998). “Screening of various types biomass for removal and recovery of heavy metals (Zn, Cu, Ni) by biosorption, sedimentation and desorption,” *Water Sci. Technol.* 38(6), 269-277.
- Balan, C., Bilba, D., and Macoveanu, M. (2009). “Studies on chromium(III) removal from aqueous solutions by sorption on Sphagnum moss peat,” *J. Serbian Chem. Soc.* 74(8-9), 953-964.
- Balasubramanian, R., Perumal, S. V., and Vijayaraghavan, K. (2009). “Equilibrium isotherm studies for the multicomponent adsorption of lead, zinc, and cadmium onto Indonesian peat,” *Ind. Eng. Chem. Res.* 48(4), 2093-2099.
- Banarjee, S. S., Joshi, M. V., and Jayaram, R. V. (2004). “Removal of Cr(VI) and Hg(II) from aqueous solutions using fly ash and impregnated fly ash,” *Sep. Sci. Technol.* 39(7), 1611-1629.
- Bansal, M., Garg, U., Singh, D., and Garg, V. K. (2009). “Removal of Cr(VI) from aqueous solutions using pre-consumer processing agricultural waste: A case study of rice husk,” *J. Hazardous Mater.* 162(1), 312-320.

- Bansode, R. R., Losso, J. N., Marshall, W. E., Rao, R. M., and Portier, R. J. (2003). "Adsorption of metal ions by pecan shell-based granular activated carbons," *Bioresour. Technol.* 89(2), 115-119.
- Baral, S. S., Das, S. N., and Rath, P. (2006). "Hexavalent chromium removal from aqueous solution by adsorption on treated sawdust," *Biochem. Eng. J.* 31(3), 216-222.
- Baral, S. S., Das, S. N., Rath, P., Chaudhury, G. R., and Swamy, Y. V. (2007). "Removal of Cr(VI) from aqueous solution using waste weed, *Salvinia cucullata*," *Chem. Ecol.* 23(2), 105-117.
- Barkat, M., Nibou, D., Chearouche, S., and Mellah, A. (2009). "Kinetics and thermodynamics studies of chromium(VI) ions adsorption onto activated carbon from aqueous solutions," *Chem. Eng. Proc.* 48(1), 38-47.
- Basci, N., Kocadagistan, E., and Kocadagistan, B. (2003). "Biosorption of Cu II from aqueous solutions by wheat shells," *Desalination* 164, 135-140.
- Basha, S., Murthy, Z. V. P., and Jha, B. (2008). "Biosorption of hexavalent chromium by chemically modified seaweed, *Cystoseira indica*," *Chem. Eng. J.* 137(3), 480-488.
- Basha, S., Murthy, Z. V. P., and Jha, B. (2009). "Removal of Cu(II) and Ni(II) from industrial effluents by brown seaweed, *Cystoseira indica*," *Ind. Eng. Chem. Res.* 48(2), 961-975.
- Basso, M. C., Cerrella, E. G., and Cukierman, A. L. (2002a). "Lignocellulosic materials as potential biosorbents of trace toxic metals from wastewater," *Indus. Eng. Chem. Res.* 41(15), 3580-3585.
- Basso, M. C., Cerrella, E. G., and Cukeirman, A. L. (2002b). "Activated carbons developed from a rapidly renewable biosources for removal of cadmium (II) and nickel(II) ions from dilute aqueous solutions," *Ind. Eng. Chem. Res.* 41(2), 180-189.
- Basso, M. C., Cerrella, E. G., and Cukierman, A. L. (2004). "Cadmium uptake by lignocellulosic materials: Effect of lignin content," *Sep. Sci. Technol.* 39(5), 1163-1175.
- Basumajumdar, A., Pal, T. K., and Bhattacharyya, S. (2003). "Biosorption of cadmium by *Aspergillus niger* from multimetal solution," *J. Indian Chem. Soc.* 80, 899-902.
- Bayramoglu, G., Bektas, S., and Arica, M. Y. (2003). "Biosorption of heavy metal ions on immobilized white-rot fungus *Trametes versicolor*," *Journal of Hazardous Materials* 101(3), 285-300.
- Bayramoglu, G., Celik, G., Yalcin, E., Yilmaz, M., and Arica, M. Y. (2005). "Modification of surface properties of *Lentinus sajor-caju* mycelia by physical and chemical methods: Evaluation of their Cr⁺⁶ removal efficiencies from aqueous medium," *J. Hazard. Mater.* 119, 219-229.
- Belhafaoui, B., Aziz, A., Elandaloussi, E., Ouali, M. S., and De Menorval, L. C. (2009). "Succinate-bonded cellulose: A regenerable and powerful sorbent for cadmium-removal from spiked high-hardness groundwater," *J. Hazardous Mater.* 169(1-3), 831-837.
- Bello, G., Cid, R., Garcia, R., and Arriagada, R. (1999). "Retention of Cr(VI) and Hg(II) in *Eucalyptus globulus*- and peach stone-activated carbons," *J. Chem. Technol. Biotech.* 74(9), 904-910.
- Benaissa, H. (2006). "Screening of new sorbent materials for cadmium removal from aqueous solutions," *J. Hazard. Mater.* 132(2-3), 189-195.

- Bendezu, S., Oyague, J., Romero, A., Garcia, R., Munoz, Y., and Escalona, N. (2005). "Chromium adsorption from tannery effluents by activated carbons prepared from coconut shells by chemical activation with KOH and ZnCl₂," *J. Chilean Chem. Soc.* 50(4), 677-684.
- Berenquer, R., Marco-Lozar, J. P., Quijada, C., Cazorla-Amoros, D., and Morallon, E. (2009). "Effect of electrochemical treatments on the surface chemistry of activated carbon," *Carbon* 47(4), 1018-1027.
- Beveridge, T. J., and Murray, R. G. E. (1980). "Sites of metal deposition in the cell wall of *Bacillus subtilis*," *J. Biotechnol.* 141, 876-887.
- Bhainsa, K. C., and D'Souza, S. F. (1999). "Biosorption of uranium(VI) by *Aspergillus fumigatus*," *Biotechnol. Techniques* 13(10), 695-699.
- Bicak, N., Sherrington, D. C., and Senkal, B. F. (1999). "Graft copolymer of acrylamide onto cellulose as mercury selective sorbent," *Reactive and Functional Polymers* 41(1-3), 69-76.
- Bingol, A., Uzun, H., Bayhan, Y. K., Karagunduz, A., Cakici, A., and Keskinler, B. (2004). "Removal of chromate anions from aqueous stream by a cationic surfactant-modified yeast," *Bioresour. Technol.* 94, 245-249.
- Bischoff, R., and Schwedt, G. (1982). "Differentiation of the chemical forms of trace amounts of copper in peas and soy meal by means of ion exchange on cellulose materials and molecular exclusion chromatography," *Anal. Chem. Acta* 142, 109-118.
- Bishnoi, N. R., Bajaj, M., Sharma, N., and Gupta, A. (2004). "Adsorption of chromium (VI) on activated rice husk carbon and activated alumina," *Bioresour. Technol.* 91(3), 305-307.
- Bishnoi, N. R., and Garima. (2005). "Fungus - An alternative for bioremediation of heavy metal containing wastewater: A review," *J. Sci. Indus. Res.* 64(2), 93-100.
- Bishnoi, N. R., Kumar, R., Kumar, S., and Rani, S. (2007). "Biosorption of Cr(III) from aqueous solution using algal biomass *Spirogyra* spp.," *J. Hazardous Mater.* 145(1-2), 142-147.
- Blanco, A., Sanz, B., Llama, M. J., and Serra, J. L. (1999). "Biosorption of heavy metals to immobilized *Phormidium laminosum* biomass," *J. Biotechnol.* 69, 227-240.
- Blazquez, G., Hernainz, F., Calero, M., Martin-Lara, M. A., and Tenorio, G. (2009). "The effect of pH on the biosorption of Cr(III) and Cr(VI) with olive stone," *Chem. Eng. J.* 148, 473-478.
- Blazquez, G., Hernainz, F., Calero, M., and Ruiz-Nunez, L. F. (2005). "Removal of cadmium ions with olive stones: The effect of some parameters," *Proc. Biochem.* 40(8), 2649-2654.
- Bozic, D., Stankovic, V., Gorgievski, M., Bogdanovic, G., and Kovacevic, R. (2009). "Adsorption of heavy metal ions by sawdust of deciduous trees," *J. Hazardous Mater.* 171(1-3), 684-692.
- Brady, D., Stoll, A., and Duncan, J. R. (1994). "Biosorption of heavy metal cations by non-viable yeast biomass," *Environ. Technol.* 15, 429-438.
- Brady, J. M., and Tobin, J. M. (1995). "Binding of hard and soft metal ions to *Rhizopus arrhizus* biomass," *Enzyme Microb. Technol.* 17(9), 791-796.

- Brown, P., Jefcoat, I. A., Parrish, D., Gill, S., and Graham, E. (2000). "Evaluation of the adsorption capacity of peanut hull pellets for heavy metals in solution," *Adv. Environ. Res.* 4, 19-29.
- Budinova, T., Ekinci, E., Yardim, F., Grimm, A., Bjornbom, E., Minkova, V., and Goranova, M. (2006). "Characterization and application of activated carbon produced by H_3PO_4 and water vapor activation," *Fuel Proc. Technol.* 87(10), 899-905.
- Bueno, B. M., Molina, F. F., Torem, M. L., de Mesquita, L. M. S., and Pino, G. A. H. (2009). "Removal of Pb(II) from aqueous solutions by biosorption with *R.opacus*," *REM – Revista Esoca de Minas* 62(4), 487-494.
- Bueno, C. I. D., and Carvalho, W. A. (2007). "Lead(II) removal in discontinuous systems by carbon activated by phosphoric acid and vapor," *Quimica Nova* 30(8), 1911-1918.
- Bulut, Y., and Tez, Z. (2007a). "Adsorption studies on ground shells of hazelnut and almond," *J. Hazardous Mater.* 149(1), 35-41.
- Bulut, Y., and Tez, Z. (2007b). "Removal of heavy metals from aqueous solution by sawdust adsorption," *J. Environ. Sci.* 19(2), 160-166.
- Bustard, M., and McHale, A. P. (1998). "Biosorption of heavy metals by distillery-derived biomass," *Bioprocess Engineering* 19, 351-353.
- Cabtingan, L. K., Agapay, R. C., Rakels, J. L. L., Ottens, M., and Van Der Wielen, L. A. M. (2001). "Potential of biosorption for the recovery of chromate in industrial wastewaters," *Ind. Eng. Chem. Res.* 40(10), 2302-2309.
- Cabuk, A., Akar, T., Tunalı, S., and Gedikli, S. (2007). "Biosorption of Pb(II) by industrial strain of *Saccharomyces cerevisiae* immobilized on the biomatrix of cone biomass of *Pinus nigra*: Equilibrium and mechanism analysis," *Chem. Eng. J.* 131(1-3), 293-300.
- Calero, M., Hernainz, F., Blazquez, G., Martin-Lara, M. A., and Tenorio, G. (2009). "Biosorption kinetics of Cd(II), Cr(III) and Pb(II) in aqueous solutions by olive stone," *Bras. J. Chem. Eng.* 26(2), 265-273.
- Calero de Hoces, M., Bermudez de Castro, F. H., Blazquez Garcia, G., and Tenorio Rivas, G. (2006). "Equilibrium modeling of removal of cadmium ions by olive stones," *Environ. Prog.* 25(3), 261-266.
- Candela, M. P., Martinez, J. M., and Macia, R. T. (1995). "Chromium(VI) removal with activated carbons," *Water Res.* 29(9), 2174-2180.
- Capasso, R., Pigna, M., de Martino, A., Pucci, M., Sannino, F., and Violante, A. (2004). "Potential remediation of waters contaminated with Cr(III), Cu, and Zn by sorption on the organic polymeric fraction of olive mill wastewater (polymerin) and its derivatives," *Environ. Sci. Technol.* 38(19), 5170-5176.
- de Castro, Dantas, T. N., Dantas Neto, A. A., de A. Moura, M. C. P., Barrow Neto, E. L., and de Paiva Telemaco, E. (2010). "Chromium adsorption by chitosan impregnated with microemulsion," *Langmuir* 17(14), 4256-4260.
- Cay, S., Uyanık, A., and Zasiç, A. O. (2004). "Single and binary component adsorption of copper(II) and cadmium(II) from aqueous solutions using tea-industry waste," *Sep. Purif. Technol.* 38, 273-280.
- Celik, A., and Demirbas, A. (2005). "Removal of heavy metal ions from aqueous solutions via adsorption onto modified lignin from pulping wastes," *Energy Sources* 27(12), 1167-1177.

- Chai, X.-S., Hou, Q. X., Zhu, J. Y., Chen, S.-L., Wang, S. F., and Lucia, L. (2003). "Carboxyl groups in wood fibers. 1. Determination of carboxyl groups by headspace gas chromatography," *Ind. Eng. Chem. Res.* 42, 5440-5444.
- Chakravarty, S., Pimple, S., Hema, S., Chaturvedi, T., Singh, S., and Gupta, K. K. (2008). "Removal of copper from aqueous solution using newspaper pulp as an adsorbent," *Journal of Hazardous Materials* 159, 396-403.
- Chamarthy, S., Seo, C. W., and Marshall, W. E. (2001). "Adsorption of selected toxic metals by modified peanut shells," *J. Chem. Technol. Biotechnol.* 76(6), 593-597.
- Chand, R., Narimura, K., Kawakita, H., and Ohto, K. (2009). "Grape waste as a biosorbent for removing Cr(VI) from aqueous solution," *J. Hazard. Mater.* 163(1), 245-250.
- Chadlia, A., Mohamed, K., Najah, L., and Farouk, M. M. (2009). "Preparation and characterization of new succinic anhydride grafted Posidonia for the removal of organic and inorganic pollutants," *J. Hazardous Mater.* 172(2-3), 1579-1590.
- Chandran, C. B., Subramanian, T. V., and Felse, P. A. (2002). "Parametric optimization of biotransportation of Cd by mixed function oxidase produced under controlled conditions in *Saccharomyces cerevisiae*," *Indian Chem. Engr.* 44(1), 223-229.
- Chang, L. W. (1996). *Toxicology of Metals*, Lewis Publ., Boca Raton, 1198 pp.
- Chang, J. S., and Hong, J. (1994). "Biosorption of mercury by the inactivated cells of *Pseudomonas aeruginosa* PU21 (Rip 64)," *Biotechnol. Bioengng.* 44(8), 999-1006.
- Chang, J. S., Law, R., and Chang, C. C. (1997). "Biosorption of lead, copper and cadmium by biomass of *Pseudomonas aeruginosa* PU21," *Water Research* 31(7), 1651-1658.
- Chauhan, G. S., Guleria, L., and Sharma R., (2005a). "Synthesis, characterization and metal ion sorption studies of graft copolymers of cellulose with glycidyl methacrylate and some comonomers," *Cellulose* 12(1), 97-110.
- Chauhan, G. S., Singh, B., Chauhan, S., Verma, M., and Mahajan, S. (2005b). "Sorption of some metal ions on cellulosic-based hydrogels," *Desalination* 181(1-3), 217-224.
- Chauhan, G. S., Singh, B., Sharma, R. K., Verma, M., Jaswal, S. C., and Sharma, R. (2006). "Use of biopolymers and acrylamide-based hydrogels for sorption of Cu^{2+} , Fe^{2+} and Cr^{6+} ions from their aqueous solutions," *Desalination* 197(1-3), 75-81.
- Chaves, T. F., de Queiroz, Z. F., de Sousa, D. N. R., Girao, J. H. S., and Rodrigues, E. D. (2009). "Use of rice husk ash (RHA) obtained from thermal energy generation as Zn(II) adsorbent in aqueous solutions," *Quimica Nova* 32(6), 1378-1383.
- Chavez-Guerrero, L., Rangel-Mendez, R., Munoz-Sandoval, E., Cullen, D. A., Smith, D. J., Terrones, H., and Terrones, M. (2008). "Production and detailed characterization of bean husk-based carbon: Efficient cadmium (II) removal from aqueous solutions," *Water Res.* 42(13), 3473-3479.
- Chen, C., and Wang, J. L. (2007a). "Characteristics of Zn^{2+} biosorption by *Saccharomyces cerevisiae*," *Biomed. Environ. Sci.* 20(6), 478-482.
- Chen, C., and Wang, J. L. (2007b). "Correlating metal ionic characteristics with biosorption capacity using QSAR model," *Chemosphere* 69(10), 1610-1616.
- Chen, C., and Wang, J. L. (2007c). "Influence of metal ionic characteristics on their biosorption capacity by *Saccharomyces cerevisiae*," *Appl. Microbiol. Biotechnol.* 74(4), 911-917.

- Chen, C., and Wang, J. L. (2008a). "Investigating the interaction mechanism between zinc and *Saccharomyces cerevisiae* using combined SEM-EDX and XAFS," *Appl. Microbiol. Biotechnol.* 79(2), 293-299.
- Chen, C., and Wang, J. L. (2008b). "Removal of Pb^{2+} , Ag^+ , Cs^+ , and Sr^{2+} from aqueous solution by brewery's waste biomass," *J. Hazard. Mater.* 151(1), 65-70.
- Chen, C., and Wang, J. L. (2010). "Removal of heavy metal ions by waste biomass of *Saccharomyces cerevisiae*," *J. Environ. Eng. – ASCE* 136(1), 95-102.
- Chen, J. P., and Wu, S. (2004a). "Acid/base-treated activated carbons: Characterization of functional groups and metal adsorptive properties," *Langmuir* 20(6), 2233-2242.
- Chen, J. P., and Wu, S. (2004b). "Simultaneous adsorption of copper ions and humic acid onto an activated carbon," *J. Colloid Interface Sci.* 280(2), 334-342.
- Chen, J. P., Wu, S. N., and Chong, K. H. (2003). "Surface modification of a granular activated carbon by citric acid for enhancement of copper adsorption," *Carbon* 41(10), 1979-1986.
- Chen, J. P., and Yang, L. (2005). "Chemical modification of *Sargassum* sp. for prevention of organic leaching and enhancement of uptake during metal biosorption," *Ind. Eng. Chem. Res.* 44(26), 9931-9942.
- Chen, J. P., and Yang, L. (2006). "Study of a heavy metal biosorption onto raw and chemically modified *Sargassum* sp. via spectroscopic and modeling analysis," *Langmuir* 22(21), 8906-8914.
- Chen, S., Zou, Y., Yan, Z., Shen, W., Shi, S., Zhang, X., and Wang, H. (2009). "Carboxymethylated-bacterial cellulose for copper and lead ion removal," *Journal of Hazardous Materials* 161(2-3), 1355-1359.
- Chen, S. X., Huang, Z. Z., Liang, J., Jin, Y., and Zeng, H. M. (2002). "Reduction adsorption of silver ions and their distribution on activated carbon fibers," *New Carbon Mater.* 17(3), 6-10.
- Chen, S. X., Xu, R. M., Huang, H. X., Yi, F. Y., Zhou, X., and Zeng, H. M. (2007). "Reduction-adsorption behavior of platinum ions on activated carbon fibers," *J. Mater. Sci.* 42(23), 9572-9581.
- Chen, S. X., and Zeng, H. M. (2003). "Improvement of the reduction capacity of activated carbon fiber," *Carbon* 41(6), 1265-1271.
- Chen, X. C., Wang, Y. P., Lin, Q., Shi, J. Y., Wu, W. X., and Chen, Y. X. (2005). "Biosorption of copper(II) and zinc(II) from aqueous solution by *Pseudomonas putida* CZ1," *Colloids Surf. B-Biointerfaces* 46(2), 101-107.
- Chen, Y. H., Wu, Q. L., Pan, N., Gong, J. H., and Pan, D. (2008). "Rayon-based activated carbon fibers treated with both alkali metal salt and Lewis acid," *Micropor. Mesopor. Mater.* 109(1-3), 138-146.
- Chergui, A., Bakhti, M. Z., Chahboub, A., Haddoum, S., Selatnia, A., and Junter, G. A. (2007). "Simultaneous biosorption of Cu^{2+} , Zn^{2+} and Cr^{6+} from aqueous solution by *Streptomyces rimosus* biomass," *Desalination* 206(1-3), 179-184.
- Cho, D. H., and Kim, E. Y. (2003). "Characterization of Pb^{2+} biosorption from aqueous solution by *Rhodotorula glutinis*," *Bioprocess Biosystem Engineering* 25, 271-277.
- Choi, S. B., and Yun, Y. S. (2004). "Lead biosorption by waste biomass of *Corynebacterium glutamicum* generated from lysine fermentation process," *Biotechnol. Lett.* 26(4), 331-336.

- Choi, Y. J., Ahn, Y. H., Kang, M. S., Jun, H. K., Kim, I. S., and Moon, S. H. (2004). "Preparation and characterization of acrylic acid-treated bacterial cellulose cation-exchange membrane," *J. Chem. Technol. Biotech.* 79(1), 79-84.
- Chojnacka, K. (2006). "Biosorption of Cr(III) ions by wheat straw and grass: A systematic characterization of new biosorbents," *Pol. J. Environ. Stud.* 15(6), 845-852.
- Chojnacka, K. (2009). *Biosorption and Bioaccumulation in Practice*, Nova Sci. Publ., New York.
- Chojnacka, K. (2010). "Biosorption and bioaccumulation - The prospects for practical applications," *Environ. Intl.* 36(3), 299-307.
- Chojnacka, K., and Michalak, I. (2009). "Using wood and bone ash to remove metal ions from solutions," *Global Next J.* 11(2), 205-217.
- Choksi, P. M., and Joshi, V. Y. (2007). "Adsorption kinetic study for the removal of nickel (II) and aluminum (III) from an aqueous solution by natural adsorbents," *Desalination* 208(1-3), 216-231.
- Chu, K. H., and Hashim, M. A. (2002). "Adsorption and desorption characteristics of zinc on ash particles derived from oil palm waste," *J. Chem. Technol. Biotech.* 77(6), 685-693.
- Chuah, T. G., Jumasiah, A., Azni, I., Katayon, S., and Choong, S. Y. T. (2005). "Rice husk as a potentially low-cost biosorbent for heavy metal and dye removal: An overview," *Desalination* 175(3), 305-316.
- Chubar, N., Carvalho, J. R., and Correia, M. J. N. (2003). "Cork biomass as biosorbent for Cu(II), Zn(II) and Ni(II)," *Colloids Surf. A – Physicochem. Eng. Aspects* 230(1-3), 57-65.
- Cimino, G., Passerini, A., and Toscano, G. (2000). "Removal of toxic cations and Cr(VI) from aqueous solution by hazelnut shell," *Water Res.* 34(11), 2955-2962.
- Cochrane, E. L., Lu, S., Gibb, S. W., and Villaescusa, I. (2006). "A comparison of low-cost biosorbents and commercial sorbents for the removal of copper from aqueous media," *J. Hazard. Mater. B* 137(1), 198-206.
- Cooney, D. O. (1998). *Adsorption Design for Wastewater Treatment*, Lewis Publ., New York, 190 pp.
- Corapcioglu, M. O., and Huang, C. P. (1987). "The adsorption of heavy metals onto hydrous activated carbon," *Wat. Res.* 21(9), 1031-1044.
- Cordero, T., Rodriguez-Mirasol, J., Tancredi, N., Piriz, J., Vivo, G., and Rodriguez, J. J. (2002). "Influence of surface composition and pore structure on Cr(III) adsorption onto activated carbons," *Ind. Eng. Chem. Res.* 41(24), 6042-6048.
- Cossich, E. S., Da Silva, E. A., Tavares, C. R. G., Cardozo, L., and Ravagnani, T. M. K. (2004). "Biosorption of chromium(III) by biomass of seaweed *Sargassum* sp. in a fixed-bed column," *Adsorption – J. Int. Adsorp. Soc.* 10(2), 129-138.
- Cox, M., Pichugin, A. A., El-Shafey, E. I., and Appleton, Q. (2005). "Sorption of precious metals onto chemically prepared carbon from flax shive," *Hydrometallurgy* 78(1-2), 137-144.
- Crini, G. (2005). "Recent developments in polysaccharide-based materials used as adsorbents in wastewater treatment," *Progress in Polymer Science* 30(1), 38-70.

- Crist, D. R., Crist, R. H., and Martin, J. R. (2003). "A new process for toxic metal uptake by a kraft lignin," *J. Chem. Technol. Biotech.* 78(2-3), 199-202.
- Crist, R. H., Martin, J. R., and Crist, D. R. (2002). "Heavy metal uptake by lignin: Comparison of biotic ligand models with an ion-exchange process," *Environ. Sci. Technol.* 36(7), 1485-1490.
- Crist, R. H., Martin, J. R., and Crist, D. R. (2004). "Use of a novel formulation of kraft lignin for toxic metal removal from process waters," *Separation Sci. Technol.* 39(7), 1535-1545.
- Cui, J. R., and Zhang, L. F. (2008). "Metallurgical recovery of metals from electronic waste: A review," *J. Hazardous Mater.* 158(2-3), 228-256.
- Dakiky, M., Khamis, M., Manassra, A., and Mereb, M. (2002). "Selective adsorption of chromium(VI) in industrial wastewater using low-cost abundantly available adsorbents," *Adv. Environ. Res.* 6(4), 533-540.
- Daneshvar, N., Salari, D., and Aber, S. (2002). "Chromium adsorption and Cr(VI) reduction to trivalent chromium in aqueous solutions by soya cake," *J. Hazard. Mater.* 94(1), 49-61.
- Dang, V. B. H., Doan, H. D., Dang-Vu, T., and Lohi, A. (2009). "Equilibrium and kinetics of biosorption of cadmium (II) and copper (II) ions by wheat straw," *Bioresour. Tech.* 100(1), 211-219.
- Das, D. D., Mahapatra, R., Pradhan, J., Das, S. N., and Thakur, R. S. (2004). "Removal of Cr(VI) from aqueous solution using activated cow dung carbon," *J. Colloid Interface Sci.* 232(2), 235-240.
- Das, N., Vimala, R., and Karthika, P. (2008). "Biosorption of heavy metals - An overview," *Indian J. Biotechnol.* 7(2), 159-169.
- Dastgheib, S. A., and Rockstraw, D. A. (2001). "Pecan shell activated carbon: Synthesis, characterization and application for the removal of copper from aqueous solution," *Carbon* 39(12), 1849-1855.
- Dastgheib, S. A., and Rockstraw, D. A. (2002a). "A model for the adsorption of single metal ion solutes in aqueous solution onto activated carbon produced from pecan shells," *Carbon* 40(11), 1843-1851.
- Dastgheib, S. A., and Rockstraw, D. A. (2002b). "A systematic study and proposed model of the adsorption of binary metal ion solutes in aqueous solution onto activated carbon produced from pecan shells," *Carbon* 40(11), 1853-1861.
- Davila-Jimenez, M. M., Elizalde-Gonzalez, M. P., Geyer, W., Mattusch, J., and Wennrich, R. (2003). "Adsorption of metal cationic from aqueous solution onto a natural and a model biocomposite," *Colloids Surf A* 219(1-3), 243-252.
- Davis, T. A., Volesky, B., and Mucci, A. (2003). "A review of the biochemistry of heavy metal biosorption by brown algae," *Water Res.* 37(18), 4311-4330.
- Dean, S. A., and Tobin, J. M. (1999). "Uptake of chromium cations and anions by milled peat," *Resour. Conserv. Recycl.* 27(1-2), 151-156.
- de Britto, J. S., da Costa, A. C. A., Luna, A. S., and Henriques, C. A. (2007). "Comparative study of ion-exchange and biosorption processes for the removal of Cd^{2+} and Zn^{2+} ions from aqueous effluents," *Adsorp. Sci. Technol.* 25(9), 661-671.
- Deepa, K. K., Sathishkumar, M., Binupriya, A. R., Murugesan, G. S., Swaminathan, K., and Yun, S. E. (2006). "Sorption of Cr(VI) from dilute solutions and wastewater by

- live and pretreated biomass of *Aspergillus flavus*,” *Chemosphere* 62(5), 833-840.
- De la Rosa, G., Gardea-Torresdey, J. L., Peralta-Videa, J. R., Herrera, I., and Contreras, C. (2003). “Use of silica-immobilized humin for heavy metal removal from aqueous solution under flow conditions,” *Bioresour. Technol.* 90(1), 11-17.
- de Mesquita, J. P., Martelli, P. B., and Gorgulho, H. D. F. (2006). “Characterization of copper adsorption on oxidized activated carbon,” *J. Braz. Chem. Soc.* 17(6), 1133-1143.
- Demiral, H., Demiral, I., Tumsek, F., and Karabacakoglu, B. (2008). “Adsorption of chromium(VI) from aqueous solution by activated carbon derived from olive bagasse and applicability of different adsorption models,” *Chem. Eng. J.* 144(2), 188-196.
- Demirbas, A. (2004). “Adsorption of lead and cadmium ions in aqueous solutions onto modified lignin from alkali glycerol delignification,” *J. Hazard. Mater.* 109(1-3), 221-226.
- Demirbas, A. (2005). “Adsorption of Cr(III) and Cr(VI) ions from aqueous solutions on to modified lignin,” *Energy Sources* 27(15), 1449-1455.
- Demirbas, A. (2007). “Adsorption of Co(II) and Hg(II) from water and wastewater onto modified lignin,” *Energy Sources Pt. A – Recov. Util. Environ. Effects* 29(2), 117-123.
- Demirbas, A. (2008). “Heavy metal adsorption onto agro-based waste materials: A review,” *J. Hazardous Mater.* 157(2-3), 220-229.
- Demirbas, E., Dizge, N., Sulak, M. T., and Kobya, M. (2009). “Adsorption kinetics and equilibrium of copper from aqueous solutions using hazelnut shell activated carbon,” *Chem. Eng. J.* 148(2-3), 480-487.
- Demirbas, E., Kobya, M., and Konukman, A. E. S. (2008). “Error analysis of equilibrium studies for the almond shell activated carbon adsorption of Cr(VI) from aqueous solutions,” *J. Hazardous Mater.* 154(1-3), 787-794.
- Demirbas, E., Kobya, M., Oncel, S., and Sencan, S. (2002). “Removal of Ni(II) from aqueous solution by adsorption onto hazelnut shell activated carbon: Equilibrium studies,” *Bioresour. Technol.* 84(3), 291-293.
- Demirbas, E., Kobya, M., Senturk, E., and Ozkan, T. (2004). “Adsorption kinetics for the removal of chromium (VI) from aqueous solutions on the activated carbons prepared from agricultural wastes,” *Water SA.* 30(4), 533-539.
- Deng, S. B., and Ting, Y. P. (2005a). “Fungal biomass with grafted poly(acrylic acid) for enhancement of Cu(II) and Cd(II) biosorption,” *Langmuir* 21(13), 5940-5948.
- Deng, S., and Ting, Y.-P. (2005b). “Characterization of PEI-modified biomass and biosorption of Cu(II), Pb(II) and Ni(II),” *Water Res.* 39(10), 2167-2177.
- Deng, S. B., and Ting, Y. P. (2005c). “Polyethylenimine-modified fungal biomass as a high-capacity biosorbent for Cr(VI) anions: Sorption capacity and uptake mechanisms,” *Environ. Sci., Technol.* 39(21), 8490-8496.
- Deng, S., Ting, Y. P., and Yu, G. (2006). “Chromate sorption and reduction kinetics onto an aminated biosorbent,” *Water Sci. Technol.* 54(10), 1-8.
- Dias, J. M., Alvim-Ferraz, M. C. M., Almeida, M. F., Rivera-Utrilla, J., and Sanchez-Polo, M. (2007). “Waste materials for activated carbon preparation and its use in aqueous-phase treatment: A review,” *J. Environ. Manag.* 85(4), 833-846.
- Diniz, V., and Volesky, B. (2005). “Biosorption of La, Eu and Yb using *Sargassum*

- biomass,” *Water Res.* 39(1), 239-247.
- Dizhbite, T., Zakis, G., Kizima A., Lazareva, E., Rossinskaya, G., Jurkane, V., Telysheva, G., and Viesturs, U. (1999). “Lignin - A useful bioresource for the production of sorption-active materials,” *Bioresour. Technol.* 67, 221-228.
- Doan, H. D., Lohi, A., Dang, V. B. H, and Dang-Vu, T. (2008). “Removal of Zn^{+2} and Ni^{+2} by adsorption in a fixed bed of wheat straw,” *Proc. Safety Environ. Prot.* 86(B4), 259-267.
- Dönmez, G., and Aksu, Z. (2002). “Removal of Cr(VI) from saline wastewaters by *Dunaliella* species,” *Process Biochem.* 38, 751-762.
- Dönmez, G., and Aksu, Z., Öztürk, A., and Kutsal, T. (1999). “A comparative study on heavy metal biosorption characteristics of some algae,” *Process Biochem.* 34(9), 885-892.
- Doyurum, S., and Celik, A. (2006). “Pb(II) and Cd(II) removal from aqueous solutions by olive cake,” *J. Hazard. Mater.* 138(1), 22-28.
- Dronnet, V. M., Renard, C. M. G. C., Axelos, M. A. V., and Thibault, J. F. (1997). “Binding of divalent metal cations by sugar-beet pulp,” *Carbohydr. Poly.* 34(1-2), 73-82.
- Dubey, S. P., Gopal, K., and Bersillon, J. L. (2009). “Utility of adsorbents in the purification of drinking water: A review of characterization, efficiency and safety evaluation of various adsorbents,” *J. Environ. Biol.* 30(3), 327-332.
- Dubey, S. P., and Krishna, G. (2007). “Adsorption of chromium (VI) on low cost adsorbents derived from agricultural waste material,” *J. Hazard. Mater.* 145(3), 465-470.
- Dubin, M. M., and Radushkevich, L. V. (1947). “Equation of the characteristic curve of activated charcoal,” *Chemisches Zentralblatt* 1, 875-889.
- Duman, G., Onalt, Y., Okutucu, C., Onenc, S., and Yanik, J. (2009). “Production of activated carbon from pine cone and evaluation of its physical, chemical, and adsorption properties,” *Energy Fuels* 23(Special Issue), 2197-2204.
- Duong, T. D., Hoang, M., and Nguyen, K. L. (2004). “Extension of Donnan theory to predict calcium ion exchange on phenolic hydroxyl sites of unbleached kraft fibers,” *J. Colloid Interface Sci.* 276(1), 6-12.
- Dupont, L., and Guillon, E. (2003). “Removal of hexavalent chromium with a lignocellulosic substrate extracted from wheat bran,” *Environmental Science and Technology* 37(18), 4235-4241.
- Dursun, A. Y. (2006). “A comparative study on determination of the equilibrium, kinetic and thermodynamic parameters of biosorption of copper(II) and lead(II) ions onto pretreated *Aspergillus niger*,” *Biochem. Eng. J.* 28(2), 187-195.
- Edgar, T. F., and Himmelblau, D. M. (1989). *Optimization of Chemical Processes*, McGraw-Hill, N.Y., 208-241.
- Edyvean, R. G. J., Williams, C. J., Wilson, M. W., and Aderhold, D. (1997). “Biosorption using unusual biomasses,” in: *Biosorbents for Metal Ions*, Wase, J., and Forster, C. (eds.), CRC Press, London, UK, 165-182.
- Elangovan, R., Philip, L., and Chandraraj, K. (2008a). “Biosorption of chromium species by aquatic weeds: Kinetics and mechanism studies,” *J. Hazard. Mater.* 152(1), 100-112.
- Elangovan, R., Philip, L., and Chandraraj, K. (2008b). “Biosorption of hexavalent and

- trivalent chromium by palm flower (*Borassus aethiopum*),” *Chem. Eng. J.* 141(1-3), 99-111.
- El-Ashtoukhy, E.-S. Z., Amin, N. K., and Abdelwahab, O. (2008). “Removal of lead(II) and copper(II) from aqueous solution using pomegranate peel as new adsorbent,” *Desalination* 223(1-3), 162-173.
- El-Hendawy, A. N. A. (2003). “Influence of HNO₃ oxidation on the structure and adsorptive properties of corncob-based activated carbon,” *Carbon* 41(4), 713-722.
- El-Hendawy, A. N. A. (2009). “The role of surface chemistry and solution pH on the removal of Pb²⁺ and Cd²⁺ ions via effective adsorbents from low-cost biomass,” *J. Hazard. Mater.* 167(1-3), 260-267.
- El-Hendawy, A. N. A., Samra, S. E., and Girgis, B. S. (2001). “Adsorption characteristics of activated carbons obtained from corncobs,” *Colloids Surf. A – Physicochem. Eng. Aspects* 180(3), 209-221.
- El Nemr, A. (2007). “Pomegranate husk as an adsorbent in the removal of toxic chromium from wastewater,” *Chem. Ecol.* 23(5), 409-425.
- El Nemr, A., Khaled, A., Abdelwahab, O., and El-Sikaily, A. (2008). “Treatment of wastewater containing toxic chromium using new activated carbon developed from date palm seed,” *J. Hazard. Mater.* 152(1), 263-275.
- El-Shafey, E. I. (2005). “Behaviour of reduction-sorption of chromium(VI) from an aqueous solution on a modified sorbent from rice husk,” *Water Air Soil Pollution* 163(1-4), 81-102.
- El-Shafey, E. I. (2007a). “Removal of Se(IV) from aqueous solution using sulphuric acid-treated peanut shell,” *J. Environ. Manag.* 84(4), 620-627.
- El-Shafey, E. I. (2007b). “Sorption of Cd(II) and Se(IV) from aqueous solution using modified rice husk,” *J. Hazardous Mater.* 147(1-2), 546-555.
- El-Shafey, E. I. (2010). “Removal of Zn(II) and Hg(II) from aqueous solution on a carbonaceous sorbent chemically prepared from rice husk,” *J. Hazardous Mater.* 175(1-3), 319-327.
- El-Shafey, E. I., and Canepa, P. (2003). “Remediation of a Cr (VI) contaminated soil: Soil washing followed by Cr (VI) reduction using a sorbent prepared from rice husk,” *J. Physique IV* 107, 415-418.
- El-Sikaily, A., El Nemr, A., Khaled, A., and Abdelwehab, O. (2007). “Removal of toxic chromium from waste water using green alga *Ulva lactuca* and its activated carbon,” *J. Hazard. Mater.* 148(1-2), 216-228.
- Erdogan, S., Onal, Y., Akmil-Basar, C., Bilmez-Erdemoglu, S., Sarici-Ozdemir, C., Koseoglu, E., and Icduygu, G. (2005). “Optimization of nickel adsorption from aqueous solution by using activated carbon prepared from waste apricot by chemical activation,” *Appl. Surf. Sci.* 252(5), 1324-1331.
- Escudero, C., Gabaldón, C., Marzal, P., and Villaescusa, I. (2008). “Effect of EDTA on divalent metal adsorption onto grape stalk and exhausted coffee wastes,” *J. Hazard. Mater.* 152(2), 476-485.
- Esposito, A., Pagnanelli, F., and Vegliò, F. (2002). “pH-related equilibria models for biosorption in single metal systems,” *Chem. Eng. Sci.* 57, 307-313.

- Fahim, N. F., Barsoum, B. N., Eid, A. E., and Khalil, M. S. (2006). "Removal of Cr (III) from tannery wastewater using activated carbon from sugar industrial waste," *J. Hazard. Mater.* 136(2), 303-309.
- Fang, J., Gu, Z. M., Gang, D. C., Liu, C. X., Ilton, E. S., and Deng, B. L. (2007). "Cr(VI) removal from aqueous solution by activated carbon coated with quaternized poly(4-vinylpyridine)," *Environ. Sci. Technol.* 41(13), 4748-4753.
- Farajzadeh, M. A., and Monji, A. B. (2004a). "Adsorption characteristics of wheat bran towards heavy metal cations," *Sep. Purif. Technol.* 38(3), 197-207.
- Farajzadeh, M. A., and Monji, A. B. (2004b). "Treated rice bran for scavenging Cr(III) and Hg(II) from acidic solution," *J. Chinese Chem. Soc.* 51(4), 751-759.
- Farinella, N. V., Matos, G. D., and Arruda, M. A. Z. (2007). "Grape bagasse as a potential biosorbent of metals in effluent treatments," *Bioresour. Technol.* 98(10), 1940-1946.
- Farinella, N. V., Matos, G. D., Lehmann, E. L., and Arruda, M. A. Z. (2008). "Grape bagasse as an alternative natural adsorbent of cadmium and lead for effluent treatment," *J. Hazardous Mater.* 154(1-3), 1007-1012.
- Faur-Brasquet, C., Reddad, Z., Kadirvelu, K., and Le Cloirec, P. (2002). "Modeling the adsorption of metal ions (Cu^{2+} , Ni^{2+} , Pb^{2+}) onto ACCs using surface complexation models," *Appl. Surf. Sci.* 196(1-4), 356-365.
- Febrianto, J., Kosasih, A. N., Sunarso, J., Jua, Yi-H., Indraswati, N., and Ismadji, S. (2009). "Equilibrium and kinetic studies in adsorption of heavy metals using biosorbent: A summary of recent studies," *J. Hazard. Mater.* 162(2-3), 616-645.
- Filipovic-Kovacevic, Z., Sipos, L., and Briski, F. (2000). "Biosorption of chromium, copper, nickel and zinc ions onto fungal pellets of *Aspergillus niger* 405 from aqueous solutions," *Food Technol. Biotechnol.* 38(3), 211-216.
- Fiol, N., Poch, J., and Villaescusa, I. (2004). "Chromium(VI) uptake by grape stalks wastes encapsulated in calcium alginate beads: Equilibrium and kinetics studies," *Chem. Speciation Bioavail.* 16(1-2), 25-33.
- Fiol, N., Villaescusa, I., Martinez, M., Miralles, N., Poch, J., and Serarols, J. (2003). "Biosorption of Cr(VI) using low cost sorbents," *Environ. Chem. Lett.* 1(2), 135-139.
- Fiol, N., Villaescusa, I., Martinez, M., Miralles, N., Poch, J., and Serarols, J. (2006). "Sorption of Pb(II), Ni(II), Cu(II) and Cd(II) from aqueous solution by olive stone waste," *Separation Purification Technol.* 50(1), 132-140.
- Foglarova, M., Prokop, J., and Milichovsky, M. (2009). "Oxidized cellulose: An application in the form of sorption filter materials," *J. Appl. Polymer Sci.* 112(2), 669-678.
- Fourest, E., Canal, C., and Roux, J. C. (1994). "Improvement of heavy metal biosorption by mycelial dead biomasses (*Rhizopus arrhizus*, *Mucor miehei* and *Penicillium chrysogenum*) – pH control and cationic activation," *FEMS Microbiol. Rev.* 14(4), 325-332.
- Fourest, E., and Roux, J. (1992). "Heavy metal biosorption by fungal mycelial by-product mechanisms and influence of pH," *Appl. Microbiol. Biotechnol.* 37(3), 399-403.
- Fourest, E., and Volesky, B. (1996). "Contribution of sulfonate groups and alginate to heavy metal biosorption by the dry biomass of *Sargassum fluitans*," *Environ. Sci. Technol.* 30(1), 277-282.

- Fourest, E., and Volesky, B. (1997). "Alginate properties and heavy metal biosorption by marine alga," *Appl. Biochem. Biotechnol.* 67, 33-34.
- Fraga, C. G., and Oteiza, P. I. (2002). "Iron toxicity and antioxidant nutrients," *Toxicology* 180(1), 23-32.
- Freer, J., Baeza, J., Maturana, H., and Palma, G. (1989). "Removal and recovery of uranium by modified *Pinus radiata* D. don bark," *J. Chem. Technol. Biotechnol.* 46(1), 41-48.
- Freundlich, H. M. F. (1907). "Über die adsorption in losungen," *Zeitschrift für Physikalische Chemie (Leipzig)*. A 57, 385-470.
- Friedman, M., and Waiss, A. C. (1972). "Mercury uptake by selected agricultural products and by-products," *Environ. Sci. Technol.* 6(5), 457-458.
- Fritz, W., and Schlünder, E. U. (1974). "Simultaneous adsorption equilibria of organics solutes in dilute aqueous solutions on activated carbon," *Chem. Eng. Sci.* 29, 1279-1282.
- Fritz, W., and Schlünder, E. U. (1981). "Competitive adsorption of two dissolved organics onto activated carbon – I," *Chem Eng Sci.* 36, 721-730.
- Fytianos, K. (2001). "Speciation analysis of heavy metals in natural waters: A review," *J. AOAC Intl.* 84(6), 1763-1769.
- Gabaldón, C., Izquierdo, M., Marzal, P., and Sempere, F. (2007). "Evaluation of biosorbents for Cu removal from wastewater in the presence of EDTA," *J. Chem. Technol. Biotechnol.* 82(10), 888-897.
- Gabaldón, C., Marzal, P., Seco, A., and González, J. A. (2000). "Cadmium and copper removal by a granular activated carbon in laboratory column systems," *Sep. Sci. Technol.* 35(7), 1039-1053.
- Gaballah, I., and Kilbertus, G. (1998). "Recovery of heavy metal ions through decontamination of synthetic solutions and industrial effluents using modified barks," *Journal of Geochemical Exploration* 62(1-3), 241-286.
- Gabriel, J., Vosahlo, J., and Baldrian, P. (1996). "Biosorption of cadmium to mycelial pellets of wood rotting fungi," *Biotechnology Techniques* 10, 345-348.
- Gadd, G. M. (1993). "Interactions of fungi with toxic metals by biosorption: A review," *Hydrometallurgy* 44, 301-316.
- Gadd, G. M. (2009). "Biosorption: Critical review of scientific rationale, environmental importance and significance for pollution treatment," *J. Chem. Technol. Biotech.* 84(1), 13-28.
- Gaikwad, R. W. (2004). "Removal of Cd (II) from aqueous solution by activated charcoal derived from coconut shell," *Electron. J. Environ. Agric. Food Chem.* 3(4), 702-709.
- Gajghate, D. G., Saxena, E. R., and Aggarwal, A. L. (1992). "Removal of chromium (VI) as chromium diphenyl carbazide (CDC) complex from aqueous solution by activated carbon," *Water Air and Soil Pollution* 65(3-4), 329-337.
- Gajghate, D. G., Saxena, E. R., and Vittal, M. (1991). "Removal of lead from aqueous solution by activated carbon," *Ind. J. Environ. Health* 33, 374-379.
- Galiatsatou, P., Metaxas, M., and Kasselouri-Rigopoulou, V. (2002). "Adsorption of zinc by activated carbons prepared from solvent extracted olive pulp," *J. Hazard. Mater.* 91(1-3), 187-203.

- Gao, H., Liu, Y., Zeng, G., Xu, W., Li, T., and Xia, W. (2008). "Characterization of Cr(VI) removal from aqueous solutions by a surplus agricultural waste, rice straw," *J. Hazardous Mater.* 150(2), 446-452.
- Garcia-Reyes, R. B., Rangel-Mendez, J. R., and Alfaro-De la Torre, M. C. (2009). "Chromium (III) uptake by agro-waste biosorbents: Chemical characterization, sorption-desorption studies, and mechanism," *J. Hazardous Mater.* 170(2-3), 845-854.
- Gardea-Torresdey, J. L., De La Rosa, G., and Peralta-Videa, J. R. (2004a). "Use of phytofiltration technologies to remove the heavy metals: A review," *Pure and Applied Chemistry* 76(4), 801-803.
- Gardea-Torresdey, J. L., Dokken, K., Tiemann, K. J., Parsons, J. G., Ramos, J., Pingitore, N. E., and Gamez, G. (2002). "Infrared and X-ray absorption spectroscopic studies on the mechanism of chromium(III) binding to alfalfa biomass," *Microchem. J.* 71(2-3), 157-166.
- Gardea-Torresdey, J. L., Gonzalez, J. H., Tiemann, K. J., Rodriguez, O., and Gamez, G. (1998). "Phytofiltration of hazardous cadmium, chromium, lead, and zinc ions by biomass of *Medicago sativa* (alfalfa). *J. Hazard. Mater.* 57(1-3), 29-39.
- Gardea-Torresdey, J. L., Hejazi, M., Tiemann, K. J., Parsons, J. G., Duarte-Gardea, M., and Henning, J. (2002). "Use of hop (*Humulus lupulus*) agricultural by-products for the reduction of aqueous lead (II) environmental health hazards," *J. Hazard. Mater.* 91(1-3), 95-112.
- Gardea-Torresdey, J. L., Peralta-Videa, J. R., Montes, M., LaRosa, G., and Corral-Diaz, B. (2004b). "Bioaccumulation of cadmium, chromium and copper by *Convolvulus arvensis* L.: Impact on plant growth and uptake of nutritional elements," *Bioresour. Technol.* 92, 229-235.
- Gardea-Torresdey, J. L., Tang, L., and Salvador, J. M. (1996a). "Copper adsorption by esterified and unesterified fractions of sphagnum peat moss and its different humic substances," *J. Hazard. Mater.* 48(1-3), 191-206.
- Gardea-Torresdey, J. L., Tiemann, K. J., Armendariz, V., Bess-Oberto, L., Chianelli, R. R., Rios, J., Parsons, J. G., and Gamez, G. (2000a). "Characterization of chromium (VI) binding and reduction to chromium (III) by the agricultural byproduct of *Avena monida* (oat) biomass," *J. Hazard. Mater.* 80(1-3), 175-188.
- Gardea-Torresdey, J. L., Tiemann, K. J., Gamez, G., Dokken, K., Cano-Aguilera, I., Furenlid, L. R., and Renner, M. W. (2000b). "Reduction and accumulation of gold(III) by *Medicago sativa* alfalfa biomass: X-ray absorption spectroscopy, pH, and temperature dependence," *Environ. Sci. Technol.* 34(20), 4392-4396.
- Gardea-Torresdey, J. L., Tiemman, K. J., Gonzalez, J. H., Cano-Aguilera, I., Henning, J. A., and Townsend, M. S. (1996b). "Removal of nickel ions from aqueous solution by biomass and silica-immobilized biomass of *Medicago sativa* (alfalfa)," *J. Hazard. Mater.* 49(2-3), 205-216.
- Garg, U. K., Kaur, M. P., Garg, V. K., and Sud, D. (2007). "Removal of hexavalent Cr from aqueous solutions by agricultural waste biomass," *J. Hazard. Mater.* 140(1-2), 60-68.

- Garg, U. K., Kaur, M. P., Garg, V. K., and Sud, D. (2008a). "Removal of Ni (II) from aqueous solution by adsorption on agricultural waste biomass using a response surface methodological approach," *Bioresour. Technol.* 99(5), 1325-1331.
- Garg, U., Kaur, M. P., Jawa, G. K., Sud, D., and Garg, V. K. (2008b). "Removal of cadmium(II) from aqueous solution by adsorption on agricultural waste biomass," *J. Hazard. Mater.* 154(1-3), 1149-1157.
- Garg, U. K., Kaur, M. P., Sud, D., and Garg, V. K. (2009). "Removal of hexavalent chromium from aqueous solution by adsorption on treated sugarcane bagasse using response surface methodological approach," *Desalination* 249(2), 475-479.
- Garg, V. K., Gupta, R., Kumar, R., and Gupta, R. K. (2004). "Adsorption of chromium from aqueous solution on treated sawdust," *Bioresour. Technol.* 92(1), 79-81.
- Geay, M., Marchetti, V., Clement, A., Loubinoux, B., and Gerardin, P. (2000). "Decontamination of synthetic solutions containing heavy metals using chemically modified sawdusts bearing polyacrylic acid chains," *Journal of Wood Science* 46(4), 331-333.
- Gérente, C., du Mensil, P. C., Andrès, Y., Thibault, J., and Le Cloirec, P. (2000). "Removal of metal ions from aqueous solution on low cost natural polysaccharides. Sorption mechanism approach," *React. Funct. Polym.* 46(2), 135-144.
- Gérente, C., Lee, V. K. C., Le Cloirec, P., and McKay, G. (2007). "Application of chitosan for the removal of metals from wastewaters by adsorption – Mechanisms and models review," *Crit. Rev. Env. Sci. Technol.* 37(1), 41-127.
- Ghimire, K. N., Inoue, J. I., Inoue, K., Kawakita, H., and Ohto, K. (2008). "Adsorptive separation of metal ions onto phosphorylated orange waste," *Separation Sci. Technol.* 43(2), 362-375.
- Ghimire, K. N., Inoue, K., Ohto, K., and Hayashida, T. (2007). "Adsorptive separation of metallic pollutants onto waste seaweeds, *Porphyra yezoensis* and *Ulva japonica*," *Separation Sci. Technol.* 42(9), 2003-2018.
- Ghimire, K. N., Inoue, K., Ohto, K., and Hayashida, T. (2008). "Adsorption study of metal ions onto crosslinked seaweed *Laminaria japonica*," *Bioresour. Technol.* 99(1), 32-37.
- Ghodbane, I., and Hamdaoui, O. (2008). "Removal of mercury(II) from aqueous media using eucalyptus bark: Kinetic and equilibrium studies," *J. Hazard. Mater.* 160(2-3), 301-309.
- Ghodbane, I., Nouri, L., Hamdaoui, O., and Chiha, M. (2007). "Kinetic and equilibrium study for the sorption of cadmium(II) ions from aqueous phase by eucalyptus bark," *J. Hazard. Mater.* 152(1), 148-158.
- Gill, R. I. S. (1989). "The use of potentiometric titration and polyelectrolyte titration to measure the surface charge of cellulose fibre," In: *Fundamentals of Papermaking: Transactions of the 9th Fundamental Research Symposium Held at Cambridge: Sept. 1989*, Vol. 1, Baker, C. F., and Punton, V. W. (eds.), Mechanical Engineering Publ. Ltd., London, 437-452.
- Girgis, B. S., Attia, A. A., and Fathy, N. A. (2007). "Modification in adsorption characteristics of activated carbon produced by H₃PO₄ under flowing gases," *Colloids Surf. A – Physicochem. Eng. Aspects* 299(1-3), 79-87.
- Girgis, B. S., Smith, E., Louis, M. M., and El-Hendawy, A. N. A. (2009). "Pilot production of activated carbon from cotton stalks using H₃PO₄," *J. Anal. Appl. Pyrol.*

- 86(1), 180-184.
- Gloaguen, V., and Morvan, H. (1997). "Removal of heavy metal ions from aqueous solution by modified barks," *J. Environ. Sci. Heal A* 32(4), 901-912.
- Gokhale, S. V., Jyoti, K. K., and Lele, S. S. (2008). "Kinetic and equilibrium modeling of chromium (VI) biosorption on fresh and spent *Spirulina platensis*/*Chlorella vulgaris* biomass," *Bioresour. Technol.* 99(9), 3600-3608.
- Gomes, N. C. M., and Linardi, V. R. (1996). "Removal of gold, silver and copper by living and nonliving fungi from leach liquor obtained from the gold mining industry," *Rev. Microbiol.* 27(4), 218-222.
- Gomez-Serrano, V., Cuerda-Correa, E. M., Fernandez-Gonzalez, M. C., Alexandre-Franco, M. F., and Macias-Garcia, A. (2005). "Preparation of activated carbons from walnut wood: A study of microporosity and fractal dimension," *Smart Mater. Struc.* 14(2), 363-368.
- Gomez-Serrano, V., Macias-Garcia, A., Espinosa-Mansilla, A., and Valenzuela-Calahorra, C. (1998). "Adsorption of mercury, cadmium and lead from aqueous solution on heat-treated and sulphurized activated carbon," *Water Res.* 32(1), 1-4.
- Gomez-Tamayo, M. D., Macias-Garcia, A., Diez, M. A. D., and Cuerda-Correa, E. M. (2008). "Adsorption of Zn(II) in aqueous solution by activated carbons prepared from evergreen oak (*Quercus rotundifolia* L.)," *J. Hazard. Mater.* 153(1-2), 28-36.
- Gonzalez, M. H., Araujo, G. C. L., Pelizaro, C. B., Menezes, E. A., Lemos, S. G., de Sousa, G. B., and Nogueira, A. R. A. (2008). "Coconut coir as biosorbent for Cr(VI) removal from laboratory wastewater," *J. Hazardous Mater.* 159(2-3), 252-256.
- Gonzalez-Serrano, E., Cordero, T., Rodriguez-Mirasol, J., Cotoruelo, L., and Rodriguez, J. J. (2004). "Removal of water pollutants with activated carbons prepared from H₃PO₄ activation of lignin from kraft black liquors," *Water Res.* 38(13), 3043-3050.
- Goyal, N., Jain, S. C., and Banerjee, U. C. (2003). "Comparative studies on the microbial adsorption of heavy metals," *Adv. Environ. Res.* 7(2), 311-319.
- Grimm, A., Zanzi, R., Björnbo, E., and Cukierman, A. L. (2008). "Comparison of different types of biomasses for copper biosorption," *Bioresour. Technol.* 99(7), 2559-2565.
- Guclu, G., Gurdag, G., and Ozgumus, S. (2003). "Competitive removal of heavy metal ions by cellulose graft copolymers," *Journal of Applied Polymer Science* 90(8), 2034-2039.
- Guibaud, G., Tixier, N., Bouju, A., and Baudu, M. (2003). "Relation between extracellular polymers composition and its ability to complex Cd, Cu and Pb," *Chemosphere* 52(10), 1701-1710.
- Guillon, E., Merdy, P., Aplincourt, M., Dumonceau, J., and Vezin, H. (2001). "Structural characterization and iron(III) binding ability of dimeric and polymeric lignin models," *J. Colloid Interface Sci.* 239(1), 39-48.
- Guo, S. H., Peng, J. H., Li, W., Yang, K. B., Zhang, L. B., Zhang, S. M., and Xia, H. Y. (2009). "Effects of CO₂ activation on porous structures of coconut shell-based activated carbons," *Appl. Surf. Sci.* 255(20), 8443-8449.
- Guo, X. Y., Zhang, S. Z., and Shan, X. Q. (2008). "Adsorption of metal ions on lignin," *Journal of Hazardous Materials* 151(1), 134-142.
- Guo, Y. P., Qi, J. R., Yang, S. F., Yu, K. F., Wang, Z. C., and Xu, H. D. (2003).

- “Adsorption of Cr(VI) on micro- and mesoporous rice husk-based active carbon,” *Mater. Chem. Phys.* 78(1), 132-137.
- Gupta, R., Ahuja, P., Khan, S., Saxena, R. K., and Mohapatra, H. (2000). “Microbial biosorbents: Meeting challenges of heavy metal pollution in aqueous solutions,” *Current Sci.* 78(8), 967-973.
- Gupta, S., and Babu, B. V. (2009). “Utilization of waste product (tamarind seeds) for the removal of Cr(VI) from aqueous solutions: Equilibrium, kinetics, and regeneration studies,” *J. Environ. Manag.* 90(10), 3013-3022.
- Gupta, V. K., and Ali, I. (2000). “Utilization of bagasse fly ash (a sugar industry waste) for the removal of copper and zinc from wastewater,” *Separation and Purification Technol.* 18(2), 131-140.
- Gupta, V. K., and Ali, I. (2004). “Removal of lead and chromium from wastewater using bagasse fly ash – A sugar industry waste,” *J. Colloid Interface Sci.* 271(2), 321-328.
- Gupta, V. K., Jain, C. K., Ali, I., Sharma, M., and Saini, V. K. (2003). “Removal of cadmium and nickel from wastewater using bagasse fly ash - A sugar industry waste,” *Water Res.* 37(16), 4038-4044.
- Gupta, V. K., Mohan, D., and Sharma, S. (1998). “Removal of lead from wastewater using bagasse fly ash - A sugar industry waste material,” *Separation Sci. Technol.* 33(9), 1331-1343.
- Gupta, V. K., Mohan, D., Sharma, S., and Park, K. T. (1999). “Removal of chromium (VI) from electroplating industry wastewater using bagasse fly ash – A sugar industry waste material,” *The Environmentalist* 19, 129-136.
- Gupta, V. K., and Rastogi, A. (2008a). “Biosorption of lead(II) from aqueous solutions by nonliving algal biomass *Oedogonium* sp. and *Nostoc* sp.—A comparative study,” *Colloids Surf. B: Biointerfaces* 64(2), 170-178.
- Gupta, V. K., and Rastogi, A. (2008b). “Equilibrium and kinetic modeling of cadmium(II) biosorption by nonliving algal biomass *Oedogonium* sp. from aqueous phase,” *J. Hazard. Mater.* 153(1-2), 759-766.
- Gupta, V. K., and Rastogi, A. (2009). “Biosorption of hexavalent chromium by raw and acid-treated green alga *Oedogonium hatei* from aqueous solutions,” *J. Hazardous Mater.* 163(1), 396-402.
- Gupta, V. K., Shrivastava, A. K., and Jain, N. (2001). “Biosorption of chromium(VI) from aqueous solutions by green algae *Spirogyra* species,” *Water Res.* 35(17), 4079-4085.
- Gurgel, L. V. A., Karnitz, Jr., O., Gil, R. P. F., and Gil, L. F. (2008). “Adsorption of Cu(II), Cd(II), and Pb(II) from aqueous single metal solutions by cellulose and mercerized cellulose chemically modified with succinic anhydride,” *Bioresour. Technol.* 99(8), 3077-3083.
- Guristik, E., Arica, M. Y., Bektas, S., and Genc, O. (2004). “Comparison of the heavy metal biosorption capacity of active, heat-inactivated and NaOH-treated *Phanerochaete chrysosporium* biosorbents,” *Eng. Life Sci.* 4(1), 86-89.
- Guzel, F., Yakut, H., and Topal, G. (2008). “Determination of kinetic and equilibrium parameters of the batch adsorption of Mn(II), Co(II), Ni(II) and Cu(II) from aqueous solution by black carrot (*Daucus carota* L.) residues,” *J. Hazard. Mater.* 153(3), 1275-1287.

- Hamadi, N. K., Chen, X.-D., Farid, M. M., and Lu, M. G. Q. (2001). "Adsorption kinetics for the removal of chromium (VI) from aqueous solution by adsorbents derived from used tyres and sawdust," *Chem. Eng. J.* 84(2), 95-105.
- Han, D., Halada, G. P., Spalding, B., and Brooks, S. C. (2009). "Electrospun and oxidized cellulosic materials for environmental remediation of heavy metals in groundwater," In: *Model Cellulosic Surfaces*, Roman, M. (ed.), *ACS Symp. Ser.* 1019, Oxford Univ. Press, USA, Ch. 11, 243-257.
- Han, I., Schlautman, M. A., and Batchelor, B. (2000). "Removal of hexavalent chromium from groundwater by granular activated carbon," *Water Environ. Res.* 72(1), 29-39.
- Hanafiah, M. A. K. M., and Ngah, W. S. W. (2009). "Preparation, characterization and adsorption mechanism of Cu(II) onto protonated rubber leaf powder," *Clean Solid Air Water* 37(9), 696-703.
- Hanif, M. A., Bhatti, H. N., Ali, M. A., Asgher, M., and Bhatti, I. A. (2010). "Heavy metals tolerance and biosorption potential of white rot fungi," *Asian J. Chem.* 22(1), 335-345.
- Hanif, M. A., Nadeem, R., Zafar, M. N., Akhtar, K., and Bhatti, H. N. (2007). "Nickel (II) biosorption by *Casia fistula* biomass," *J. Hazard. Mater.* 139(2), 345-355.
- Hanna, O. T., and Sandall, O. C. (1995), *Computational Methods in Chemical Engineering*, Prentice-Hall International, N.J., 127-130.
- Harman, G., Patrick, R., and Spittler, T. (2007). "Removal of heavy metals from polluted waters using lignocellulosic agricultural waste products," *Indust. Biotechnol.* (Winter), 366-374.
- Harmita, H., Karthikeyan, K. G., and Pan, X. J. (2009). "Copper and cadmium sorption onto kraft and organosolv lignins," *Bioresour. Technol.* 100(24), 6183-6191.
- Harry, I. D., Saha, B., and Cumming, I. W. (2008). "Effect of electrochemical reduction and oxidation of a viscose rayon based activated carbon cloth for Cr(VI) sorption from aqueous solution," *Ind. Eng. Chem. Res.* 47(17), 6734-6741.
- Hasan, S. H., Ranjan, D., and Talat, M. (2009a). "'Rice polish' for the removal of arsenic from aqueous solution: Optimization of process variables," *Ind. Eng. Chem. Res.* 48(9), 4194-4201.
- Hasan, S. H., Ranjan, D., and Talat, M. (2010). "Water hyacinth biomass (WHB) for the biosorption of hexavalent chromium: Optimization of process parameters," *BioRes.* 5(2), 563-575.
- Hasan, S. H., Srivastava P., Ranjan, D., and Talat, M. (2009b). "Biosorption of Cr(VI) from aqueous solution using *A. hydrophila* in up-flow column: Optimization of process variables," *Appl. Microbiol. Biotechnol.* 83(3), 567-577.
- Hasan, S. H., Talat, M., and Rai, S. (2007). "Sorption of cadmium and zinc from aqueous solutions by water hyacinth (*Eichhornia crassipes*)," *Bioresour. Technol.* 98, 918-928.
- Hasar, H., Cuci, Y., Obek, E., and Dilekoglu, M. F. (2003). "Removal of zinc(II) by activated carbon prepared from almond husks under different conditions," *Adsorp. Sci. Technol.* 21(9), 799-808.
- Hashem, A. (2006). "Amidoximated sunflower stalks (ASFS) as a new adsorbent for removal of Cu(II) from aqueous solution," *Polymer-Plastics Technology and Engineering* 45(1), 35-42.

- Hashem, A., Abdel-Lateff, A., Farag, S., and Hussein, D. M. (2008). "Treatment of alhagi residues with tartaric acid for the removal of Zn(II) ions from aqueous solution," *Adsorp. Sci. Technol.* 26(9), 661-678.
- Hashem, A., Abdel-Halim, E. S., El-Tahlawy, K. F., and Hebeish, A. (2005a). "Enhancement of adsorption of Co (II) and Ni (II) ions onto peanut hulls through esterification using citric acid," *Adsorp. Sci. Technol.* 23(5), 367-380.
- Hashem, A., Akasha, R. A., Ghith, A., and Hussein, D. A. (2005b). "Adsorbent based on agricultural wastes for heavy metal and dye removal: A review," *Energy Edu. Sci. Technol.* 19, 69-86.
- Hashem, A., Abou-Okeil, A., El-Shafie, A., and El-Sakhawy, M. (2006a). "Grafting of high-cellulose pulp extracted from sunflower stalks for removal of Hg (II) from aqueous solution," *Polym.-Plast. Technol. Eng.* 45(1), 135-141.
- Hashem, A., Elhmmali, M. M., Hussein, H. A., and Senousi, M. A. (2006b). "Utilization of sawdust-based materials as adsorbent for wastewater treatment," *Polymer-Pastics Technol. Eng.* 45(7), 821-827.
- Hawari, A. H., and Mulligan, C. N. (2006). "Biosorption of lead(II), cadmium(II), copper(II) and nickel(II) by anaerobic granular biomass," *Bioresour. Technol.* 97(4), 692-700.
- Hawari, A. H., and Mulligan, C. N. (2006). "Heavy metals uptake mechanisms in a fixed-bed column by calcium-treated anaerobic biomass," *Process Biochem.* 41(1), 187-198.
- Heinze, T., Helbig, K., and Klemm, D. (1993). "Investigation of metal-ion adsorption of carboxymethyl cellulose gel beads," *Acta Polymerica* 44(2), 108-109.
- Hernainz, F., Calero, M., Blazquez, G., Martin-Lara, M. A., and Tenorio, G. (2008). "Comparative study of the biosorption of cadmium(II), chromium(III), and lead(II) by olive stone," *Environ. Prog.* 27(4), 469-478.
- Hernainz, F., Calero, M., Blazquez, G., Tenorio, G., and Martin-Lara, M. A. (2009). "Effect of the presence of chromium (III) on the removal of lead (II) from aqueous solutions by agricultural wastes," *J. Environ. Eng. ASCE* 135(12), 1348-1356.
- Herrero, R., Cordero, B., Lodeiro, P., Rey-Castro, C., and Sastre de Vicente, M. E. (2006). "Interactions of cadmium(II) and protons with dead biomass of marine algae *Fucus* sp.," *Mar. Chem.* 99(1-4), 106-116.
- Herrington, T. M., and Petzold, J. C. (1992). "An investigation into the nature of charge on the surface of papermaking woodpulp. 2. Analysis of potentiometric titration data," *Colloids Surf.* 64, 109-118.
- Hiemenz, P. C., and Rajagopalan, R. (1997). *Principles of Colloid and Surface Chemistry*, Marcel Dekker, New York.
- Ho, Y. S. (2003). "Removal of copper ions from aqueous solution by tree fern," *Water Res.* 37(10), 2323-2330.
- Ho, Y. S. (2004). "Second order kinetic model for sorption of cadmium onto tree fern: A comparison of linear and non-linear methods," *Wat. Res.* 40(1), 119-125.
- Ho, Y. S. (2005). "Effect of pH on lead removal from water using tree fern as the sorbent," *Bioresour. Technol.* 96(11), 1292-1296.
- Ho, Y., Huang, C. T., and Haung, H. W. (2002). "Equilibrium sorption isotherm for metal ions on tree fern," *Process Biochem.* 37(12), 1421-1430.

- Ho, Y. S., and McKay, G. (1998b). "A comparison of chemisorption kinetic models applied to pollutant removal on various sorbents," *Process Safety and Environmental Protection* 76(4), 332-340.
- Ho, Y. S., and McKay, G. (1999a). "Pseudo-second order model for sorption processes," *Process Biochem.* 34(5), 451-465.
- Ho, Y. S., and McKay, G. (1999b). "Competitive sorption of copper and nickel ions from aqueous solution using peat," *Adsorption* 5(4), 409-417.
- Ho, Y. S., and McKay, E., (2000). "The kinetics of sorption of divalent metal ions onto Sphagnum moss peat," *Water Res.* 34(3), 735-742.
- Ho, Y. S., and McKay, G. (2003). "Sorption of dyes and copper ions onto biosorbents," *Process Biochem.* 38(7), 1047-1061.
- Ho, Y. S., McKay, G., Wase, D. A. J., and Foster, C. F. (2000a). "Study of the sorption of divalent metal ions on to peat," *Adsorp. Sci. Technol.* 18(7), 639-650.
- Ho, Y. S., Ng, J. C. Y., and McKay, G. (2000b). "Kinetics of pollutant sorption by biosorbents: Review," *Separ. Purif. Methods* 29(2), 189-232.
- Ho, Y. S., and Ofomaja, A. E. (2005). "Kinetics and thermodynamics of lead ion sorption on palm kernel fibre from aqueous solution," *Proc. Biochem.* 40(11), 3455-3461.
- Ho, Y. S., and Ofomaja, A. E. (2006a). "Biosorption thermodynamics of cadmium on coconut copra meal as biosorbent," *Biochem. Eng. J.* 30(2), 117-123.
- Ho, Y. S., and Ofomaja, A. E. (2006b). "Pseudo-second-order model for lead ion sorption from aqueous solutions onto palm kernel fiber," *J. Hazardous Mater.* 129(1-3), 137-142.
- Ho, Y. S., and Ofomaja, A. E. (2006). "Kinetic studies of copper ion adsorption on palm kernel fibre," *J. Hazardous Mater.* 137(3), 1796-1802.
- Ho, Y. S., Porter, J. F., and McKay, G. (2002). "Equilibrium isotherm studies for the sorption of divalent metal ions onto peat: Copper, nickel and lead single component systems," *Water, Air, and Soil Pollution* 141, 1-33.
- Ho, Y. S., Wase, D. A. J., and Forster, C. F. (1995). "Batch nickel removal from aqueous solution by sphagnum moss peat," *Water Res.* 29(5), 1327-1332.
- Ho, Y. S., Wase, D. A. J., and Forster, C. F. (1996). "Kinetic studies of competitive heavy metal adsorption by sphagnum moss peat," *Environ. Technol.* 17(1), 71-77.
- Holan, Z. R., and Volesky, B. (1995). "Accumulation of cadmium, lead and nickel by fungal and wood biosorbents," *Appl. Environ. Microbiol.* 53(2), 133-146.
- Holan, Z. R., Volesky, B., and Prasetyo, I. (1993). "Biosorption of cadmium by biomass of marine-algae," *Biotechnology and Bioengineering* 41(8), 819-825.
- Holan, Z. R., and Volesky, B. (1995). "Accumulation of cadmium, lead and nickel by fungal and wood biosorbents," *Applied Biochemistry Biotechnology* 53(2), 133-146.
- Horikoshi, T., Nakajima, A., and Sakaguchi, T. (1981). "Studies on the accumulation of heavy metal elements in biological systems, XIX: Accumulation of uranium by microorganisms," *Eur. J. Appl. Microbiol. Biotechnol.* 12(2), 90-96.
- Horsfall, M., and Abia, A. A. (2003). "Sorption of cadmium(II) and zinc(II) ions from aqueous solutions by cassava waste biomass (*Manihot sculenta* Cranz)," *Water Res.* 37(20), 4913-4923.

- Horsfall Jr., M., Abia, A. A., and Spiff, A. I. (2006). "Kinetic studies on the adsorption of Cd^{2+} , Cu^{2+} and Zn^{2+} ions from aqueous solutions by cassava (*Manihot sculenta* Cranz) tuber bark waste," *Bioresour. Technol.* 97(2), 283-291.
- Horsfall, M., Ogban, F., and Akporhonor, E. E. (2005). "Biosorption of Pb^{2+} from aqueous solution by waste biomass of aerial roots of *Rhizophora mangle* (red mangrove)," *Chem. Biodivers.* 2(9), 1246-1255.
- Horsfall, M., and Spiff, A. I. (2004). "Studies on the effect of pH on the sorption of Pb^{2+} and Cd^{2+} ions from aqueous solutions by *Caladium bicolor* (Wild Cocoyam) biomass," *Electron. J. Biotechnol.* 7(3), 313-323.
- Horsfall, M., and Spiff, A. I. (2005a). "Effects of temperature on the sorption of Pb^{2+} and Cd^{2+} from aqueous solution by *Caladium bicolor* (Wild Cocoyam) biomass," *Electron J. Biotechnol.* 8(2), 162-169.
- Horsfall, M., and Spiff, A. I. (2005b). "Effect of 2-mercaptoethanoic acid treatment of fluted pumpkin waste (*Telfairia occidentalis* Hook. f.) on the sorption of Ni^{2+} ions from aqueous solution," *J. Sci. Indus. Res.* 64(8), 613-620.
- Horsfall, M., and Spiff, A. I. (2005c). "Sorption of lead, cadmium, and zinc on sulfur-containing chemically modified wastes of fluted pumpkin (*Telfairia occidentalis* Hook f.)," *Chem. Biodivers.* 2(3), 373-385.
- Hosea, M., Greene, B., McPherson, R., Henzl, M., Alexander, M. D., and Darnall, D. W., (1986). "Accumulation of elemental gold on alga *Chlorella vulgaris*," *Inorg. Chim. Acta* 123(3), 161-165.
- Hu, Z., Lei, L., Li, Y., and Hi, Y. (2003). "Chromium adsorption on high-performance activated carbons from aqueous solutions," *Sep. Purif. Technol.* 31(1), 13-18.
- Huang, L. Y., Ou, Z. Y., Boving, T. B., Tyson, J., and Xing, B. S., (2009). "Sorption of copper by chemically modified aspen wood fibers," *Chemosphere* 76(8), 1056-1061.
- Huang, C. P., and Wu, M. H. (1977). "The removal of chromium (VI) from dilute solution by activated carbon," *Water Res.* 11(8), 673-679.
- Igwe, J. C., Abia, A. A., and Ibeh, C. A. (2008). "Adsorption kinetics and intra-particulate diffusivities of Hg, As and Pb ions on unmodified and thiolated coconut fiber," *Int. J. Environ. Sci. Technol.* 5(1), 83-92.
- Imamoglu, M., and Tekir, O. (2008). "Removal of copper (II) and lead (II) ions from aqueous solutions by adsorption on activated carbon from a new precursor hazelnut husks," *Desalination* 228(1-3), 108-113.
- Inbaraj, B. S., Sridharan, R., Nandhakumar, V., and Sulochana, N. (2006). "Sorption of mercury(II) by an adsorbent derived from fruit shell of *Terminalia catappa*," *J. Indian Chem. Soc.* 83(5), 446-452.
- Inbaraj, B. S., and Sulochana, N. (2004). "Carbonised jackfruit peel as and adsorbent for the removal of Cd (II) from aqueous solution," *Bioresour. Technol.* 94(1), 49-52.
- Inbaraj, B. S., and Sulochana, N. (2006). "Mercury adsorption on a carbon sorbent derived from fruit shell of *Terminalia catappa*," *J. Hazardous Mater.* 133(1-3), 283-290.
- Iqbal, M., Saeed, A., and Akhtar, N. (2002). "Petiolar felt-seath of palm: A new biosorbent for the removal of heavy metals from contaminated water," *Bioresour. Technol.* 81(2), 151-153.

- Iqbal, M., and Saeed, A. (2002). "Removal of heavy metals from contaminated water by petiolar felt-sheath of palm," *Environ. Technol.* 23(10), 1091-1098.
- Iqbal, M., Saeed, A., Edyvean, R. G. J., O'Sullivan, B., and Styring, P. (2005). "Production of fungal biomass immobilized loofa sponge (FBILS)-discs for the removal of heavy metal ions and chlorinated compounds from aqueous solution," *Biotechnol. Lett.* 27(17), 1319-1323.
- Iqbal, M., Saeed, A., and Kalim, I. (2009a). "Characterization of adsorptive capacity and investigation of mechanism of Cu^{2+} , Ni^{2+} and Zn^{2+} adsorption on mango peel waste from constituted metal solution and genuine electroplating effluent," *Separation Sci. Technol.* 44(15), 3770-3791.
- Iqbal, M., Saeed, A., and Zafar, S. I. (2007). "Hybrid biosorbent: An innovative matrix to enhance the biosorption of Cd(II) from aqueous solution," *J. Hazardous Mater.* 148(1-2), 47-55.
- Iqbal, M., Saeed, A., and Zafar, S. I. (2009b). "FTIR spectrophotometry, kinetics and adsorption isotherms modeling, ion exchange, and EDX analysis for understanding the mechanism of Cd^{2+} and Pb^{2+} removal by mango peel waste," *J. Hazardous Mater.* 164(1), 161-171.
- Izquierdo, M., Gabaldon, C., Marzal, P., and Alvarez-Hornos, F. J. (2010). "Modeling of copper fixed-bed biosorption from wastewater by *Posidonia oceanica*," *Bioresour. Technol.* 101(2), 510-517.
- Jain, J. S., and Snoeyink, V. L. (1973). "Adsorption from bisolute systems on active carbon," *J. WPCF* 45(12), 2463-2479.
- Jalali-Rad, R., Ghafourian, H., Asef, Y., Dalir, S. T., Sahafipour, M. H., and Gharanjik, B. M. (2004). "Biosorption of cesium by native and chemically modified biomass of marine algae: Introduce the new biosorbents for biotechnology applications," *J. Hazard. Mater. B* 116(1-2), 125-134.
- Jalali, R., Ghafourian, H., Asef, Y., Davarpanah, S. J., and Sepehr, S. (2002). "Removal and recovery of lead using nonliving biomass of marine algae," *J. Hazard. Mater.* 92(3), 253-262.
- Jaramillo, J., Gomez-Serrano, V., and Alvarez, P. M. (2009). "Enhanced adsorption of metal ions onto functionalized granular activated carbons prepared from cherry stones," *J. Hazard. Mater.* 161(2-3), 670-676.
- Jia, Y. F., and Thomas, K. M. (2000). "Adsorption of cadmium ions on oxygen surface sites in activated carbon," *Langmuir* 16(3), 1114-1122.
- Jia, Y. F., Steele, C. J., Hayward, I. P., and Thomas, K. M. (1998). "Mechanism of adsorption of gold and silver species on activated carbons," *Carbon* 36(9), 1299-1308.
- Jia, Y. F., Xiao, B., and Thomas, K. M. (2002). "Adsorption of metal ions on nitrogen surface functional groups in activated carbons," *Langmuir* 18(2), 470-478.
- Johns, M. M., Marshall, W. E., and Toles, C. A. (1998). "Agricultural byproducts as granular activated carbons for adsorbing dissolved metals and organics," *J. Chem. Technol. Biotechnol.* 71(2), 131-140.
- Joseph, O., Rouez, M., Metivier-Pignon, H., Bayard, R., Emmanuel, E., and Gourdon, R. (2009). "Adsorption of heavy metals on to sugar cane bagasse: Improvement of

- adsorption capacities due to anaerobic degradation of the biosorbent.” *Environ. Technol.* 30(13), 1371-1379.
- Jusoh, A., Shiung, L. S., Ali, N., and Noor, M. J. M. M. (2007). “A simulation study of the removal efficiency of granular activated carbon on cadmium and lead,” *Desalination* 206(1-3), 9-16.
- Kacar, Y., Arpa, C., Tan, S., Denizli, A., Genc, O., and Arica, M. Y. (2002). “Biosorption of Hg(II) and Cd(II) from aqueous solutions: Comparison of biosorptive capacity of alginates and immobilized live and heat inactivated *Phanerochaete chrysosporium*,” *Process Biochem.* 37(6), 601-610.
- Kadirvelu, K., Faur-Brasquet, C., and Le Cloirec, P. (2000). “Removal of Cu(II), and Ni(II) by adsorption on activated carbon cloths,” *Langmuir* 16, 8404-8409.
- Kadirvelu, K., Senthilkumar, P., Thamaraiselvi, K., and Subburam, V. (2002). “Activated carbon prepared from biomass as adsorbent: Elimination of Ni(II) from aqueous solution,” *Bioresour. Technol.* 81, 87-90.
- Kadirvelu, K., Thamaraiselvi, K., and Namasivayam, C. (2001). “Removal of heavy metal from industrial wastewaters by adsorption on to activated carbon prepared from an agricultural solid waste,” *Bioresour. Technol.* 76(1), 63-65.
- Kaikake, K., Hoaki, K., Sunanda, H., Dhakal, R. P., and Baba, Y. (2007). “Removal characteristics of metal ions using degreased coffee beans: Adsorption equilibrium of cadmium(II),” *Bioresour. Technol.* 98(15), 2787-2791.
- Kalavathy, M. H., Karthikeyan, T., Rajgopal, S., and Miranda, L. R. (2005). “Kinetic and isotherm studies of Cu(II) adsorption onto H₃PO₄-activated rubber wood sawdust,” *J. Colloid Interf. Sci.* 292(2), 354-362.
- Kamel, S., Hassan, E. M., and El-Sakhawy, M. (2006). “Preparation and application of acrylonitrile-grafted cyanoethyl cellulose for the removal of copper(II) ions,” *Journal of Applied Polymer Science* 100(1), 329-334.
- Kang, H. Y., Park, S. S., and Rim, Y. S. (2006). “Preparation of activated carbon from paper mill sludge by KOH-activation,” *Kor. J. Chem. Eng.* 23(6), 948-953.
- Kannan, N., and Rengasamy, G. (2005a). “Comparison of Cd adsorption on various activated carbon,” *Water Air Soil Pollut.* 163(1-4), 185-201.
- Kannan, N., and Rengasamy, G. (2005b). “Studies on the removal of nickel(II) ions by adsorption using various carbons - A comparative study,” *Fresenius Environ. Bull.* 14(6), 435-443.
- Kapoor, A., and Viraraghavan, T. (1995). “Fungal biosorption - An alternative treatment option for heavy metal bearing wastewaters: A review,” *Biores. Technol.* 53(3), 195-206.
- Kapoor, A., and Viraraghavan, T. (1998a). “Biosorption of heavy metals on *Aspergillus niger*: Effect of pretreatment,” *Bioresour. Technol.* 63(2), 109-113.
- Kapoor, A., and Viraraghavan, T. (1997). “Heavy metal biosorption sites in *Aspergillus niger*,” *Biores. Technol.* 61(3), 221-227.
- Kapoor, A., and Viraraghavan, T. (1998b). “Removal of heavy metals from aqueous solutions using immobilized fungal biomass in continuous mode,” *Water Res.* 32(6), 1968-1977.
- Kapoor, A., Viraraghavan, T., and Cullimore, D. R. (1999). “Removal of heavy metals using the fungus *Aspergillus niger*,” *Bioresour. Technol.* 70(1), 95-104.

- Kadirvelu, K., Faur-Brasquet, C., and Le Cloirec, P. (2000). "Removal of Cu(II), and Ni(II) by adsorption activated carbon cloths," *Langmuir* 16(22), 8404-8409.
- Kalavathy, M. H., Karthikeyan, T., Rajgopal, S., and Miranda, L. R. (2005). "Kinetic and isotherm studies of Cu(II) adsorption onto H₃PO₄-activated rubber wood sawdust," *J. Colloid Interface Sci.* 292(2), 354-362.
- Karnitz, O., Gurgel, L. V. A., de Freitas, R. P., and Gil, L. F. (2009). "Adsorption of Cu(II), Cd(II), and Pb(II) from aqueous single metal solutions by mercerized cellulose and mercerized sugarcane bagasse chemically modified with EDTA dianhydride (EDTAD)," *Carbohydr. Polymers* 77(3), 643-650.
- Karnitz, O., Gurgel, L. V. A., and Gil, L. F. (2010). "Removal of Ca(II) and Mg(II) from aqueous single metal solutions by mercerized cellulose and mercerized sugarcane bagasse grafted with EDTA dianhydride (EDTAD)," *Carbohydrate Polymers* 79(1), 184-191.
- Karnitz, Jr., O., Gurgel, L. V. A., Melo, J. C. P., Botaro, V. R., Melo, T. M. S., Gil, R. P. F., and Gil, L. F. (2007). "Adsorption of heavy metal ion from aqueous single metal solution by chemically modified sugarcane bagasse," *Biores. Technol.* 98(6), 1291-1297.
- Karthikeyan, T., Rajgopal, S., and Miranda, L. R. (2005). "Chromium (VI) adsorption from aqueous solution by *Hevea brasiliensis* saw dust activated carbon," *J. Hazard. Mater.* 124(1-3), 192-199.
- Karthikeyan, K. G., Tshabalala, M. A., Wang, D., and Kalbasi, M. (2004). "Solution chemistry effects on orthophosphate adsorption by cationized solid wood residues," *Environ. Sci. Technol.* 38, 904-911.
- Karunasagar, D., Arunachalam, J., Rashmi, K., Latha, J. N. L., and Mohan, P. M. (2003). "Biosorption of inorganic and methyl mercury by a biosorbent from *Aspergillus niger*," *World J. Microbiol. Biotechnol.* 9(3), 291-295.
- Karunasagar, D., Krishna, M. V. B., Rao, S. V., and Arunachalam, J. (2005). "Removal and preconcentration of inorganic and methyl mercury from aqueous media using a sorbent prepared from the plant *Coriandrum sativum*," *J. Hazardous Mater.* 118(1-3), 133-139.
- Kelley, C., Mielke, R. E., Dimaquibo, D., Curtis, A. J., and Dewitt, J. G. (1999). "Adsorption of Eu(III) onto roots of water hyacinth," *Environ. Sci. Technol.* 33(9), 1439-1443.
- Keskinkan, O., Goksu, M. Z. L., Basibuyuk, M., and Forster, C. F. (2004). "Heavy metal adsorption properties of a submerged aquatic plant (*Ceratophyllum demersum*)," *Bioresour. Technol.* 92, 197-200.
- Khalid, N., Ahmad, S., Kiani, S. N., and Ahmed, J. (1998a). "Removal of lead from aqueous solutions using rice husk," *Sep. Sci. Technol.* 33(15), 2349-2362.
- Khalid, N., Ahmad, S., Kiani, S. N., and Ahmed, J. (1999). "Removal of mercury from aqueous solutions by adsorption to rice husks," *Separ. Sci. Technol.* 34(16), 3139-3153.
- Khalid, N., Rahman, A., Ahmad, S., Kiani, S. N., and Ahmed, J. (1998b). "Adsorption of cadmium from aqueous solutions on rice husk," *Radiochimica Acta* 83(3), 157-162.

- Khan, A. R., Al-Wahebam, I. R., and Al-Haddad, A. (1996). "A generalised equation for adsorption isotherms for multicomponent organic pollutants in dilute aqueous solution," *Envir. Technol.* 17, 13-23.
- Khan, M. N., and Wahab, M. F. (2007). "Characterization of chemically modified corncobs and its application in the removal of metal ions from aqueous solution," *J. Hazard. Mater.* 141(1), 237-244.
- Khezami, L., and Capart, R. (2005). "Removal of chromium (VI) from aqueous solution by activated carbons: Kinetic and equilibrium studies," *J. Hazard. Mater.* 123(1-3), 223-231.
- Kikuchi, Y., Qian, Q. R., Machida, M., and Tatsumoto, H. (2006). "Effect of ZnO loading to activated carbon on Pb(II) adsorption from aqueous solution," *Carbon* 44(2), 195-202.
- Kim, D. S. (2004). "Activated carbon from peach stones using phosphoric acid activation at medium temperatures," *J. Environ. Sci. Health Pt. A – Toxic/Haz. Subst. Environ. Eng.* 39(5), 1301-1318.
- Kim, Y. H., Park, J. Y., and Yoo, Y. J. (1998). "Modeling of biosorption by marine brown *Undaria pinnatifida* based on surface complexation mechanism," *Korean J. Chem. Eng.* 15(2), 157-163.
- Kim, Y. H., Park, J. Y., Yoo, Y. J., and Kwak, J. W. (1999). "Removal of lead using xanthated marine brown alga, *Undaria pinnatifida*," *Process Biochem.* 34(6-7), 647-652.
- Kim, Y. H., Park, J. Y., Yoo, Y. J., Ryoo, B. I., and Lee, W. W. (1996). "Removal of copper using marine brown alga, *Undaria pinnatifida* modified with oxime," *Biohecnol. Techniques* 10(12), 923-928.
- Kim, Y. H., Yoo, Y. J., and Lee, H. Y. (1995). "Characteristic of lead adsorption by *Undaria pinnatifida*," *Biotechnology Letters* 17(3), 345-350.
- King, P., Anuradha, K., Lahari, S. B., Kumar, Y. P., and Prasad, V. S. R. K. (2008a). "Biosorption of zinc from aqueous solution using *Azadirachta indica* bark: Equilibrium and kinetic studies," *J. Hazard. Mater.* 152(1), 324-329.
- King, P., Rakesh, N., Beenalahari, S., Kumar, Y. P., and Prasad, V. S. R. K. (2007). "Removal of lead from aqueous solution using *Syzygium cumini* L.: Equilibrium and kinetic studies," *J. Hazardous Mater.* 142(1-2), 340-347.
- King, P., Rakesh, N., Lahari, S. B., Kumar, Y. P., and Prasad, V. S. R. K. (2008b). "Biosorption of zinc onto *Syzygium cumini* L.: Equilibrium and kinetic studies," *Chem. Eng. J.* 144(2), 181-187.
- King, P., Srinivasa, P., Kumar, Y. P., and Prasad, V. S. R. K. (2006). "Sorption of copper(II) ion from aqueous solution by *Tectona grandis* l.f. (teak leaves powder)," *J. Hazard. Mater. B* 136(3), 560-566.
- Kiran, B., and Kaushik, A. (2008). "Cyanobacterial biosorption of Cr(VI): Application of two parameter and Bohart Adams models for batch and column studies," *Chem. Eng. J.* 144(3), 391-399.
- Kiran, B., Kaushik, A., and Kaushik, C. P. (2007). "Biosorption of Cr(VI) by native isolate of *Lyngbya putealis* (HH-15) in the presence of salts," *J. Hazard. Mater.* 141(3), 662-667.

- Klimmek, S., Stan, H. J., Wilke, A., Bunke, G., and Buchholz, R. (2001). "Comparative analysis of the biosorption of cadmium, lead, nickel, and zinc by algae," *Environ. Sci. Technol.* 35(21), 4283-4288.
- Klasson, K. T., Wartelle, L. H., Rodgers, J. E., and Lima, I. M. (2009). "Copper(II) adsorption by activated carbons from pecan shells: Effect of oxygen level during activation," *Indus. Crops Prod.* 30(1), 72-77.
- Kobyas, M. (2004a). "Removal of Cr(VI) from aqueous solutions by adsorption onto hazelnut shell activated carbon: Kinetic and equilibrium studies," *Bioresour. Technol.* 91(3), 317-321.
- Kobyas, M. (2004b). "Adsorption kinetics and equilibrium studies of Cr(VI) by hazelnut shell activated carbon," *Adsorp. Sci. Technol.* 22(1), 51-64.
- Kobyas, M., Demirbas, E., and Bayramoglu, M. (2004). "Modelling the effects of adsorbent dose and particle size on the adsorption of Cr(VI) ions from aqueous solutions," *Adsorp. Sci. Technol.* 22(7), 583-594.
- Kobyas, M., Demirbas, E., Senturk, E., and Ince, M. (2005). "Adsorption of heavy metal ions from aqueous solutions by activated carbon prepared from apricot stone," *Bioresour. Technol.* 96(13), 1518-1521.
- Kobyas, M., Demirbas, E., Oncel, M. S., and Sencan, S. (2002). "Adsorption kinetic models applied to nickel ions on hazelnut shell activated carbons," *Adsorp. Sci. Technol.* 20(2), 179-188.
- Kogej, A., and Pavko, A. (2001). "Comparison of *Rhizopus nigricans* in a pelleted growth form with some other types of waste microbial biomass as biosorbents for metal ions," *World J. Microbiol. Biotechnol.* 17(7), 677-685.
- Kongsuwan, A., Patnukao, P., and Pavasant, P. (2009). "Binary component sorption of Cu(II) and Pb(II) with activated carbon from *Eucalyptus camaldulensis* Dehn bark," *J. Indus. Eng. Chem.* 15(4), 465-470.
- Kostal, J., Prabhukumar, G., Lao, U. L., Chen, A., Matsumoto, M., Mulchandani, A., and Chen, W. (2005). "Customizable biopolymers for heavy metal remediation," *J. Nanopart. Res.* 7(4-5), 517-523.
- Kratochvil, D., Fourest, E., and Volesky, B. (1995). "Biosorption of copper by *Sargassum fluitans* biomass in fixed-bed column," *Biotechnol. Lett.* 17(7), 777-782.
- Kratochvil, D., Pimentel, P., and Volesky, B. (1998). "Removal of trivalent and hexavalent chromium by seaweed biosorbent," *Environ. Sci. Technol.* 32(18), 2693-2698.
- Kratochvil, D., and Volesky, B. (1998). "Advances in biosorption of heavy metals," *Trends. Biotechnol.* 16: 291-300.
- Kratochvil, D., Volesky, B., and Demopoulos, G. (1997). "Optimizing Cu removal/recovery in a biosorption column," *Water Res.* 31(9), 2327-2339.
- Kriaa, A., Hamdi, N., and Srasra, E. (2010). "Removal of Cu (II) from water pollutant with Tunisian activated lignin prepared by phosphoric acid activation," *Desalination* 250(1), 179-187.
- Krishnan, K. A., and Anirudhan, T. S. (2002a). "Removal of mercury(II) from aqueous solutions and chlor-alkali industry effluent by steam activated and sulphurised activated carbons prepared from bagasse pith: Kinetics and equilibrium studies," *J. Hazardous Mater.* 92(2), 161-183.

- Krishnan, K. A., and Anirudhan, T. S. (2002b). "Uptake of heavy metals in batch systems by sulfurized steam activated carbon prepared from sugarcane bagasse pith," *Indus. Eng. Chem. Res.* 41(20), 5085-5093.
- Krishnan, K. A., and Anirudhan, T. S. (2003). "Removal of cadmium(II) from aqueous solutions by steam-activated sulphurised carbon prepared from sugar-cane bagasse pith: Kinetics and equilibrium studies," *Water SA* 29(2), 147-156.
- Krishnan, K. A., and Anirudhan, T. S. (2008a). "Kinetic and equilibrium modelling of cobalt(II) adsorption onto bagasse pith based sulphurised activated carbon," *Chem. Eng. J.* 137(2), 257-264.
- Krishnani, K. K., and Ayyappan, S. (2006). "Heavy metals remediation of water using plants and lignocellulosic agrowastes," *Rev. Environ. Contam. Toxicol.* 188, 59-84.
- Krishnani, K. K., Meng, X. G., Christodoulatos, C., and Boddu, V. M. (2008b). "Biosorption mechanism of nine different heavy metals onto biomatrix from rice husk," *J. Hazardous Mater.* 153(3), 1222-1234.
- Krishnani, K. K., Parimala, V., and Meng, X. G. (2004). "Detoxification of chromium(VI) in coastal water using lignocellulosic agricultural waste," *Water SA* 30(4), 541-545.
- Kubota, H., and Shigehisa, Y. (1995). "Introduction of amidoxime groups into cellulose and its ability to adsorb metal ions," *Journal of Applied Polymer Science* 56, 147-151.
- Kula, I., Ugurlu, M., Karaoglu, H., and Celik, A. (2008). "Adsorption of Cd(II) ions from aqueous solutions using activated carbon prepared from olive stone by ZnCl₂ activation," *Bioresour. Technol.* 99(3), 492-501.
- Kumar, A., and Rao, N. N., and Kaul, S. N. (2000). "Alkali-treated straw and insoluble straw xanthate as low cost adsorbents for heavy metal removal – Preparation, characterization, and application," *Bioresour. Technol.* 92(2), 151-155.
- Kumar, U. (2006). "Agricultural products and by-products as a low cost adsorbent for heavy metal removal from water and wastewater: A review," *Sci. Res. Essay* 1(2), 33-37.
- Kumar, R., Bishnoi, N. R., Garima, and Bishnoi, K. (2008). "Biosorption of chromium(VI) from aqueous solution and electroplating wastewater using fungal biomass," *Chem. Eng. J.* 135(3), 202-208.
- Kumar, U., and Bandyopadhyay, M. (2006a). "Sorption of cadmium from aqueous solution using pretreated rice husk," *Bioresour. Technol.* 97(1), 104-109.
- Kumar, U., and Bandyopadhyay, M. (2006b). "Fixed bed column study for Cd(II) removal from wastewater using treated rice husk," *J. Hazardous Mater.* 129(1-3), 253-259.
- Kumar, Y. P., King, P., and Prasad, V. S. R. K. (2006a). "Equilibrium and kinetic studies for the biosorption system of copper(II) ion from aqueous solution using *Tectona grandis* L.f. leaves powder," *J. Hazard. Mater.* B137, 1211-1217.
- Kumar, Y. P., King, P., and Prasad, V. S. R. K. (2006b). "Zinc biosorption on *Tectona grandis* L.f. leaves biomass: Equilibrium and kinetic studies," *Chem. Eng. J.* 124(1-3), 63-70.
- Kumar, Y. P., King, P., and Prasad, V. S. R. K. (2006c). "Comparison for adsorption modelling of copper and zinc from aqueous solution by *Ulva fasciata* sp.," *J. Hazardous Mater.* 137(2), 1246-1251.

- Kurek, E., and Majewska, M. (2004). "In vitro remobilization of Cd immobilized by fungal biomass," *Geoderma* 122(2-4), 235-246.
- Kurniawan, T. A., Chan, G. Y. S., Lo, W.-H., and Babel, S. (2006a). "Physicochemical treatment techniques for wastewater laden with heavy metals," *Chemical Engineering Journal* 118(1-2), 83-98.
- Kurniawan, T. A., Chan, G. Y. S., Lo, W. H., and Babel, S. (2006b). "Comparison of low-cost adsorbents for treating wastewater laden with heavy metals," *Sci. Total Environ.* 366(2-3), 409-426.
- Kutahyali, C., and Eral, M. (2010). "Sorption studies of uranium and thorium on activated carbon prepared from olive stones: Kinetic and thermodynamic aspects," *J. Nuclear Mater.* 396(2-3), 251-256.
- Kuyucak, N., and Volesky, B. (1989). "Accumulation of cobalt by marine alga," *Biotechnology & Bioengineering* 33(7), 809-814.
- Lacour, S., Bollinger, J. C., Serpaud, B., Chantron, P., and Arcos, R. (2001). "Removal of heavy metals in industrial wastewaters by ion-exchanger grafted textiles," *Anal. Chim. Acta* 428(1), 121-132.
- Lalvani, S. B., Hubner, A., and Wiltowski, T. S. (2000). "Chromium adsorption by lignin," *Energy Sources*. 22(1), 45-56.
- Lalvani, S. B., Wiltowski, T., Hubner, A., Wetson, A., and Mandich, N. (1998). "Removal of hexavalent chromium and metal cations by selective and novel carbon adsorbent," *Carbon* 36(7-8), 1219-1226.
- Lalvani, S. B., Wiltowski, T. S., Murphy, D., and Lalvani, L. S. (1997). "Metal removal from process water by lignin," *Environ. Technol.* 18(11), 1163-1168.
- Langmuir, I. (1916). "The constitution and fundamental properties of solids and liquids," *J. Am. Chem. Soc.* 38, 2221-2295.
- Langmuir, I. (1918). "The adsorption of gases on plane surface of glass, mica and platinum," *J. Am. Chem. Soc.* 40, 1361-1403.
- Larous, S., Meniai, A. H., and Lehocine, M. B. (2005). "Experimental study of the removal of copper from aqueous solutions by adsorption using sawdust," *Desalination* 185(1-3), 483-490.
- Laszlo, J. A., and Dintzis, F. R. (1994). "Crop residues as ion exchange materials. Treatment of soy bean hull and sugar beet fiber (pulp.) with epichlorhydrin to improve cation exchange capacity and physical stability," *J. Appl. Polym. Sci.* 52(4), 531-538.
- Lawrance, G. A. (2010). *Introduction to Coordination Chemistry*, Wiley, Chichester, UK.
- Lee, D. C., Park, C. J., Yung, J. E., and Jeong, Y. H. (2000). "Screening of hexavalent chromium biosorbent from marine algae," *Applied Microbiology and Biotechnology* 54, 445-448.
- Lee, H. S., and Suh, J. H. (2000). "Continuous biosorption of heavy metal ions by Ca-loaded *Laminaria japonica* in fixed bed column," *Kor. J. Chem. Eng.* 17(4), 477-479.
- Lee, I. H., Kuan, Y. C., and Chern, J. M. (2007). "Equilibrium and kinetics of heavy metal ion exchange," *J. Chinese Inst. Chem. Eng.* 38(1), 71-84.
- Lee, M. G., Lim, J. H., and Kam, S. K. (2002). "Biosorption characteristics in the mixed heavy metal solution by biosorbents of marine brown algae," *Korean J. Chem. Eng.* 19(2), 277-284.

- Lee, S. H., Jung, C. H., Chung, H., Lee, M. Y., and Yang, J. W. (1998). "Removal of heavy metals from aqueous solution by apple residues," *Process Biochem.* 33(2), 205-211.
- Lee, S. H., Shon, J. S., Chung, H. S., Lee, M. Y., and Yang, J. W. (1999). "Effect of chemical modification of carboxyl groups in apple residues on metal ion binding," *Kor. J. Chem. Eng.* 16(5), 576-580.
- Lee, S.-H., and Yang, J.-W. (1997). "Removal of copper in aqueous solution by apple wastes," *Sep. Sci. Technol.* 32(8), 1371-1387.
- Lehrfeld, J. (1996). "Conversion of agricultural residues into cation exchange materials," *J. Appl. Polym. Sci.* 61(12), 2099-2105.
- Leusch, A., Holan, Z. R., and Volesky, B. (1995). "Biosorption of heavy metals (Cd, Cu, Ni, Pb, Zn) by chemically reinforced biomass of marine algae," *J. Chem. Tech. Biot.* 62(3), 279-288.
- Leyva-Ramos R., Bemal-Jacome, L. A., and Acosta-Rodriguez, I. (2005). "Adsorption of cadmium(II) from aqueous solution on natural and oxidized corncob," *Sep. Puri. Technol.* 45, 41-49.
- Leyva-Ramos, R., Bernal-Jacome, L. A., Guerrero-Coronado, R. M., and Fuentes-Rubio, L. (2001). "Competitive adsorption of Cd(II) and Zn(II) from aqueous solution onto activated carbon," *Separ. Sci. Technol.* 36(16), 3673-3687.
- Leyva-Ramos, R., Diaz-Flores, P. E., Aragon-Pina, A., Mendoza-Barron, J., and Guerrero-Coronado, R. M. (2005). "Adsorption of cadmium(II) from an aqueous solution onto activated carbon cloth," *Separ. Sci. Technol.* 40(10), 2079-2094.
- Leyva-Ramos, R., Fuentes-Rubio, L., Guerrero-Coronado, R. M., and Mendoza-Barron, J. (1995). "Adsorption of Cr(III) from aqueous solutions onto activated carbon," *J. Chem. Technol. Biotechnol.* 62(1), 64-67.
- Leyva-Ramos, R., Martinez, J., and Guerrero-Coronado, R. (1994). "Adsorption of Cr(VI) from aqueous solutions onto activated carbon," *Water Sci. Technol.* 30(9), 191-197.
- Leyva-Ramos, R., Rangel-Mendez, J. R., Mendoza-Barron, J., Fuentes-Rubio, L., and Coronado, R. M. (1997). "Adsorption of cadmium (II) from aqueous solution onto activated carbon," *Wat. Sci. Tech.* 35(7), 205-211.
- Li, C., Chen, H., and Li, Z. (2004a). "Adsorptive removal of Cr(VI) by Fe-modified steam exploded wheat straw," *Process Biochem.* 39(5), 541-545.
- Li, K., and Wang, X. (2009). "Adsorptive removal of Pb(II) by activated carbon prepared from *Spartina alterniflora*: Equilibrium, kinetics and thermodynamics," *Bioresour. Technol.* 100(11), 2810-2815.
- Li, Q., Wu, S., Liu, G., Liao, X., Deng, X., Sun, D., Hu, Y., and Huang, Y. (2004b). "Simultaneous biosorption of cadmium(II) and lead(II) ions by pretreated biomass of *Phanerochaete chrysosporium*," *Sep. Purif. Technol.* 34(1-3), 135-142.
- Li, Q., Zhai, J., Zhang, W., Wan, M., and Zhou, J. (2007). "Kinetic studies of adsorption of Pb(II), Cr(III) and Cu(II) from aqueous solution by sawdust and modified peanut husk," *J. Hazard. Mater.* 141(1), 163-167.
- Li, X., Tang, Y., Cao, X., Lu, D., Luo, F., and Shao, W. (2008). "Preparation and evaluation of orange peel cellulose adsorbents for effective removal of cadmium, zinc, cobalt and nickel," *Colloids Surf. A.* 317(1-3), 512-521.

- Li, X. M., Tang, Y. R., Xuan, Z. X., Liu, Y. H., and Luo, F. (2007). "Study on the preparation of orange peel cellulose adsorbents and biosorption of Cd(II) from aqueous solution," *Separation and Purification Technology* 55(1), 69-75.
- Li, X.-M., Liao, D.-X., Xu, X.-Q., Yang, Q., Zeng, G.-M., Zheng, W., and Guo, L., (2008). "Kinetic studies for the biosorption of lead and copper ions by *Penicillium simplicissimum* immobilized within loofa sponga," *J. Hazard. Mater.* 159(2-3), 610-615.
- Lillo-Rodenas, M. A., Cazorla-Amoros, D., and Linares-Solano, A. (2003). "Understanding chemical reactions between carbons and NaOH and KOH - An insight into the chemical activation mechanism," *Carbon* 41(2), 267-275.
- Lin, C. C., and Lai, Y. T. (2006). "Adsorption and recovery of lead(II) from aqueous solutions by immobilized *Pseudomonas aeruginosa* PU21 beads," *J. Hazard. Mater.* 137(1), 99-105.
- Lindgren, J., Öhman, L.-O., Gunnars, S., and Wågberg, L. (2002). "Charge determinations of cellulosic fibers of different origin – Comparison between different methods," *Nordic Pulp Paper Res. J.* 17(1), 89-96.
- Liou, T. H., and Wu, S. J. (2009). "Characteristics of microporous/mesoporous carbons prepared from rice husk under base- and acid-treated conditions," *J. Harard Mater.* 171(1-3), 693-703.
- Lister, S. K., and Line, M. A. (2001). "Potential utilization of sewage sludge and paper mill waste for biosorption of metals from polluted waterways," *Bioresour. Technol.* 79(1), 35-39.
- Liu, M., Deng, Y., Zhan, H., and Zhang, X. (2002). "Adsorption and desorption of copper(II) from solutions on new spherical cellulose adsorbent," *Journal of Applied Polymer Science* 84(3), 478-485.
- Liu, M., Deng, Y., Zhan, H., Zhang, X., Liu, W., and Zhan, H. (2001). "Removal and recovery of chromium(III) from aqueous solutions by a spheroidal cellulose adsorbent," *Water Environmental Research* 73(3), 322-328.
- Liu, S. X., Chen, X., Chen, X. Y., Liu, Z. F., and Wang, H. L. (2007). "Activated carbon with excellent chromium(VI) adsorption performance prepared by acid-base surface modification," *J. Hazard. Mater.* 141(1), 315-319.
- Liu, X. M., Dai, X. D., Zhang, J., Song, H., and Yan, Z. F. (2008). "Preparation of high surface area activated carbons by KOH activation promoted by alkali metal halides," *New Carbon Mater.* 23(2), 133-138.
- Lloyd-Jones, P. J., Rangel-Mendez, J. R., and Streat, M. (2004). "Mercury sorption from aqueous solution by chelating ion exchange resins, activated carbon and a biosorbent," *Process Safety Environ. Protec.* 82(B4), 301-311.
- Lo, W., Chua, H., Lam, K. H., and Bi, S. P. (1999). "A comparative investigation on the biosorption of lead by filamentous fungal biomass," *Chemosphere* 39, 2723-2736.
- Lodeiro, P., Barriada, J. L., Herrero, R., and Sastre de Vicente, M. E. (2006). "The marine microalga *Cystoseira baccata* as biosorbent for cadmium(II) and lead(II) removal: Kinetic and equilibrium studies," *Environ. Pollut.* 142(2), 264-273.
- Lodeiro, P., Cordero, B., Barriada, J. L., Herrero, R., and de Vicente, M. E. S. (2005). "Biosorption of cadmium by biomass of brown marine macroalgae," *Bioresour. Technol.* 96(16), 1796-1803.

- Lodeiro, P., Fuentes, A., Herrero, R., and de Vicente, M. E. S. (2008). "Cr-III binding by surface polymers in natural biomass: The role of carboxylic groups," *Environ. Chem.* 5(5), 355-365.
- Lodeiro, P., Herrero, R., and de Vicente, M. E. S. (2006). "Thermodynamic and kinetic aspects on the biosorption of cadmium by low cost materials: A review," *Environ. Chem.* 3(6), 400-418.
- Lohani, M. B., Singh, A., Rupainwar, D. C., and Dhar, D. N. (2008). "Studies on efficiency of guava (*Psidium guajava*) bark as bioadsorbent for removal of Hg (II) from aqueous solutions," *J. Hazard. Mater.* 159(2-3), 626-629.
- Lopez-Ramon, M. V., Stoeckli, F., Moreno-Castilla, C., and Carrasco-Marin, F. (1999). "On the characterization of acidic and basic surface sites on carbons by various techniques," *Carbon* 37(8), 1215-1221.
- Loukidou, M. X., Karapantsios, T. D., Zouboulis, A. I., and Matis, K. A. (2004a). "Diffusion kinetic study of cadmium (II) biosorption by *Aeromonas caviae*," *J. Chem. Technol. Biotechnol.* 79(7), 711-719.
- Loukidou, M. X., Zouboulis, A. I., Karapantsios, T. D., and Matis, K. A. (2004b). "Equilibrium and kinetic modeling of chromium(VI) biosorption by *Aeromonas caviae*," *Colloids Surf. A: Physicochem. Eng. Aspects* 242(1-3), 93-104.
- Low, K. S., Lee, C. K., and Lee, C. Y. (2001). "Quaternized wood as sorbent for hexavalent chromium," *Appl. Biochem. Biotech.* 90(1), 75-87.
- Low, K. S., Lee, C. K., and Lee, P. K. (1993). "Sorption of copper by dye-treated oil palm fibers," *Bioresour. Technol.* 44(2), 109-112.
- Low, K. S., Lee, C. K., and Lee, P. L. (1997). "Chromium(III) sorption enhancement through NTA - Modification of biological materials," *Bull Environ. Contam. Toxic* 58(3), 380-386.
- Low, K. S., Lee, C. K., and Leo, A. C. (1995a). "Removal of metals from electroplating wastes using banana pith," *Bioresour. Technol.* 51(2-3), 227-231.
- Low, K. S., Lee, C. K., and Liew, S. C. (2000). "Sorption of cadmium and lead from aqueous solutions by spent grain," *Process Biochem.* 36(1-2), 59-64.
- Low, K. S., Lee, C. K., and Mak, S.M. (2004). "Sorption of copper and lead by citric acid modified wood," *Wood Science and Technology* 38, 629-640.
- Low, K. S., Lee, C. K., and Tai, C. H. (1994). "Biosorption by water hyacinth roots," *J. Environ. Sci. Heal.* A29(1), 171-188.
- Low, K. S., Lee, C. K., Wong, S. Y., and Tang, P. L. (2000). "Metal sorption enhancement of rice hull through chemical modification," *Environ. Technol.* 21(11), 1239-1244.
- Low, K. S., Lee, C. K., and Yong, S. L. (1995b). "Effect of dye modification on the sorption of copper by coconut husk," *Environ. Technol.* 16(9), 877-883.
- Lu, G. Q., Low, J. C. F., Lin, C. Y., and Lua, A. C. (1995). "Surface area development of sewage sludge during pyrolysis," *Fuel* 74(3), 344-348.
- Lu, S., and Gibb, S. W. (2008). "Copper removal from wastewater using spent-grain as biosorbent," *Bioresour. Technol.* 99(6), 1509-1517.
- Luef, E., Prey, T., and Kubicek, C. P. (1991). "Biosorption of zinc by fungal mycelial wastes," *Appl. Microbiol. Biotechnol.* 34(5), 688-692.

- Luo, F., Liu, Y. H., Li, X. M., Xuan, Z. X., and Ma, J. T. (2006). "Biosorption of lead ion by chemically-modified biomass of marine brown algae *Laminaria japonica*," *Chemosphere* 64(7), 1122-1127.
- Luoma, S. N., and Rainbow, P. S. (2008). *Metal Contamination in Aquatic Environments: Science and Lateral Managment*, Cambridge Univ. Press, New York.
- Lyubchik, S. I., Lyubchik, A. I., Galushko, O. L., Tikhonova, L. P., Vital, J., Fonseca, I. M., and Lyubchik, S. B. (2004). "Kinetics and thermodynamics of the Cr(III) adsorption on the activated carbon from co-mingled wastes," *Colloids Surf. A – Physicochem. Eng. Aspects* 242(1-3), 151-158.
- Ma, W., and Tobin, J. M. (2004). "Determination and modeling of effects of pH on peat biosorption on chromium, copper and cadmium," *Biochem. Eng. J.* 18(1), 33-40.
- Macchi, G., Marani, D., and Tirivanti, G. (1986). "Uptake of mercury by exhausted coffee grounds," *Environ. Technol. Lett.* 7(8), 431-444.
- Machado, R., Carvalho, J. R. M., and Correia, J. N. (2002). "Removal of trivalent chromium(III) from solution by biosorption in cork powder," *J. Chem. Technol. Biotechnol.* 77(12), 1340-1348.
- Machida, M., Kikuchi, Y., Aikawa, M., and Tatsumoto, H. (2004). "Kinetics of adsorption and desorption of Pb(II) in aqueous solution on activated carbon by two-site adsorption model," *Colloids Surf. A* 240(1-3), 179-186.
- Macias-Garcia, A., Gomez-Serrano, V., Alexandre-Franco, M. F., and Valenzuela-Calahorro, C. (2003). "Adsorption of cadmium by sulphur dioxide treated activated carbon," *J. Hazard. Mater.* 103(1-2), 141-152.
- Macias-Garcia, A., Valenzuela-Calahorro, C., Espinosa-Mansilla, A., Bernalte-Garcia, A., and Gomez-Serrano, V. (2004). "Adsorption of Pb²⁺ in aqueous solution by SO₂-treated activated carbon," *Carbon* 42(8-9), 1755-1764.
- Madrid, Y., and Camara, C. (1997). "Biological substrates for metal preconcentration and speciation," *Trac-Trends Anal Chem* 16(1), 36-44.
- Maekawa, E., and Koshijima, T. (1984). "Properties of 2,3-dicarboxy cellulose combined with various metallic ions," *Journal of Applied Polymer Science* 29(7), 2289-2297.
- Maekawa, E., and Koshijima, T. (1990). "Preparation and characterisation of hydroxamic acid derivatives and its metal complexes derived from cellulose," *Journal of Applied Polymer Science* 40(9-10), 1601-1613.
- Malik, D. J., Strelko, V., Streat, M., and Puziy, A. M. (2002). "Characterisation of novel modified active carbons and marine algal biomass for the selective adsorption of lead," *Water Res.* 36(6), 1527-1538.
- Malik, U. R., Hasany, S. M., and Subhani, M. S. (2005). "Sorpitive potential of sunflower stem for Cr(III) ions from aqueous solutions and its kinetic and thermodynamic profile," *Talanta* 66(1), 166-173.
- Malik, U. R., Hasany, S. M., and Subhani, M. S. (2006). "Sunflower stem: A novel and economical scavenger for Hg(II) ions from aqueous solutions and its kinetic and thermodynamic investigation," *Radiochimica Acta* 94(3), 153-159; "Sunflower stem: a novel and economical scavenger for Hg(II) ions from aqueous solutions and its kinetic and thermodynamic investigation (vol 94, pg 153, 2006)," *Radiochimica Acta* 94(5), 300.

- Malkoc, E. (2006). "Ni(II) removal from aqueous solutions using cone biomass of *Thuja orientalis*," *J. Hazard. Mater.* 137(2), 899-908.
- Malkoc, E., and Nuhoglu, Y. (2003). "The removal of chromium(VI) from synthetic wastewater by *Ulothrix zonata*," *Fresenius Environ. Bull.* 12(4), 376-381.
- Malkoc, E., and Nuhoglu, Y. (2005). "Investigation of Ni II removal from aqueous solutions using tea factory waste," *J. Hazard. Mater.* B127(1-3), 120-128.
- Malkoc, E., and Nuhoglu, Y. (2006a). "Fixed bed studies for the sorption of chromium(VI) onto tea factory waste," *Chem. Eng. Sci.* 61(13), 4363-4372.
- Malkoc, E., and Nuhoglu, Y. (2006b). "Removal of Ni(II) ions from aqueous solutions using waste of tea factory: Adsorption on a fixed-bed column," *J. Hazardous Mater.* 135(1-3), 328-336.
- Malkoc, E., and Nuhoglu, Y. (2007a). "Determination of kinetic and equilibrium parameters of the batch adsorption of Cr(VI) onto waste acorn of *Quercus ithaburensis*," *Chem. Eng. Processing* 46(10), 1020-1029.
- Malkoc, E., and Nuhoglu, Y. (2007b). "Potential of tea factory waste for chromium(VI) removal from aqueous solutions: Thermodynamic and kinetic studies," *Separ. Purif. Technol.* 54(3), 291-298.
- Malkoc, E., Nuhoglu, Y., and Abali, Y. (2006a). "Cr(VI) adsorption by waste acorn of *Quercus ithaburensis* in fixed beds: Prediction of breakthrough curves," *Chem. Eng. J.* 119(1), 61-68.
- Malkoc, E., Nuhoglu, Y., and Dundar, M. (2006b). "Adsorption of chromium(VI) on pomace – An olive oil industry waste: Batch and column studies," *J. Hazard. Mater.* 138(1), 142-151.
- Mameri, N., Boudries, N., Addour, L., Belhocine, D., Lounici, H., Grib, H., and Paus, A. (1999). "Batch zinc biosorption by a bacterial nonliving *Streptomyces rimosus* biomass," *Water Res.* 33(6), 1347-1354.
- Manju, G. N., Raji, C., and Anirudhan, T. S. (1998). "Evaluation of coconut husk carbon for the removal of arsenic from water," *Water Res.* 32(10), 3062-3070.
- Maranon, E., and Sastre, H. (1991a). "Heavy metal removal in packed beds using apple wastes," *Bioresour. Technol.* 38(1), 39-43.
- Maranon, E., and Sastre, H. (1991b). "Ion-exchange equilibria of heavy metals onto chemically modified apple residues," *Solvent Extraction Ion Exchange* 9(3), 515-531.
- Maranon, E., and Sastre, H. (1991c). "Preparation of cation exchangers from apple residues. 2. Exchange properties," *Afinidad* 48(434), 255-258.
- Maranon, E., and Sastre, H. (1992a). "Behavior of lignocellulosic apple residues in the sorption of trace metals in packed beds," *Reactive Polymers* 18(2), 173-176.
- Maranon, E., and Sastre, H. (1992b). "Preconcentration and removal of trace metals from water by apple waste," *Bioresour. Technol.* 40(1), 73-76.
- Maranon, E., Contreras, A., and Sastre, H. (1991). "Preparation of cation exchangers from apple residues. 1. Treatments and characterization," *Afinidad* 48(433), 180-182.
- Marchetti, V., Clement, A., Gerardin, P., and Loubinoux, B. (2000a). "Synthesis and use of esterified sawdusts bearing carboxyl group for removal of cadmium(II) from water," *Wood Sci. Technol.* 34(2), 167-173.

- Marchetti, M., Clement, A., Loubinoux, B., and Gerardin, P. (2000b). "Decontamination of synthetic solutions containing heavy metals using chemically modified sawdusts bearing polyacrylic acid chains," *Journal of Wood Science* 46(4), 331-333.
- Marin, J., and Ayele, J. (2002). "Removal of some heavy metal cations from aqueous solutions by spruce sawdust. I. Study of the binding mechanism through batch experiments," *Environ. Technol.* 23(10), 1157-1171.
- Marin, J., and Ayele, J. (2003). "Removal of some heavy metal cations from aqueous solutions by spruce sawdust. II. Adsorption-desorption through column experiments," *Environ. Technol.* 24(4), 491-502.
- Marshall, W. E., and Johns, M. M. (1996). "Agricultural byproducts as metal adsorbents: Sorption properties and resistance to mechanical abrasion," *J. Chem. Tech. Biotechnol.* 66(2), 192-198.
- Marshall, W. E., and Wartelle, L. H. (2006). "Chromate (CrO_4^{2-}) and copper (Cu^{2+}) adsorption by dual-functional ion exchange resins made from agricultural by-products," *Water Research* 40 (13), 2541-2548.
- Marshall, W. E., Wartelle, L. H., and Akin, D. E. (2007). "Flax shive as a source of activated carbon for metals remediation," *BioResources* 2(1), 82-90.
- Marshall, W. E., Wartelle, L. H., Boler, D. E., John, M. M., and Toles, C. A. (1999). "Enhanced metal adsorption by soybean hulls modified with citric acid," *Bioresour. Technol.* 69(3), 263-268.
- Martínez, M., Miralles, N., Hidalgo, S., Fiol, N., Villaescusa, I., and Poch, J. (2006a). "Removal of lead(II) and cadmium(II) from aqueous solutions using grape stalk waste," *J. Hazard. Mater. B* 133, 203-211.
- Martinez-Garcia, G., Bachmann, R. T., Williams, C. J., Burgoyne, A., and Edyvean, R. G. J. (2006b). "Olive oil waste as a biosorbent for heavy metals," *Internat. Biodeter. Biodegrad.* 58(3-4), 231-238.
- Martin-Lara, M. A., Hernainz, F., Calero, M., Blazquez, G., and Tenorio, G. (2009). "Surface chemistry evaluation of some solid wastes from olive-oil industry used for lead removal from aqueous solutions," *Biochem. Eng. J.* 44(2-3), 151-159.
- Martin-Lara, M. A., Pagnanelli, F., Mainelli, S., Calero, M., and Toro, L. (2008). "Chemical treatment of olive pomace: Effect on acid-basic properties and metal biosorption capacity," *J. Hazardous Mater.* 156(1-3), 448-457.
- Mata, Y. N., Blazquez, M. L., Ballester, A., Gonzalez, F., and Munoz, J. A. (2008). "Characterization of the biosorption of cadmium, lead and copper with the brown alga *Fucus vesiculosus*," *J. Hazardous Mater.* 158(2-3), 316-323.
- Matheickal, J. T., and Yu, Q. M. (1999). "Biosorption of lead (II) and copper (II) from aqueous solutions by pre-treated biomass of Australian marine algae," *Bioresour. Technol.* 69(3), 223-229.
- Matheickal, J. T., Yu, Q., and Woodburn, G. M. (1999). "Biosorption of cadmium from aqueous solutions by pre-treated biomass of marine alga *Duruvillaea potatorum*," *Wat. Res.* 33(2), 335-342.
- McKay, G., Allen, S. J., and McConvey, I. F. (1984). "The adsorption of dyes from solution – Equilibrium and column studies," *Water, Air, and Soil Pollut.* 21, 127-129.
- Mehta, S. K., and Gaur, J. P. (2005). "Use of algae for removing heavy metal ions from wastewater," *Crit. Rev. Biotechnol.* 25(3), 113-152.

- Melo, J. S., and D'Souza, S. F. (2004). "Removal of chromium by mucilaginous seeds of *Ocimum basilicum*," *Bioresour. Technol.* 92(2), 151-155.
- Mengistie, A. A., Rao, T. S., Rao, A. V. P., and Singanan, M. (2008). "Removal of lead(II) ions from aqueous solutions using activated carbon from *Militia ferruginea* plan leaves," *Bull. Chem. Soc. Ethiopia* 22(3), 349-360.
- Merdy, P., Guillon, E., Aplincourt, M., and Duomonceau, J. (2000). "Interaction of metallic cations with lignins, Part 1: Stability of iron (III), manganese (II) and copper (II) complexes with phenolic lignin model compounds: coumaric, ferulic and sinapic acids and coniferyl alcohol," *J. Chem. Res. S* (2), 76-77.
- Merdy, P., Guillon, E., Aplincourt, M., Dumonceau, J., and Vezin, H. (2002). "Copper sorption on a straw lignin: Experiments and EPR characterization," *J. Colloid Interf. Sci.* 245(1), 24-31.
- Merdy, P., Guillon, E., Frapart, Y. M., and Aplincourt, M. (2003). "Iron and manganese surface complex formation with extracted lignin. Part 2: Characterisation of magnetic interaction between transition metal and quinonic radical by EPR microwave power saturation experiments," *New J. Chem.* 27(3), 577-582.
- Meunier, N., Blais, J. F., and Tyagi, R. D. (2002). "Selection of a natural sorbent to remove toxic metals from acidic leachate produced during soil decontamination," *Hydrometallurgy* 67(1-3), 19-30.
- Meunier, N., Blais, J. F., and Tyagi, R. D. (2003a). "Selectivity of cococa shells for removal of metals from soil decontamination effluents," *J. Environ. Eng. Sci.* 2(1), 1-8.
- Meunier, N., Laroulandie, J., Blais, J. F., and Tyagi, R. D. (2003b). "Lead removal from acidic solutions by sorption on cocoa shells: Effect of some parameters," *J. Environ. Eng. ASCE* 129(8), 693-698.
- Michie, R. I. (1961). "Sorption of copper by cellulose," *Nature* 190(477), 803-805.
- Milenkovic, D. D., Dasic, P. V., and Veljkovic, V. B. (2009). "Ultrasound-assisted adsorption of copper(II) ions on hazelnut shell activated carbon," *Ultrason. Sonochem.* 16(4), 557-563.
- Min, S. H., Han, J. S., Shin, E. W., and Park, J. K. (2004). "Improvement of cadmium ion removal by base treated juniper fiber," *Water Res.* 38(5), 1289-1295.
- Mise, S. R., and Shantha, G. M. (1993). "Adsorption studies of chromium(VI) from synthetic aqueous solution by activated carbon derived from bagasse," *J. Environ. Sci. Heath. Pt. A – Environ. Sci. Eng. Toxic Hazard. Subst. Control* 28(10), 2263-2280.
- Mishra, S. P., Prasad, S. K., Dubey, R. S., Mishra, M., Tiwari, D., and Lee, S. M. (2007). "Biosorptive behaviour of rice hulls for Cs-134 from aqueous solutions: A radiotracer study," *Appl. Radiation Isotopes* 65(3), 280-286.
- Mishra, S. P., Tiwari, D., Dubey, R. S., and Mishra, M. (1998). "Removal behaviour of rice (*Oryza sativa*) hulls for submicro concentrations of Hg^{2+} and Cr^{3+} from aqueous solutions: A radiotracer study," *Radiochem. Acta* 80(1), 47-52.
- Mishra, S. P., Tiwari, D., Prasad, S. K., Dubey, R. S., and Mishra, M. (2007). "Biosorptive behavior of mango (*Mangifera indica*) and neem (*Azadirachta indica*) barks for Cs-134 from aqueous solutions: A radiotracer study," *J. Radioanal. Nucl. Chem.* 272(2), 371-379.

- Mistova, E., Parschova, H., and Matejka, Z. (2007). "Selective sorption of metal oxoanions from dilute solution by bead cellulose sorbent," *Separation Sci. Technol.* 42(6), 1231-1243.
- Mistova, E., Parschova, H., Jelinek, L., Matejka, Z., Plichta, Z., and Benes, M. (2008). "Selective sorption of metal oxoanions from dilute solution by chemically modified brown seaweed *Ascophyllum nodosum*," *Separation Sci. Technol.* 43(11-12), 3168-3182.
- Miyauchi, T., Kuroki, K., Ishikawa, N., Takahashi, M., and Mori, H. (2007). "Preparation and characterization of cation exchanger based on woody biomass modified by synthetic polymer," *Bunseki Kagaku* 56(1), 9-15.
- Modak, J. M., and Natarajan, K. A. (1995). "Biosorption of metals using nonliving biomass - A review," *Miner. Metall. Proc.* 12(4), 189-196.
- Modak, J. M., Natarajan, K. A., and Saha, B. (1996). "Biosorption of copper and zinc using waste *Aspergillus niger* biomass," *Miner. Metall. Process* 13(2), 52-57.
- Mohammad, A., Ajmal, M., Yousuf, R., and Ahmed, A. (1997). "Adsorption of Cu(II) from water on the seed and seed shell of *Mangifera indica* (Mango)," *Ind. J. Chem. Technol.* 4(5), 223-227.
- Mohan, D., and Pittman, C. U. (2006). "Activated carbons and low cost adsorbents for remediation of tri- and hexavalent chromium from water," *J. Hazardous Mater.* 137(2), 762-811.
- Mohan, D., and Pittman, C. U. (2007). "Arsenic removal from water/wastewater using adsorbents – A critical review," *J. Hazard. Mater.* 142(1-2), 1-53.
- Mohan, D., Pittman, C. U., Bricka, M., Smith, F., Yancey, B., Mohammad, J., Steele, P. H., Alexandre-Franco, M. F., Gomez-Serrano, V., and Gong, H. (2007). "Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production," *J. Colloid Interface Sci.* 310(1), 57-73.
- Mohan, D., Pittman Jr., C. U., and Steele, P. H. (2006). "Single, binary and multi-component adsorption of copper and cadmium from aqueous solutions on kraft lignin – A biosorbent," *J. Colloid Interface Sci.* 297(2), 489-504.
- Mohan, D., Pittman, C. U., and Steele, P. H. (2006). "Pyrolysis of wood/biomass for bio-oil: A critical review," *Energy & Fuels* 20(3), 848-889.
- Mohan, D., and Singh, K. P. (2002). "Single- and multi-component adsorption of cadmium and zinc using activated carbon derived from bagasse-an agricultural waste," *Wat. Res.* 36(9), 2304-2318.
- Mohan, D., Singh, K. P., and Singh, V. K. (2005). "Removal of hexavalent chromium from aqueous solution using low-cost activated carbons derived from agricultural waste materials and activated carbon fabric cloth," *Ind. Eng. Chem. Res.* 44(4), 1027-1042.
- Mohan, D., Singh, K. P., and Singh, V. K. (2006). "Trivalent chromium removal from wastewater using low cost activated carbon derived from agricultural waste material and activated carbon fabric cloth," *J. Hazardous Mater.* 135(1-3), 280-295.
- Mohan, S., and Sreelakshmi, G. (2008). "Fixed bed column study for heavy metal removal using phosphate treated rice husk," *J. Hazard. Mater.* 153(1-2), 75-82.
- Mohanty, K., Jha, M., Biswas, M. N., and Meikap, B. C. (2005). "Removal of chromium (VI) from dilute aqueous solutions by activated carbon developed from *Terminalia*

- arjuna* nuts activated with zinc chloride,” *Chem. Eng. Sci.* 60(11), 3049-3059.
- Mohanty, K., Jha, M., Meikap, B. C., and Biswas, M. N. (2006). “Biosorption of Cr(VI) from aqueous solutions by *Eichhornia crassipes*,” *Chem. Eng. J.* 117(1), 71-77.
- Montanher, S. F., Oliveira, E. A., and Rollemberg, M. C. (2005). “Removal of metal ions from aqueous solutions by sorption onto rice bran,” *J. Hazard. Mater. B* 117(2-3), 207-211.
- Mor, S., Ravindra, K., and Bishnoi, N. R. (2007). “Adsorption of chromium from aqueous solution by activated alumina and activated charcoal,” *Bioresour. Technol.* 98, 954-957.
- Mouni, L., Merabet, D., Bouzaza, A., and Belkhiri, L. (2010). “Removal of Pb^{2+} and Zn^{2+} from the aqueous solutions by activated carbon prepared from dates stone,” *Desal. Water Treat.* 16(1-3), 66-73.
- Mugisidi, D., Rinaldo, A., Soedarsono, J. W., and Hikam, M. (2007). “Modification of activated carbon using sodium acetate and its regeneration using sodium hydroxide for the adsorption of copper from aqueous solution,” *Carbon* 45(5), 1081-1084.
- Mungasavalli, D. P., Viraraghavan, T., and Jin, Y. C., (2007). “Biosorption of chromium from aqueous solutions by pretreated *Aspergillus niger*: Batch and column studies,” *Colloids Surf. A: Physicochem. Eng. Aspects* 301(1-3), 214-223.
- Muraleedharan, T. R., and Venkobachar, C. (1990). “Mechanism of biosorption of copper (II) by *Ganoderma lucidum*,” *Biotechnology & Bioengineering* 35(3), 320-325.
- Murphy, V., Hughes, H., and McLoughlin, P. (2007). “Cu(II) binding by dried biomass of red, green and brown macroalgae,” *Water Res.* 41(4), 731-740.
- Murphy, V., Hughes, H., and McLoughlin, P. (2008). “Comparative study of chromium biosorption by red, green and brown seaweed biomass,” *Chemosphere* 70(6), 1128-1134.
- Murphy, V., Hughes, H., and McLoughlin, P. (2009a). “Enhancement strategies for Cu(II), Cr(III) and Cr(VI) remediation by a variety of seaweed species,” *J. Hazardous Mater.* 166(1), 318-326.
- Murphy, V., Tofail, S. A. M., and Hughes, H., and McLoughlin, P. (2009b). “A novel study of hexavalent chromium detoxification by selected seaweed species using SEM-EDX and XPS analysis,” *Chem. Eng. J.* 148(2-3), 425-433.
- Murugan, M., and Subramanian, E. (2003). “Biosorbent *Cupressus* female cone in the efficient treatment of effluent containing Cr(VI),” *Journal of Scientific and Industrial Research* 62, 1071-1078.
- Mussatto, S. I., Fernandes, M., Rocha, G. J. M., Orfao, J. J. M., Teixeira, J. A., and Roberto, I. C. (2010). “Production, characterization and application of activated carbon from brewer's spent grain lignin,” *Bioresour. Technol.* 101(7), 2450-2457.
- Muthukumaran, K., and Balasubramanian, N., and Ramakrishna, T. V. (1995). “Removal and recovery of chromium from plating waste using chemically activated carbon,” *Metal Finishing* 93(11), 46-53.
- Nada, A. A. M. A., Alkady, M. Y., and Fekry, H. M. (2007a). “Synthesis and characterization of grafted cellulose used in water and metal ions sorption,” *BioResources* 3(1), 46-59.

- Nada, A. M. A., Eid, M. A., El Bahnasawy, R. M., and Khalifa, M. N. (2002a). "Preparation and characterization of cation exchangers from agricultural residues," *J. Appl. Polymer Sci.* 85(4), 792-800.
- Nada, A. M. A., Eid, M. A., Sabry, A., and Khalifa, M. N. (2003). "Preparation and some applications of phosphosulfonated bagasse and wood cation exchangers," *J. Appl. Polym. Sci.* 90(1), 1250-1258.
- Nada, A. M. A., Eid, M. A., El-Bahnsawy, R. M., and Khalifa, M. N. (2002b). "Preparation and characterization of cation exchangers from agricultural residue," *J. Appl. Poly, Sci.* 85(4), 792-800.
- Nada, A. M. A., El-Mongy, S. A., and El-Sayed, E. S. A. (2009a). "Effect of different treatments on cellulose toward carboxylation and its application for metal ion absorption," *BioResources* 4(1), 80-93.
- Nada, A. M. A., El-Sherif, S., Nasr, A., and Kamel, M. (2007b). "Infrared spectroscopic and thermal analysis of prepared cation exchangers from cellulose materials," *J. Mol. Structure* 841(1-3), 1-6.
- Nada, A. M. A., and El-Wakil, N. A. (2006). "Molecular structure and ion exchange of amidoximate cellulosic materials," *J. Appl. Polym. Sci.* 102(1), 303-311.
- Nada, A. M. A., El-Wakil, N., Hassan, M. L., and Adel, A. (2006). "Differential adsorption of heavy metal ions by cotton stalks cation-exchangers containing multiple functional groups," *J. Appl. Polym. Sci.* 101(6), 4124-4132.
- Nada, A. M. A., Hamed, S. S., Soliman, S. I., and El-Mongy, S. (2005). "Spectroscopic and ion exchange studies on modified cotton linters," *J. Sci. & Ind. Res.* 64, 1003.
- Nada, A. M. A., and Hassan, M. L. (2003). "Phosphorylated cation exchangers from cotton stalks and its constituents," *J. Appl. Polym. Sci.* 89(11) 2950-2956.
- Nada, A. M. A., and Hassan, M. (2006). "Ion exchange properties of carboxylated bagasse," *J. Appl. Polym. Sci.* 102(2), 1399-1404.
- Nada, A. M. A., Hassan, M. L., and Adel, A. (2008). "Application of phosphorylated chitin and wood pulp for removal of heavy metal ions," *O Papel* 69(8), 84-97.
- Nada, A. M. A., Kassem, N. F., and Mohamed, S. H. (2008). "Characterization and properties of ion exchangers produced from lignin precipitated after peroxyacid pulping," *BioResources* 3(2), 538-548.
- Nada, A. A. M. A., Mahdy, A. A., and El-Gendy, A. A. (2009b). "Spectroscopy and chemical studies of cationic exchangers prepared from corn cobs," *BioResources* 4(3), 1017-1031.
- Naddafi, K., Nabizadeh, R., Saeedi, R., Mahvi, A. H., Vaezi, F., Yaghmaeian, K., Ghasri, A., and Nazmara, S. (2007). "Biosorption of lead(II) and cadmium(II) by protonated *Sargassum glaucescens* biomass in a continuous packed bed column," *J. Hazardous Mater.* 147(3), 785-791.
- Nadeem, M., Mahmood, A., Shahid, S. A., Shah, S. S., Khalid, A. M., and McKay, G. (2006). "Sorption of lead from aqueous solution by chemically modified carbon adsorbents," *J. Hazard. Mater.* 138(3), 604-613.
- Nakajima, A., and Baba, Y. (2004). "Mechanism of hexavalent chromium adsorption by persimmon tannin gel," *Water Res.* 38(12), 2859-2864.
- Nakajima, A., and Tsuruta, T. (2004). "Competitive biosorption of thorium and uranium by *Micrococcus luteus*," *J. Radioanal. Nucl. Chem.* 260(1), 13-18.

- Nakajima, A., Yasuda, M., Yokoyama, H., Ohya-Nishiguchi, H., and Kamada, H. (2001). "Copper biosorption by chemically treated *Micrococcus luteus* cells," *World J. Microbiol. Biotechnol.* 17(4), 343-347.
- Namasivayam, C., and Kadirvelu, K. (1997). "Agricultural solid wastes for the removal of heavy metals: Adsorption of Cu(II) by coirpith carbon," *Chemosphere* 34(2), 377-399.
- Namasivayam, C., and Kadirvelu, K. (1999). "Uptake of mercury (II) from wastewater by activated carbon from an unwanted agricultural solid by-product: coirpith," *Carbon* 37(1), 79-84.
- Namasivayam, C., and Periasamy, K. (1993). "Bicarbonate-treated peanut hull carbon for mercury(II) removal from aqueous solution," *Water Res.* 27(11), 1663-1668.
- Namasivayam, C., and Sureshkumar, M. V., (2008). "Removal of chromium(VI) from water and wastewater using surfactant modified coconut coir pith as a biosorbent," *Bioresour. Technol.* 99(7), 2218-2225.
- Namasivayam, C., and Sureshkumar, M. V. (2009). "Removal and recovery of molybdenum from aqueous solutions by adsorption onto surfactant-modified coir pith, a lignocellulosic polymer," *Clean – Soil Air Water* 37(1), 60-66.
- Namasivayam, C., and Yamuna, R. T. (1995a). "Adsorption of chromium(VI) by low-cost adsorbent: Biogas residual slurry," *Chemosphere* 30(3), 561-578.
- Namasivayam, C., and Yamuna, R. T. (1995b). "Waste biogas residual slurry as an adsorbent for the removal of Pb(II) from aqueous solution and radiator manufacturing industry waste water," *Bioresour. Technol.* 52(2), 125-131.
- Namasivayam, C., and Yamuna, R. T. (1999). "Studies on chromium (III) removal from aqueous solution by adsorption onto biogas residual slurry and its application to tannery wastewater treatment," *Water Air Soil Pollution* 133(1-4), 371-384.
- Nasir, M. H., Nadeem, R., Akhtar, K., Hanif, M. A., and Khalid, A. M. (2007). "Efficacy of modified distillation sludge of rose (*Rosa centifolia*) petals for lead and zinc removal from aqueous solutions," *J. Hazard. Mater.* 147(3), 1006-1014.
- Navarro, R. R., Sumi, K., and Matsumura, M. (1999). "Improved metal affinity of chelating adsorbents through graft polymerization," *Water Research* 33(9), 2037-2044.
- Navarro, R. R., Sumi, K., Fujii, N., and Matsumura, M. (1996). "Mercury removal from wastewater using porous cellulose carrier modified with polyethyleneimine," *Water Research* 30(10), 2488-2494.
- Navarro, R., Tatsumi, K., Sumi, K., and Matsumura, M. (2001). "Role of anions on heavy metal sorption of a cellulose modified with poly(glycidyl methacrylate) and polyethyleneimine," *Water Res.* 35(11), 2724-2730.
- Netzer, A., and Hughes, D. E. (1984). "Adsorption of copper, lead and cobalt by activated carbon," *Water Res.* 18(8), 927-933.
- Ngah, W. S. W., and Hanafiah, M. A. K. M. (2008a). "Adsorption of copper on rubber (*Hevea brasiliensis*) leaf powder: Kinetic, equilibrium and thermodynamic studies," *Biochem. Eng. J.* 39(3), 521-530.
- Ngah, W. S. W., and Hanafiah, M. A. K. M. (2008b). "Biosorption of copper ions from dilute aqueous solutions on base treated rubber (*Hevea brasiliensis*) leaves powder:

- kinetics, isotherm, and biosorption mechanisms,” *J. Environ. Sci. – China* 20(10), 1168-1176.
- Ngah, W. S. W., and Hanafiah, M. A. K. M. (2009). “Surface modification of rubber (*Hevea brasiliensis*) leaves for the adsorption of copper ions: Kinetic, thermodynamic and binding mechanisms,” *J. Chem. Technol. Biotech.* 84(2), 192-201.
- Ninham, B. W., and Lo Nostro, P. (2010). *Molecular Forces and Self Assembly: In Colloid, Nano Sciences and Biology*, Cambridge Univ. Press, Cambridge, UK.
- Niu, H., Xu, X. S., Wang, J. H., and Volesky, B. (1993). “Removal of lead from aqueous solutions by *Penicillium* biomass,” *Biotechnol. Bioeng.* 42(6), 785-787.
- Nomanbhay, S. M., and Palanisamy, K. (2005). “Removal of heavy metal from industrial wastewater using chitosan coated oil palm shell charcoal,” *Electron. J. Biotechnol.* 8(1), 43-53.
- Nourbakhsh, M., Sag, Y., Özer, D., Aksu, Z., Kutsal, T., and Caglar, A. (1994). “A comparative study of various biosorbents for removal of chromium(VI) ions from industrial wastewaters,” *Process Biochem.* 29(1), 1-5.
- Nouri, L., Ghodbane, I., Hamdaoui, O., and Chiha, M. (2007). “Batch sorption dynamics and equilibrium for the removal of cadmium ions from aqueous phase using wheat bran,” *J. Hazard. Mater.* 149(1), 115-125.
- Nuhoglu, Y., Malkoc, E., Gurses, A., and Canpolat, N. (2002). “The removal of Cu(II) from aqueous solutions by *Ulothrix zonata*,” *Bioresour. Technol.* 85(3), 331-333.
- Nuhoglu, Y., and Oguz, E. (2003). “Removal of copper(II) from aqueous solutions by biosorption on the cone biomass of *Thuja orientalis*,” *Process Biochem.* 38, 1627-1631.
- O’Connell, D. W., Aszalos, B., Birkinshaw, C., and O’Dwyer, T. F. (2010). “A study of the mechanisms of divalent copper binding to a modified cellulose adsorbent,” *J. Appl. Polymer Sci.* 116(5), 2496-2503.
- O’Connell, D. W., Birkinshaw, C., and O’Dwyer, T. F. (2006a). “A chelating cellulose adsorbent for the removal of Cu(II) from aqueous solutions,” *Journal of Applied Polymer Science* 99(6), 2888-2897.
- O’Connell, D. W., Birkinshaw, C., and O’Dwyer, T. F. (2006b). “A modified cellulose adsorbent for the removal of Ni(II) from aqueous solutions,” *Journal of Chemical Technology and Biotechnology* 81(11), 1820-1828.
- O’Connell, D. W., Birkinshaw, C., and O’Dwyer, T. F. (2006c). “Removal of lead(II) from aqueous solutions using a modified cellulose adsorbent,” *Adsorption Science and Technology* 24(4), 337-347.
- O’Connell, D. W., Birkinshaw, C., and O’Dwyer, T. F. (2008). “Heavy metal adsorbents prepared from the modification of cellulose: A review,” *Bioresour. Technol.* 99(15), 6709-6724.
- O’Cooney, D. (1998). *Adsorption Design for Wastewater Treatment*, CRC Press, Boca Raton, Florida, USA, pp. 9-25.
- Ofomaja, A. E., and Ho, Y. S. (2007). “Effect of pH on cadmium biosorption by coconut copra meal,” *J. Hazardous Mater.* 139(2), 356-362.
- Ofomaja, A. E., and Ho, Y. S. (2008). “Kinetic biosorption study of cadmium onto coconut copra meal as biosorbent,” *Intl. J. Environ. Pollution* 34(1-4), 466-476.

- Ogden, K. L., Ogden, G. E., Hanners, J. L., and Unkefer, P. J. (1996). "Remediation of low-level mixed waste: Cellulose-based materials and plutonium," *J. Hazardous Mater.* 51(1-3), 115-130.
- Oguz, E. (2005). "Adsorption characteristics and the kinetics of Cr(VI) on *Thuja orientalis*," *Colloids Surf. A* 252(2-3), 121-128.
- Oh, M., and Tshabalala, M. A. (2007). "Pelletized ponderosa pine bark for adsorption of toxic heavy metals from water," *BioResources* 2(1), 66-81.
- Oh, W. C. (2005). "Effect of acid pretreatment on the metal loading of activated carbon," *J. Indus. Eng. Chem.* 11(1), 137-144.
- Okieimen, F. E., Okundia, E. U., and Ogbeifun, D. E. (1991). "Sorption of cadmium and lead ions on modified groundnut (*Arachis hypogea*) husks," *J. Chem. Tech. Biotechnol.* 51(1), 97-103.
- Oliveira, E. A., Montanher, S. F., Andnade, A. D., Nobrega, J. A., and Rollemberg, M. C. (2005). "Equilibrium studies for the sorption of chromium and nickel from aqueous solutions using raw rice bran," *Process Biochem.* 40(11), 3485-3490.
- Oliveira, W. E., Franca, A. S., Oliveira, L. S., and Rocha, S. D. (2008). "Untreated coffee husks as biosorbents for the removal of heavy metals from aqueous solutions," *J. Hazard. Mater.* 152(3), 1073-1081.
- Omar, N. B., Merroun, M. L., Gonzalez-Munoz, M. T., and Arias, J. M. (1996). "Brewery yeast as a biosorbent for uranium," *Journal of Applied Bacteriology* 81, 283-287.
- Onyancha, D., Mavura, W., Ngila, J. C., Ongoma, P., and Chacha, J. (2008). "Studies of chromium removal from tannery wastewaters by algae biosorbents, *Spirogyra condensata* and *Rhizoclonium hieroglyphicum*," *J. Hazardous Mater.* 158(2-3), 605-614.
- Oo, C. W., Kassim, M. J., and Pizzi, A. (2009). "Characterization and performance of *Rhizophora apiculata* mangrove polyflavonoid tannins in the adsorption of copper (II) and lead (II)," *Industr. Crops Prods.* 30(1), 152-161.
- Orhan, Y., and Buyukgungor, H. (1993). "The removal of heavy metals by using agricultural wastes," *Wat. Sci. Technol.* 28(2), 247-255.
- Orhan, Y., Hrenovic, J., and Buyukgungor, H. (2006). "Biosorption of heavy metals from wastewater by biosolids," *Eng. Life Sci.* 6(4), 399-402.
- Orlando, U. S., Baes, A., Nishijima, W., and Okada, M. (2002). "Preparation of chelating agents from sugarcane bagasse by microwave radiation as an alternative ecologically benign procedure," *Green Chemistry* 4(6), 555-557.
- Owlad, M., Aroua, M. K., Daud, W. A. W., and Baroutian, S. (2009). "Removal of hexavalent chromium-contaminated water and wastewater: A review," *Water Air Soil Pollut.* 200(1-4), 59-77.
- Ozcan, A. S., Tunali, S., Akar, T., and Ozcan, A. (2009). "Biosorption of lead(II) ions onto waste biomass of *Phaseolus vulgaris* L.: Estimation of the equilibrium, kinetic and thermodynamic parameters," *Desalination* 244(1-3), 188-198.
- Ozdemir, G., Ceyhan, N., Ozturk, T., Akirmak, F., and Cosar, T. (2004). "Biosorption of chromium(VI), cadmium(II) and copper(II) by *Pantoea* sp. TEM 18," *Chem. Eng. J.* 102(3), 249-253.

- Ozer, A. (2007). "Removal of Pb(II) ions from aqueous solutions by sulphuric acid-treated wheat bran," *J. Hazard. Mater.* 141(3), 753-761.
- Ozer, A., Ekiz, H. I., Ozer, D., Kutsal, T., and Caglar, A. (1997). "A staged purification process to remove heavy metal ions from wastewater using *Rhizopus arrhizus*," *Process Biochem.* 32(4), 319-326.
- Ozer, A., and Ozer, D. (2003). "Comparative study of the biosorption of Pb(II), Ni(II) and Cr(VI) ions onto *S. cerevisiae*: Determination of biosorption heats," *J. Hazard. Mater.* 100(1-3), 219-229.
- Ozer, A., and Ozer, D. (2004). "The adsorption of Cr(VI) on sulphuric acid-treated wheat bran," *Environ. Technol.* 25(6), 689-697.
- Ozer, A., Ozer, D., and Ekiz, H. I. (2004a). "The equilibrium and kinetic modeling of the biosorption of copper(II) ions on *Cladophora crispata*," *Adsorption* 10(4), 317-326.
- Ozer, A., Ozer, D., and Ozer, A. (2004b). "The adsorption of copper(II) ions on to dehydrated wheat bran (DWB): Determination of the equilibrium and thermodynamic parameters," *Process Biochem.* 39(12), 2183-2191.
- Ozer, A., and Pirincci, H. B. (2006). "The adsorption of Cd(II) ions on sulphuric acid treated wheat bran," *J. Hazard. Mater. B* 137(2), 849-855.
- Ozer, A., and Tumen, F. (2003). "Cd(II) adsorption from aqueous solution by activated carbon from sugar beet pulp impregnated with phosphoric acid," *Fresenius Environ. Bull.* 12(9), 1050-1058.
- Padilha, P. M., Campos, J. T. S., Moreira, J. C., and Federici, C. C. (1995). "Study on ion-exchange and adsorptive properties of cellulose and modified cellulose," *Quimica Nova* 18(6), 529-533.
- Padmesha, T. V. N., Vijayaraghavana, K., Sekaranb, G., and Velan, M. (2006). "Application of two-and three-parameter isotherm models: Biosorption of Acid Red 88 onto *Azolla microphylla*," *Bioremediation Journal* 10(1-2), 37-44.
- Pagnanelli, F., Mainelli, S., De Angelis, S., and Toro, L. (2005a). "Biosorption of protons and heavy metals onto olive pomace: Modelling of competition effects," *Water Res.* 39(8), 1639-1651.
- Pagnanelli, F., Mainelli, S., and Toro, L. (2005b). "Optimisation and validation of mechanistic models for heavy metal bio-sorption onto a natural biomass," *Hydrometallurgy* 80(1-2), 107-125.
- Pagnanelli, F., Mainelli, S., Vegliò, F., and Toro, L. (2003). "Heavy metal removal by olive pomace: Biosorbent characterisation and equilibrium modeling," *Chem. Eng. Sci.* 58(20), 4709-4717.
- Pagnanelli, F., Papini, M. P., Toro, L., Trifoni, M., and Veglio, F. (2000). "Biosorption of metal ions on *Arthrobacter* sp.: Biomass characterization and biosorption modeling," *Environ. Sci. Technol.* 34(13), 2773-2778.
- Palma, G., Freer, G. J., and Beeza, J. (2003). "Removal of metal ions by modified *Pinus radiata* bark and tannins from water solutions," *Water Res.* 37(20), 4974-4980.
- Panda, G. C., Das, S. K., Chatterjee, S., Maity, P. B., Bandopadhyay, T. S., and Guha, A. K. (2006). "Adsorption of cadmium on husk of *Lathyrus sativus*: Physico-chemical study," *Colloids Surf. B – Interfaces* 50(1), 49-54.

- Parab, H., Joshi, S., Shenoy, N., Lali, A., Sarma, U. S., and Sudersanan, M. (2006b). "Determination of kinetic and equilibrium parameters of the batch adsorption of Co(II), Cr(III) and Ni(II) onto coir pith," *Process Biochem.* 41(3), 609-615.
- Parab, H., Joshi, S., Shenoy, N., Verma, R., Lali, A., and Sudersanan, M. (2005). "Uranium removal from aqueous solution by coir pith: Equilibrium and kinetic studies," *Bioresour. Technol.* 96(11), 1241-1248.
- Parab, H., Joshi, S., Shenoy, N., Lali, A., Sarma, U. S., and Sudersanan, M. (2006a). "Determination of kinetic and equilibrium parameters of the batch adsorption of Co(II), Cr(III) and Ni(II) onto coir pith," *Process Biochem.* 41(3), 609-615.
- Parab, H., Joshi, S., Shenoy, N., Lali, A., Sarma, U. S., and Sudersanan, M. (2008). "Esterified coir pith as an adsorbent for the removal of Co(II) from aqueous solution," *Bioresour. Technol.* 99(6), 2083-2086.
- Parab, H., Joshi, S., Sudersanan, M., Shenoy, N., Lali, A., and Sarma, U. (2010). "Removal and recovery of cobalt from aqueous solutions by adsorption using low cost lignocellulosic biomass – coir pith," *J. Environ. Sci. Health Pt. A Toxic/Haz. Subst. Environ. Eng.* 45(5), 603-611.
- Parajuli, D., Adhikari, C. R., Kawakita, H., Kajiyama, K., Ohto, K., and Inoue, K. (2008). "Reduction and accumulation of Au(III) by grape waste: A kinetic approach," *Reactive Functional Poly.* 68(8), 1194-1199.
- Parajuli, D., Kawakita, H., Inoue, K., and Funaoka, M. (2006). "Recovery of gold(III), palladium(II), and platinum(IV) by aminated lignin derivatives," *Ind. Eng. Chem. Res.* 45(19), 6405-6412.
- Pardo, R., Herguedas, M., Barrado, E., and Vega, M. (2003). "Biosorption of cadmium, copper, lead and zinc by inactive biomass of *Pseudomonas putida*," *Anal. Bioanal. Chem.* 376(1), 26-32.
- Park, D., Lim, S.-R., Yun, Y.-S., and Park, J. M. (2007a). "Reliable evidences that the removal mechanism of hexavalent chromium by natural biomaterials is adsorption-coupled reduction," *Chemosphere* 70(2), 298-305.
- Park, D., Lim, S.-R., Yun, Y.-S., and Park, J. M. (2008a). "Development of new Cr(VI)-biosorbent from agricultural biowaste," *Bioresour. Technol.* 99(18), 8810-8818.
- Park, D., Park, J. M., and Yun, Y. S. (2006a). "Mechanisms of the removal of hexavalent chromium by biomaterials or biomaterial-based activated carbons," *J. Hazardous Mater.* 137(2), 1254-1257.
- Park, D., Park, J. M., and Yun, Y. S. (2006). "Comment on "Sorption of Cr(VI) from dilute solutions and wastewater by live and pretreated biomass of *Aspergillus flavus*" by Deepa *et al.*," *Chemosphere* 63(6), 1060-1062.
- Park, D., Yun, Y. S., Ahn, C. K., and Park, J. M. (2007b). "Kinetics of the reduction of hexavalent chromium with the brown seaweed *Ecklonia* biomass," *Chemosphere* 66(5), 939-946.
- Park, D., Yun, Y. S., Cho, H. Y., and Park, J. M. (2004a). "Chromium biosorption by thermally treated biomass of the brown seaweed, *Ecklonia* sp.," *Indus. Eng. Chem. Res.* 43(26), 8226-8232.
- Park, D., Yun, Y. S., Jo, J. H., and Park, J. M. (2005a). "Effects of ionic strength, background electrolytes, heavy metals, and redox-active species on the reduction of

- hexavalent chromium by *Ecklonia* biomass,” *J. Microbiol. Biotechnol.* 15(4), 780-786.
- Park, D., Yun, Y. S., Jo, J. H., and Park, J. M. (2005b). “Mechanism of hexavalent chromium removal by dead fungal biomass of *Aspergillus niger*,” *Water Res.* 39(4), 533-540.
- Park, D., Yun, Y. S., Jo, J. H., and Park, J. M. (2006b). “Biosorption process for treatment of electroplating wastewater containing Cr(VI): Laboratory-scale feasibility test,” *Ind. Eng. Chem. Res.* 45(14), 5059-5065.
- Park, D., Yun, Y. S., Kim, J. Y., and Park, J. M. (2008b). “How to study Cr(VI) biosorption: Use of fermentation waste for detoxifying Cr(VI) in aqueous solution,” *Chem. Eng. J.* 136(2-3), 173-179.
- Park, D., Yun, Y. S., Lee, D. S., Lim, S. R., and Park, J. M. (2006c). “Column study on Cr(VI)-reduction using the brown seaweed *Ecklonia* biomass,” *J. Hazardous Mater.* 137(3), 1377-1384.
- Park, D., Yun, Y. S., Lee, H. W., and Park, J. M. (2008c). “Advanced kinetic model of the Cr(VI) removal by biomaterials at various pHs and temperatures,” *Bioresour. Technol.* 99(5), 1141-1147.
- Park, D., Yun, Y. S., and Park, J. M. (2004b). “Reduction of hexavalent chromium with the brown seaweed *Ecklonia* biomass,” *Environ. Sci. Technol.* 38(18), 4860-4864.
- Park, D., Yun, Y. S., and Park, J. M. (2005c). “Use of dead fungal biomass for the detoxification of hexavalent chromium: Screening and kinetics,” *Process Biochem.* 40(7), 2559-2565.
- Park, D., Yun, Y. S., and Park, J. M. (2005d). Studies on hexavalent chromium biosorption by chemically-treated biomass of *Ecklonia* sp,” *Chemosphere* 60(10), 1356-1364.
- Park, D., Yun, Y. S., and Park, J. M. (2006). “Comment on “Chromate ion adsorption by agricultural byproducts modified with dimethyloldihydroxyethylene urea and choline chloride” by Wartelle and Marshall,” *Water Res.* 40(7), 1501-1504.
- Park, D., Yun, Y. S., and Park, J. M. (2006). “Comment on the removal mechanism of hexavalent chromium by biomaterials or biomaterial-based activated carbons,” *Indus. Eng. Chem. Res.* 45(7), 2405-2407.
- Park, D., Yun, Y. S., and Park, J. M. (2008d). “XAS and XPS studies on chromium-binding groups of biomaterial during Cr(VI) biosorption,” *J. Colloid Interface Sci.* 317(1), 54-61.
- Park, S. J., Jang, Y. S., Shim, J. W., and Ryu, S. K. (2003). “Studies on pore structures and surface functional groups of pitch-based activated carbon fibers,” *J. Colloid Interface Sci.* 260(2), 259-264.
- Park, S. J., and Kim, Y. M. (2004). “Influence of anodic treatment on heavy metal ion removal by activated carbon fibers,” *J. Colloid Interface Sci.* 278(2), 276-281.
- Parsons, J. G., Hejazi, M., Tiemann, K. J., Henning, J., and Gardea-Torresdey, J. L. (2002). “An XAS study of the binding of copper(II), zinc(II), chromium(III) and chromium(VI) to hops biomass,” *Microchem. J.* 71(2-3), 211-219.
- Parsons, J. G., Tiemann, K. J., Peralta-Videa, J. R., and Gardea-Torresdey, J. L. (2006). “Sorption of uranyl cations onto inactivated cells of alfalfa biomass investigated using chemical modification, ICP-OES, and XAS,” *Environ. Sci. Technol.* 40(13),

- 4181-4188.
- Pearson, R. G. (1963). "Hard and soft acids and bases," *J. Am. Chem. Soc.* 85, 3533-3539.
- Pehlivan, E., Altuna, T., Cetin, S., and Bhanger, M. I. (2009a). "Lead sorption by waste biomass of hazelnut and almond shell," *J. Hazardous Mater.* 167(1-3), 1203-1208.
- Pehlivan, E., Altun, T., and Parlayici, S. (2009b). "Utilization of barley straws as biosorbents for Cu^{2+} and Pb^{2+} ions," *J. Hazard. Mater.* 164, 982-986.
- Pehlivan, E., Cetin, S., and Yanik, B. H. (2006). "Equilibrium studies for the sorption of zinc and copper from aqueous solutions using sugar beet pulp and fly ash," *J. Hazardous Mater.* 135(1-3), 193-199.
- Pehlivan, E., Yanik, B. H., Ahmetli, G., and Pehlivan, M. (2008). "Equilibrium isotherm studies for the uptake of cadmium and lead ions onto sugar beet pulp," *Bioresour. Technol.* 99(9), 3520-3527.
- Periasamy, K., and Namasivayamm, C. (1994). "Process development for removal and recovery of cadmium from waste water by a low-cost adsorbent – Adsorption rates and equilibrium studies," *Indus. Eng. Chem. Res.* 33(2), 317-320.
- Periasamy, K., and Namasivayam, C. (1995a). "Removal of nickel(II) from aqueous solution and nickel plating industry waste water using an agricultural waste – peanut hulls," *Waste Manag.* 15(1), 63-68.
- Periasamy, K., and Namasivayam, C. (1995b). "Adsorption of Pb(II) by peanut hull carbon from aqueous solution," *Separation Sci. Technol.* 30(10), 2223-2237.
- Periasamy, K., and Namasivayam, C. (1996). "Removal of copper(II) by adsorption onto peanut hull carbon from water and copper plating industry wastewater," *Chemosphere* 32(4), 769-789.
- Peternele, W. S., Winkler-Hechenleitner, A. A., and Gomez Pineda, E. A. (1999). "Adsorption of Cd(II) and Pb(II) onto functionalized formic lignin from sugar cane bagasse," *Bioresource Technology, Bioprocessing and Characterization of Lignocellulosics* 68(1), 95-100.
- Phan, N. H., Rio, S., Faur, C., Le Coq, L., Le Cloirec, P., and Nguyen, T. H. (2006). "Production of fibrous activated carbons from natural cellulose (jute, coconut) fibers for water treatment applications," *Carbon* 44(12), 2567-2577.
- Pino, G. H., de Mesquita, L. M. S., Torem, M. L., and Pinto, G. A. S. (2006). "Biosorption of heavy metals by powder of green coconut shell," *Sep. Sci. Technol.* 41(14), 3141-3153.
- Pokhrel, D., and Viraraghavan, T. (2006). "Arsenic removal from aqueous solution by iron oxide-coated fungal biomass: A factorial design analysis," *Water, Air, Soil Pollut.* 173(1-4), 195-208.
- Pokhrel, D., and Viraraghavan, T. (2008). "Arsenic removal from an aqueous solution by modified A-niger biomass: Batch kinetic and isotherm studies," *J. Hazardous Mater.* 150(3), 818-825.
- Poleo, N., Oliveros, S., Colina, M., Rincon, N., Mesa, J., and Colina, G. (2010). "Study of different chemical activations on obtaining activated carbon from *Hymenaea courbaril* L shell for cadmium (II) removal," *Revista Tecnica Fac. Ingen. Univ. del Zulia* 33(1), 29-38.

- Pollard, S. J. T., Fowler, G. D., Sollars, C. J., and Perry, R. (1992). "Low-cost adsorbents for waste and waste-water treatment – A review," *Sci. Total Environ.* 116(1-2), 31-52.
- Popa, K., Cecal, A., Drochioiu, G., and Humelnicu, D. (2003). "*Saccharomyces cerevisiae* as uranium bioaccumulating material: The influence of contact time, pH and anion nature," *Nukleonika* 48, 121-125.
- Prabhakaran, S. K., Vijayaraghavan, K., and Balasubramanian, R. (2009). "Removal of Cr(VI) ions by spent tea and coffee dusts: Reduction to Cr(III) and biosorption," *Ind. Eng. Chem. Res.* 48(4), 2113-2117.
- Pradhan, S., Singh, S., and Rai, L. C. (2007). "Characterization of various functional groups present in the capsule of *Microcystis* and study of their role in biosorption of Fe, Ni, and Cr," *Bioresour. Technol.* 98(3), 595-601.
- Prakasham, R. S., Merrie, J. S., Sheela, R., Saswathi, N., and Ramkrishna, S. V. (1999). "Biosorption of chromium(VI) by free and immobilized *Rhizopus arrhizus*," *Environ. Pollut.* 104(3), 421-427.
- Prasad, A. G. D., and Abdullah, M. A. (2010). "Biosorption of Cr(VI) from synthetic wastewater using the fruit shell of gulmohar (*Delonix regia*): Application to electroplating wastewater," *BioResources* 5(2), 838-853.
- Prasanjit, B., and Sumathi, S. (2005). "Uptake of chromium by *Aspergillus foetidus*," *Journal of Material Cycles and Waste Management* 7(2), 88-92.
- Preetha, B., and Viruthagiri, T. (2005). "Biosorption of zinc (II) by *Rhizopus arrhizus*; equilibrium and kinetic modeling," *African J. Biotechnol.* 4(6), 506-508.
- Preetha, B., and Viruthagiri, T. (2007a). "Application of response surface methodology for the biosorption of copper using *Rhizopus arrhizus*," *J. Hazardous Mater.* 143(1-2), 506-510.
- Preetha, B., and Viruthagiri, T. (2007b). "Batch and continuous biosorption of chromium(VI) by *Rhizopus arrhizus*," *Separ. Purif. Technol.* 57(1), 126-133.
- Price, M. S., Classen, J. J., and Payne, G. A. (2001). "*Aspergillus niger* absorbs copper and zinc from swine wastewater," *Bioresour. Technol.* 77(1), 41-49.
- Puranik, P. R., and Paknikar, K. M. (1997). "Biosorption of lead and zinc from solutions using *Streptovercillium cinnamoneum* waste biomass," *J. Biotechnol.* 55(2), 113-124.
- Puranik, P. R., and Paknikar, K. M. (1999). "Influence of co-cations on biosorption of lead and zinc – A comparative evaluation in binary and multimetal systems," *Bioresour. Technol.* 70(3), 269-276.
- Puranik, P. R., Chabukswar, N. S., and Paknikar, K. M. (1995). "Cadmium biosorption by *Streptomyces pimprina* waste biomass," *Appl. Microbiol. Biotechnol.* 43(6), 1118-1121.
- Puziy, A. M., Poddubnaya, O. I., Martinez-Alonso, A., Suarez-Garcia, F., Tascon, J. M. D. (2002). "Synthetic carbons activated with phosphoric acid - I. Surface chemistry and ion binding properties," *Carbon* 40(9), 1493-1505.
- Py, X., Guillot, A., and Cagnon, B. (2004). "Nanomorphology of activated carbon porosity: Geometrical models confronted to experimental facts," *Carbon* 42(8-9), 1743-1754.

- Pyrzynska, K. (2010). "Sorption of Cd(II) onto carbon-based materials-a comparative study," *Microchimica Acta* 169(1-2), 7-13.
- Pyrzynska, K., and Trojanowicz, M. (1999). "Functionalized cellulose sorbents for preconcentration of trace metals in environmental analysis," *Crit. Rev. Anal. Chem.* 29(4), 313-321.
- Qadeer, R., Hanif, I., and Hanif, J. (1996). "Effect of different cations on the adsorption of Dy^{3+} , Gd^{3+} , Eu^{3+} and Sm^{3+} ions on activated charcoal from aqueous solutions," *Adsorption Sci. Technol.* 13(1), 27-29.
- Qadeer, R., Hanif, J., and Hanif, I. (1995a). "Kinetics of strontium ions adsorption on activated charcoal from aqueous solutions," *J. Chem. Soc. Pakistan* 17(2), 74-77.
- Qadeer, R., Hanif, J., Saleem, M., and Afjal, M. (1992). "Selective adsorption of thorium on activated charcoal from electrolytic aqueous solution," *J. Radioanal. Nucl. Chem.* 157(2), 321-334.
- Qadeer, R., Hanif, J., Saleem, M., and Afzal, M. (1995b). "Kinetics and thermodynamics of some metal ions adsorption on activated charcoal from aqueous solutions," *J. Chem. Soc. Pakistan* 17(2), 82-86.
- Qaiser, S., Saleemi, A. R., and Ahmad, M. M. (2007). "Heavy metal uptake by agro based waste materials," *Elec. J. Biotechnol.* 10(3), 409-416.
- Qaiser, S., Saleemi, A. R., and Umar, M. (2009). "Biosorption of lead from aqueous solution by *Ficus religiosa* leaves: Batch and column study," *J. Hazardous Mater.* 166(2-3), 998-1005.
- Qi, B. C., and Aldrich, C. (2008). "Biosorption of heavy metals from aqueous solutions with tobacco dust," *Bioresour. Technol.* 99(13), 5595-5601.
- Quek, S. Y., Wase, D. A. J., and Forster, C. F. (1998). "The use of sago waste for the sorption of lead and copper," *Water SA* 24, 251-256.
- Quintana, G. C., Rocha, G. J. M., Gonçalves, A. R., and Velásquez, J. A. (2008). "Evaluation of heavy metal removal by oxidised lignins in acid media from various sources," *BioResources* 3(4), 1092-1102.
- Rai, P. K. (2009). "Heavy metal phytoremediation from aquatic ecosystems with special reference to macrophytes," *Crit. Rev. Environ. Sci. Technol.* 39(9), 697-753.
- Rajeshwarisivaraj and Subburam, V. (2002). "Activated parthenium carbon as an adsorbent for the removal of dyes and heavy metal ions from aqueous solution," *Biores. Technol.* 85, 205-206.
- Raji, C., and Anirudhan, T. S. (1997). "Chromium(VI) adsorption by sawdust carbon: Kinetics and equilibrium," *Ind. J. Chem. Technol.* 4(5), 228-236.
- Raji, C., and Anirudhan, T. S. (1998). "Batch Cr(IV) removal by polyacrylamide grafted sawdust: Kinetics and thermodynamics," *Water Research* 32(12), 3772-3780.
- Raji, C., Manju, G. N., and Anirudhan, T. S. (1997). "Removal of heavy metal ions from water using sawdust-based activated carbon," *Ind. J. Eng. Mater. Sci.* 4(6), 254-260.
- Randall, J. M., Bermann, R. L., Garret, V., and Waiss, A. C. (1974). "Use of bark to remove heavy metal ions," *Forest Products. J.* 24(9), 80-84.
- Rangel-Mendez, J. R., and Streat, M. (2002). "Adsorption of cadmium by activated carbon cloth: Influence of surface oxidation and solution pH," *Water Res.* 36(5), 1244-1252.

- Ranjan, D., Talat, M., and Hasan, S. H. (2009a). "Biosorption of arsenic from aqueous solution using agricultural residue 'rice polish'," *J. Hazardous Mater.* 166(2-3), 1050-1059.
- Ranjan, D., Talat, M., and Hasan, S. H. (2009b). "Rice polish: An alternative to conventional adsorbents for treating arsenic bearing water by up-flow column method," *Indus. Eng. Chem. Res.* 48(23), 10180-10185.
- Rao, K. S., Anand, S., and Venkateswarlu, P. (2010). "Adsorption of cadmium(II) ions from aqueous solution by *Tectona grandis* L. F. (teak leaves powder)," *BioResources* 5(1), 438-454.
- Rao, M., and Parwate, A. V. (2002). "Utilization of low-cost adsorbents for the removal of heavy metals from wastewater – A review," *J. Environ. Pollut. Control* 5, 12-23.
- Rao, M., Parwate, A. V., and Bhole, A. G. (2002). "Removal of Cr and Ni from aqueous solution using bagasse and fly ash," *Waste Manage.* 22(7), 821-830.
- Reddad, Z., Gerente, C., Andres, Y., Ralet, M.-C., Thibault, J.-F., and Cloirec, P. L. (2002d). "Ni (II) and Cu (II) binding properties of native and modified sugar beet pulp," *Carbohydr. Polym.* 49(1), 23-31.
- Reddad, Z., Gerente, C., Andres, Y., and Le Cloirec, P. (2002a). "Modeling of single and competitive metal adsorption onto a natural polysaccharide," *Environ. Sci. Technol.* 36(10), 2242-2248.
- Reddad, Z., Gerente, C., Andres, Y., and Le Cloirec, P. (2002b). "Adsorption of several metal ions onto a low cost biosorbent: Kinetic and equilibrium studies," *Environ. Sci. Technol.* 36(9), 2067-2073.
- Reddad, Z., Gerente, C., Andres, Y., and Le Cloirec, P. (2003). "Mechanisms of Cr(III) and Cr(VI) removal from aqueous solutions by sugar beet pulp," *Environ. Technol.* 24(2), 257-264.
- Reddad, Z., Gerente, C., Andrés, Y., Ralet, M. C., Thibault, J. F., and Le Cloirec, P. (2002e). "Ni(II) and Cu(II) binding properties of native and modified sugar beet pulp," *Carbohydr. Polymers* 49(1), 23-31.
- Rincon, C. D. G., Garcia, V., Quintero-Guzman, M. W., Moreno-Pirajan, J. C., and Giraldo-Gutierrez, L. (2007). "Evaluation of the properties of activated carbon fibers designed for Zn^{2+} and Cd^{2+} adsorption," *AFINIDAD* 64(531), 623-631.
- Rincón, J., González, F., Ballester, A., Blázquez, M. L., and Muñoz, J. A. (2005). "Biosorption of heavy metals by chemically-activated alga *Fucus vesiculosus*," *J. Chem. Technol. Biotechnol.* 80, 1403-1407.
- Riversa-Utrilla, J., and Sanchez-Polo, M. (2003a). "Adsorption of Cr(III) on ozonised activated carbon. Importance of π -cation interactions," *Water Res.* 37, 3335-3340.
- Rivera-Utrilla, J., Toledo, I. B., Ferro-Garcia, M. A., and Moreno-Satilla, C. (2003b). "Biosorption of Pb(II), Cd(II), and Cr(VI) on activated carbon from aqueous solutions," *Carbon* 41(2), 323-330.
- Roberts, E. J., and Rowland, S. P. (1973). "Removal of mercury from aqueous solutions by nitrogen-containing chemically modified cotton," *Environ. Sci. Technol.* 7(6), 552-555.
- Rocha, S. C. S., Cavalcante, J. D., da Silva, M. G. C., and Pinho, C. G. (2006). "Influence of the drying conditions of *Sargassum* sp. alga on the bioadsorption of hexavalent chromium," *Environ. Technol.* 27(9), 979-990.

- Rocha, J. C., Toscano, I. A. S., and Burba, P. (1997). "Lability of heavy metal species in aquatic humic substances characterized by ion exchange with cellulose phosphate," *Talanta* 44(1), 69-74.
- Romera, E., Gonzalez, F., Ballester, A., Blazquez, M. L., and Munoz, J. A. (2006). "Biosorption with algae: A statistical review," *Crit. Rev. Biotechnol.* 26(4), 223-235.
- Romero-Gonzalez, J., Peralta-Videa, J. R., Rodriguez, E., Delgado, M., and Gardea-Torresdey, J. L. (2006). "Potential of *Agave lechuguilla* biomass for Cr(III) removal from aqueous solutions: Thermodynamic studies," *Bioresour. Technol.* 97(1), 178-182.
- Romero-Gonzalez, J., Peralta-Videa, J. R., Rodríguez, E., Ramirez, S. L., and Gardea-Torresdey, J. L. (2005). "Determination of thermodynamic parameters of Cr(VI) adsorption from aqueous solution onto *Agave lechuguilla* biomass," *J. Chem. Thermodyn.* 37(4), 343-347.
- Romero-Gonzalez, M. E., Williams, C. J., and Gardiner, P. H. E. (2001). "Study of the mechanisms of cadmium biosorption by dealginated seaweed waste," *Environ. Sci. Technol.* 35, 3025-3030.
- Rudie, A. W., Ball, A., and Patel, N. (2006). "Ion exchange of H^+ , Na^+ , Mg^{2+} , Ca^{2+} , Mn^{2+} , and Ba^{2+} on wood pulp," *J. Wood Chem. Technol.* 26(3), 259-272.
- Saeed, A., Akhter, M. W., and Iqbal, M. (2005a). "Removal and recovery of heavy metals from aqueous solution using papaya wood as a new biosorbents," *Sep. Purif. Technol.* 45(1), 25-31.
- Saeed, A., and Iqbal, M. (2003). "Bioremoval of Cd from aqueous solution by black gram husk (*Cicer arietinum*)," *Water Res.* 37(14), 3472-3480.
- Saeed, A., Iqbal, M., and Akhtar, M. W. (2005b). "Removal and recovery of lead (II) from single and multiple, (Cd, Ni, Cu, Zn) solutions by crop milling waste (black gram husk)," *J. Hazard. Mater.* 117(1), 65-73.
- Saeed, A., Iqbal, M., and Höll, W. H. (2009). "Kinetics, equilibrium and mechanism of Cd^{2+} removal from aqueous solution by mungbean husk," *J. Hazardous Mater.* 168(2-3), 1467-1475.
- Sag, Y. (2001). "Biosorption of heavy metals by fungal biomass and modeling of fungal biosorption: A review," *Separation Purification Methods* 30(1), 1-48.
- Sag, Y., and Kutsal, T., (1996). "Fully competitive biosorption of Cr(VI) and Fe(III) ions from binary metal mixtures by *R. arrhizus*: Use of the competitive Langmuir model," *Process Biochem.* 31(6), 573-585.
- Saha, B., Tai, M.H., and Streat, M. (2003). "Adsorption of transition metals from aqueous solutions by modified activated carbons," *Chem. Eng. Res. Des.* 81, 1343-1353.
- Şahin, Y., and Öztürk, A. (2005). "Biosorption of chromium(VI) ions from aqueous solution by the bacterium *Bacillus thuringiensis*," *Process Biochem.* 40(5), 1895-1901.
- Saito, T., and Isogai, A. (2005). "Ion-exchange behavior of carboxylate groups in fibrous cellulose oxidized by the TEMPO-mediated system," *Carbohydrate Polymers* 61, 183-190.
- Salam, A., Pawlak, J. J., Venditti, R. A., and El-Tahlawy, K. (2010). "Synthesis and characterization of starch citrate-chitosan foam with superior water and saline absorbance properties," *Biomacromol.* 11, 1453-1459.

- Salamatinia, B., Kamaruddin, A. H., and Abdullah, A. Z. (2007). "Removal of Zn and Cu from wastewater by sorption on oil palm tree-derived biomasses," *Journal of Applied Sciences* 7(15), 2020-2027.
- Salamatinia, B., Kamaruddin, A. H., and Abdullah, A. Z. (2010). "Regeneration and reuse of spent NaOH-treated oil palm frond for copper and zinc removal from wastewater," *Chem. Eng. J.* 156(1), 141-145.
- Saleem, M., Qadeer, R., Hanif, J., and Afzal, M. (1994). "Effects of pH on the adsorption of Ce^{3+} , Sm^{3+} , Eu^{3+} and Gd^{3+} ions on activated charcoal," *J. Radioanal. Nuclear Chem.* 182(2), 415-419.
- Salehizadeh, H., and Shojaosadati, S. A. (2003). "Removal of metal ions from aqueous solution by polysaccharide produced from *Bacillus firmus*," *Water Research* 17, 4231-4235.
- Saliba, R., Gauthier, H., and Gauthier, R. (2005). "Adsorption of heavy metal ions on virgin and chemically-modified lignocellulosic materials," *Adsorption Science and Technology* 23(4), 313-322.
- Saliba, R., Gauthier, H., Gauthier, R., and Petit-Ramel, M. (2000). "Adsorption of copper(II) and chromium(III) ions onto amidoximated cellulose," *J. Appl. Polymer Sci.* 75(13), 1624-1631.
- Saliba, R., Gauthier, H., Gauthier, R., and Petit-Ramel, M. (2001). "Amidoximated cellulose as scavenger for cadmium and nickel cations," *Cellulose Chem. Technol.* 35(5-6), 435-449.
- Saliba, R., Gauthier, H., Gauthier, R., and Petit-Ramel, M. (2002a). "The use of amidoximated cellulose for the removal of metal ions and dyes from waste waters," *Cellulose* 9(2), 183-191.
- Saliba, R., Gauthier, H., Gauthier, R., and Petit-Ramel, M. (2002b). "The use of eucalyptus barks for the adsorption of heavy metal ions and dyes," *Adsorp. Sci. Technol.* 20(2), 119-129.
- Salim, R., Al-Subu, M. M., and Sahrhage, E. (1992). "Uptake of cadmium from water by beech leaves," *J. Environ. Sci. Health. A* 27(3), 603-627.
- Salinas, E., Orellano, M. E. D., Rezza, I., Martinez, L., Marchesvsky, E., and Tosetti, M. S. D. (2000). "Removal of cadmium and lead from dilute aqueous solutions by *Rhodotorula rubra*," *Bioresour. Technol.* 72(2), 107-112.
- Samantanoi, S., Mohanty, A. K., and Misra, M. (1997). "Removal of hexavalent chromium by Kendu fruit gum dust," *J. Appl. Polymer Sci.* 66(8), 1485-1452.
- Santhy, K., and Selvapathy, P. (2004). "Removal of heavy metals from wastewater by adsorption on coir pith activated carbon," *Separ. Sci. Technol.* 39(14), 3331-3351.
- Sanyahumbi, D., Duncan, J. R., Zhao, M., and VanHile, R. (1998). "Removal of lead from solution by the non-viable biomass of the water fern *Azolla filiculoides*," *Biotechnology Letters* 20(8), 745-747.
- Sari, A., Mendil, D., Tuzen, M., and Soylak, M. (2008). "Biosorption of Cd(II) and Cr(III) from aqueous solution by moss (*Hylocomium splendens*) biomass: Equilibrium, kinetic and thermodynamic studies," *Chem. Eng. J.* 144(1), 1-9.
- Sari, A., Mendil, D., Tuzen, M., Soylak, M. (2009). "Biosorption of palladium(II) from aqueous solution by moss (*Racomitrium lanuginosum*) biomass: Equilibrium, kinetic and thermodynamic studies." *J. Hazardous Mater.* 162(2-3), 874-879.

- Sari, A., and Tuzen, M., (2008). "Biosorption of total chromium from aqueous solution by red algae (*Ceramium virgatum*): Equilibrium, kinetic and thermodynamic studies," *J. Hazard. Mater.* 160(2-3), 349-355.
- Sari, A., and Tuzen, M. (2009a). "Biosorption of As(III) and As(V) from aqueous solution by macrofungus (*Inonotus hispidus*) biomass: Equilibrium and kinetic studies," *J. Hazardous Mater.* 164(2-3), 1372-1378.
- Sari, A., and Tuzen, M. (2009b). "Equilibrium, thermodynamic and kinetic studies on aluminum biosorption from aqueous solution by brown algae (*Padina pavonica*) biomass," *J. Hazardous Mater.* 171(1-3), 973-979.
- Sari, A., and Tuzen, M. (2009c). "Removal of mercury(II) from aqueous solution using moss (*Drepanocladus revolvens*) biomass: Equilibrium, thermodynamic and kinetic studies," *J. Hazardous Mater.* 171(1-3), 500-507.
- Sari, A., and Tuzen, M. (2009d). "Kinetic and equilibrium studies of biosorption of Pb(II) and Cd(II) from aqueous solution by macrofungus (*Amanita rubescens*) biomass," *J. Hazardous Mater.* 164(2-3), 1004-1011.
- Sari, A., Tuzen, M., Uluozlu, O. D., and Soylak, M. (2007). "Biosorption of Pb(II) and Ni(II) from aqueous solution by lichen (*Cladonia furcata*) biomass," *Biochem. Eng. J.* 37(2), 151-158.
- Sarin, V., and Pant, K. K. (2006). "Removal of chromium from industrial waste by using eucalyptus bark," *Bioresour. Technol.* 97(1), 15-20.
- Sarkar, B. (ed.) (2002). *Heavy Metals in the Environment*, Marcel Dekker, New York, 725 pp.
- Savova, D., Petrov, N., Yardim, M. F., Ekinci, E., Budinova, T., Razvigorova, M., and Minkova, V. (2003). "The influence of the texture and surface properties of carbon adsorbents obtained from biomass products on the adsorption of manganese ions from aqueous solution," *Carbon* 41(10), 1897-1903.
- Sawalha, M. F., Peralta-Videa, J. R., Romero-Gonzalez, J., Duarte-Gardea, M., and Gardea-Torresdey, J. L. (2007). "Thermodynamic and isotherm studies of the biosorption of Cu(II), Pb(II), and Zn(II) by leaves of saltbush (*Atriplex canescens*)," *J. Chem. Thermodyn.* 39(3), 488-492.
- Sawalha, M. F., Peralta-Videa, J. R., Romero-Gonzalez, J., and Gardea-Torresdey, J. L. (2006). "Biosorption of Cd(II), Cr(III), and Cr(VI) by saltbush (*Atriplex canescens*) biomass: Thermodynamic and isotherm studies," *J. Colloid Interface Sci.* 300(1), 100-104.
- Say, R., Denizli, A., and Arica, M. Y. (2001). "Biosorption of cadmium(II), lead(II) and copper(II) with the filamentous fungus *Phanerochaete chrysosporium*," *Bioresour. Technology* 76(1), 67-70.
- Say, R., Yilmaz, N., and Denizli, A. (2003a). "Biosorption of cadmium, lead, mercury, and arsenic ions by the fungus *Penicillium purpurogenum*," *Sep. Sci. Technol.* 38(9), 2039-2053.
- Say, R., Yilmaz, N., and Denizli, A. (2003b). "Removal of heavy metal ions using the fungus *Penicillium canescens*," *Adsorpt. Sci. Technol.* 21(7), 643-650.
- Say, R., Yilmaz, N., and Denizli, A. (2003c). "Removal of chromium(VI) ions from synthetic solutions by the fungus *Penicillium purpurogenum*," *Eng. Life Sci.* 4(3), 276-280.

- Sayan, E. (2006). "Ultrasound-assisted preparation of activated carbon from alkaline impregnated hazelnut shell: An optimization study on removal of Cu^{2+} from aqueous solution," *Chem. Eng. J.* 115(3), 213-218.
- Schneider, I. A. H., Rubio, J., Misra, M., and Smith, R.W. (1995). "*Eichhornia crassipes* as biosorbent for heavy metal ions," *Miner. Eng.* 8(9), 979-988.
- Schneider, I. A. H., Rubio, J., and Smith, R. W. (2001). "Biosorption of metals onto plant biomass: Exchange adsorption or surface precipitation?," *Int. J. Mineral Processing* 62(1-4), 111-120.
- Schiewer, S. (1999). "Modelling complexation and electrostatic attraction in heavy metal biosorption by *Sargassum* biomass," *J. Applied Phycology* 11(1), 79-87.
- Schiewer, S., and Volesky, B. (1995). "Modeling of the proton-metal ion-exchange in biosorption," *Environ. Sci. Technol.* 29(12), 3049-3058.
- Schiewer, S., and Volesky, B. (1996). "Modeling multi-metal ion exchange in biosorption," *Environ. Sci. Technol.* 30(10), 2921-2927.
- Schiewer, S., and Volesky, B. (1997a). "Ionic strength and electrostatic effects in biosorption of divalent metal ions and protons," *Environ. Sci. Technol.* 31(9), 2478-2485.
- Schiewer, S., and Wong, M. H. (1999). "Metal binding stoichiometry and isotherm choice in biosorption," *Environ. Sci. Technol.* 33(21), 3821-3828.
- Schiewer, S., and Wong, M. H. (2000). "Ionic strength effects in biosorption of metals by marine algae," *Chemosphere* 41(1-2), 271-282.
- Sciban, M., and Klasnja, M. (2004a). "Study of the adsorption of copper(II) ions from water onto wood sawdust, pulp and lignin," *Adsorp. Sci. Technol.* 22(3), 195-206.
- Sciban, M., and Klasnja, M. (2004b). "Wood saw dust and wood originate materials as adsorbents for heavy metal ions," *Holz Roh Werkst.* 62(1), 69-73.
- Sciban, M., Klasnja, M., and Skrbic, B. (2006a). "Modified hardwood sawdust as adsorbent of heavy metal ions from water," *Wood Sci. Technol.* 40(3), 217-227.
- Sciban, M., Klasnja, M., and Skrbic, B. (2006b). "Modified softwood sawdust as adsorbent of heavy metal ions from water," *J. Hazardous Mater.* 136(2), 226-271.
- Sciban, M., Klasnja, M., and Skrbic, B. (2008). "Adsorption of copper ions from water by modified agricultural by-products," *Desalination* 229(1-3), 170-180.
- Sciban, M., Radetic, B., Kevresan, D., and Klasnja, M. (2007). "Adsorption of heavy metals from electroplating wastewater by wood sawdust," *Bioresour. Technol.* 98(2), 402-409.
- Scott, C. D. (1992). "Removal of dissolved metals by plant tissue," *Biotechnol. Bioengng.* 39(10), 1064-1068.
- Seidel, A., and Gelbin, D. (1988). "On applying the ideal adsorbed solution theory to multicomponent adsorption equilibria of dissolved organic components on activated carbon," *Chem. Eng. Sci.* 43, 79-89.
- Seidel-Morgenstern, A., and Guichon, G. (1993). "Modelling of the competitive isotherms and the chromatographic separation of two enantiomers," *Chem. Eng. Sci.* 48, 2787-2797.
- Sekar, M., Sakthi, V., and Rengaraj, S. (2004). "Kinetics and equilibrium adsorption study of lead(II) onto activated carbon prepared from coconut shell," *J. Colloid Interface Sci.* 279(2), 307-313.

- Sekhar, K. C., Subramanian, S., Modak, J. M., and Natarajan, K. A. (1998). "Removal of metal ions using an industrial biomass with reference to environmental control," *Intl. J. Mineral Proc.* 53(1-2), 107-120.
- Seki, K., Saito, N., and Aoyama, M. (1997). "Removal of heavy metal ions from solutions by coniferous barks," *Wood Sci. Technol.* 31(6), 441-447.
- Selatnia, A., Bakhti, M. Z., Madani, A., Kertous, L., and Mansouri, Y. (2004a). "Biosorption of Cd^{2+} from aqueous solution by a NaOH-treated bacterial dead *Streptomyces rimosus* biomass," *Hydrometallurgy* 75(1-4), 11-24.
- Selatnia, A., Boukazoula, A., Kechid, N., Bakhti, M. Z., and Chergui, A. (2004b). "Biosorption of Fe^{3+} from aqueous solution by a bacterial dead *Streptomyces rimosus* biomass," *Process Biochem.* 39(11), 1643-1651.
- Selatnia, A., Boukazoula, A., Kechid, N., Bakhti, M. Z., Chergui, A., and Kerchich, Y. (2004c). "Biosorption of lead (II) from aqueous solution by a bacterial dead *Streptomyces rimosus* biomass," *Biochem. Eng. J.* 19(2), 127-135.
- Selatnia, A., Madani, A., Bakhti, M. Z., Kertous, L., Mansouri, Y., and Yous, R. (2004d). "Biosorption of Ni^{2+} from aqueous solution by a NaOH-treated bacterial dead *Streptomyces rimosus* biomass," *Miner. Eng.* 17(7-8), 903-911.
- Selvaraj, K., Manomani, S., and Pattabhi, S. (2003). "Removal of hexavalent chromium using distillery sludge," *Bioresour. Technol.* 89(2), 207-211.
- Selvi, K., Pattabhi, S., and Kadirvelu, K. (2001). "Removal of Cr(VI) from aqueous solution by adsorption onto activated carbon," *Bioresour. Technol.* 80(1), 87-89.
- Selomulya, C., Meeyoo, V., and Amal, R. (1999). "Mechanisms of Cr(VI) removal from water by various types of activated carbons," *J. Chem. Technol. Biotechnol.* 74(2), 111-122.
- Sharma, D. C., and Forster, C. F. (1993). "Removal of hexavalent chromium using sphagnum moss peat," *Water Res.* 27(7), 1201-1208.
- Sharma, D. C., and Forster, C. F. (1994a). "A preliminary examination into the adsorption of hexavalent chromium using low-cost adsorbents," *Bioresour. Technol.* 47(3), 257-264.
- Sharma, D. C., and Forster, C. F. (1994b). "The treatment of chromium wastewaters using the sorptive potential of leaf mould," *Bioresour. Technol.* 49(1), 31-40.
- Sharma, D. C., and Forster, C. F. (1995a). "Column studies into the adsorption of chromium(VI) using sphagnum moss peat," *Bioresour. Technol.* 52(3), 261-267.
- Sharma, D. C., and Forster, C. F. (1995b). "Continuous adsorption and desorption of chromium ions by sphagnum moss peat," *Process Biochem.* 30(4), 293-298.
- Sharma, D. C., and Forster, C. F. (1996a). "A comparison of the sorptive characteristics of leaf mould and activated carbon columns for the removal of hexavalent chromium," *Proc. Biochem.* 31(3), 213-218.
- Sharma, D. C., and Forster, C. F. (1996b). "Removal of hexavalent chromium from aqueous solutions by granular activated carbon," *Water SA* 22(2), 153-160.
- Sharma, R. K., and Chauhan, G. S. (2009). "Synthesis and characterization of graft copolymers of 2-hydroxyethyl methacrylate and some comonomers onto extracted cellulose for use in separation technologies," *BioResources* 4(3), 986-1005.
- Sheindorf, C., Rebhum, M., and Sheintuch, M. (1981). "A Freundlich-type multicomponent isotherm," *J. Colloid Interface Sci.* 79, 136-142.

- Shen, J. C., and Duvnjak, Z. (2004). "Effects of temperature and pH on adsorption isotherms for cupric and cadmium ions in their single and binary solutions using corncob particles as adsorbent," *Separ. Sci. Technol.* 39(13), 3023-3041.
- Shen, J. C., and Duvnjak, Z. (2005a). "Adsorption isotherms for cupric and cadmium ions on corncob particles," *Separ. Sci. Technol.* 40(7), 1461-1481.
- Shen, J. C., and Duvnjak, Z. (2005b). "A reversible surface reaction model with an effectiveness factor and its application to sorption kinetics of cupric ions on corncob particles," *Separ. Purification Technol.* 44(1), 69-77.
- Shen, J. C., and Duvnjak, Z. (2005c). "Adsorption kinetics of cupric and cadmium ions on corncob particles," *Process Biochem.* 40(11), 3446-3454.
- Sheng, P. X., Tan, L. H., Chen, J. P., and Ting, Y. P. (2004a). "Biosorption performance of two brown marine algae for removal of chromium and cadmium," *J. Dispersion Sci. Technol.* 25(5), 679-686.
- Sheng, P. X., Ting, Y. P., and Chen, J. P. (2007). "Biosorption of heavy metal ions (Pb, Cu, and Cd) from aqueous solutions by the marine alga *Sargassum* sp. in single- and multiple-metal systems," *Indus. Eng. Chem. Res.* 46(8), 2438-2444.
- Sheng, P. X., Ting, Y. P., Chen, J. P., and Hong, L. (2004b). "Sorption of lead, copper, cadmium, zinc and nickel by marine algal biomass: Characterization of biosorptive capacity and investigation of mechanisms," *J. Colloid Interface Sci.* 275(1), 131-141.
- Sheng, P. X., Wee, K. H., Ting, Y. P., and Chen, J. P. (2008). "Biosorption of copper by immobilized marine algal biomass," *Chem. Eng. J.* 136(2-3), 156-163.
- Shibi, I. G., and Anirudhan, T. S. (2002). "Synthesis, characterisation, and application as a mercury(II) sorbent of banana stalk-polyacrylamide grafted copolymer bearing carboxyl groups," *Industrial Engineering and Chemical Research* 41(22), 5341-5352.
- Shibi, I. G., and Anirudhan, T. S. (2005). "Adsorption of Co(II) by a carboxylate-functionalized polyacrylamide grafted lignocellulosics," *Chemosphere* 58(8), 1117-1126.
- Shibi, I. G., and Anirudhan, T. S. (2006). "Polymer-grafted banana (*Musa paradisiaca*) stalk as an adsorbent for the removal of lead(II) and cadmium(II) ions from aqueous solutions: Kinetic and equilibrium studies," *Journal of Chemical Technology and Biotechnology* 81(3), 433-444.
- Shim, J.-W., Park, S.-J., and Ryu, S.-K. (2001). "Effect of modification with HNO₃ and NaOH on metal adsorption by pitch-based activated carbon fibers," *Carbon* 39(11), 1635-1642.
- Shin, E. J., Lauve, A., Carey, M., Bukovsky, E., Ranville, J. F., Euans, R. J., and Herring, A. M. (2008). "The development of bio-carbon adsorbents from lodgepole pine to remediate acid mine drainage in the Rocky Mountains," *Biomass Bioenergy* 32(3), 267-276.
- Shin, E. W., Karthikeyan, K. G., and Tshabalala, M. A. (2007). "Adsorption mechanism of cadmium on juniper bark and wood," *Bioresour. Technol.* 98(3), 588-594.
- Shukla, A., Zhang, Y. H., Dubey, P., Margrave, J. L., and Shukla, S. S. (2002). "The role of sawdust in the removal of unwanted materials from water," *Journal of Hazardous Materials* 95(1-2), 137-152.

- Shukla, S. R., Gaikar, V. G., Pai, R. S., and Suryavanshi, U. S. (2009). "Batch and column adsorption of Cu(II) on unmodified and oxidized coir," *Separation Sci. Technol.* 44(1), 40-62.
- Shukla, S. R., and Pai, R. S. (2005a). "Adsorption of Cu (II), Ni (II) and Zn (II) on modified jute fibres," *Bioresour. Technol.* 96(13), 1430-1438.
- Shukla, S., and Pai, R. S. (2005b). "Removal of Pb(II) from solution using cellulose-containing materials," *J. Chem. Technol. Biotech.* 80(2), 176-183.
- Shukla, S. R., and Pai, R. S. (2005c). "Adsorption of Cu(II), Ni(II) and Zn(II) on dye loaded groundnut shells and sawdust," *Separ. Purif. Technol.* 43(1), 1-8.
- Shukla, S. R., Pai, R. S., and Shendarkar, A. D. (2006). "Adsorption of Ni(II), Zn(II) and Fe(II) on modified coir fibres," *Separation Purification Technol.* 47(3), 141-147.
- Shukla, S. S., Yu, L. J., Dorris, K., and Shukla, A. (2005d). "Removal of nickel from aqueous solutions by saw dust," *J. Hazard. Mater.* 121(1-3), 243-246.
- Silva, J. I. R., Ferreira, A. C. D., and da Costa, A. C. A. (2009). "Uranium biosorption under dynamic conditions: Preliminary tests with *Sargassum filipendula* in real radioactive wastewater containing Ba, Cr, Fe, Mn, Pb, Ca and Mg," *J. Radioanal. Nuclear Chem.* 279(3), 909-914.
- Simkovic, I. (1999). "Preparation of anion exchangers from beach sawdust and wheat straw," *Industrial Crops and Products* 10(3), 167-173.
- Singh, C. K., Sahu, J. N., Mahalik, K. K., Mohanty, C. R., Mohan, B. R., and Meikap, B. C. (2007). "Studies on the removal of Pb(II) from wastewater by activated carbon developed from *Tamarind* wood activated with sulphuric acid," *J. Hazard. Mater.* 153(1-2), 221-228.
- Singh, K. K., Rastogi, R., and Hasan, S. H. (2005a). "Removal of Cr(VI) from wastewater using rice bran," *J. Colloid Interface Sci.* 290(1), 61-68.
- Singh, K. K., Rastogi, R., and Hasan, S. H. (2005b). "Removal of cadmium from waste water using agricultural waste 'rice polish'," *J. Hazard. Mater.* 121(1-3), 51-58.
- Singh, K. K., Singh, A. K., and Hasan, S. H. (2006). "Low cost bio-sorbent 'wheat bran' for the removal of cadmium from wastewater: Kinetic and equilibrium studies," *Bioresour. Technol.* 97(8), 994-1001.
- Singh, V. K., and Tiwari, P. N. (1997). "Removal and recovery of chromium(VI) from industrial wastewater," *J. Chem. Technol. Biotechnol.* 69, 376-382.
- Sjöström, E. (1993). *Wood Chemistry: Fundamentals and Applications*, Academic Press, San Diego, CA, USA.
- Skowronski, T., Pirszel, J., and Pawlik-Skowronska, B. (2001). "Heavy metal removal by the waste biomass of *Penicillium chrysogenum*," *Water Qual. Res. J. Can.* 36(4), 793-803.
- Sokker, H. H., Badawy, S. M., Zayed, E. M., Eldien, F. A. N., and Farag, A. M. (2009). "Radiation-induced grafting of glycidyl methacrylate onto cotton fabric waste and its modification for anchoring hazardous wastes from their solutions," *J. Hazardous Mater.* 168(1), 137-144.
- Soleimani, M., and Kaghazchi, T. (2007). "Agricultural waste conversion to activated carbon by chemical activation with phosphoric acid," *Chem. Eng. Technol.* 30(5), 649-654.

- Soleimani, M., and Kaghazchi, T. (2008). "The investigation of the potential of activated hard shell of apricot stones as gold adsorbents," *J. Indus. Eng. Chem.* 14(1), 28-37.
- Southichak, B., Nakano, K., Nomura, M., Chiba, N., and Nishimura, O. (2006a). "*Phragmites australis*: A novel biosorbent for the removal of heavy metals from aqueous solution," *Water Res.* 40(12), 2295-2302.
- Southichak, B., Nakano, K., Nomura, M., Chiba, N., and Nishimura, O. (2006b). "Pb(II) biosorption on reed biosorbent derived from wetland: Effect of pretreatment on functional groups," *Water Sci. Technol.* 54(10), 133-141.
- Southichak, B., Nakano, K., Nomura, M., Chiba, N., and Nishimura, O. (2009). "Differences in adsorption mechanisms of heavy metal by two different plant biomasses: Reed and brown seaweed," *Water Sci. Technol.* 59(2), 339-346.
- Spanelova, M., Machovic, V., and Brezina, M. (2003). "Characterization and sorption properties of *Aspergillus niger* waste biomass," *Cent. Eur. J. Chem.* 1(3), 192-200.
- Sreejalekshmi, K. G., Krishnan, K. A., and Anirudhan, T. S. (2009). "Adsorption of Pb(II) and Pb(II)-citric acid on sawdust activated carbon: Kinetic and equilibrium isotherm studies," *J. Hazardous Mater.* 161(2-3), 1506-1523.
- Sricharoenchaiikul, V., Pechyen, C., Aht-ong, D., and Atong, D. (2008). "Preparation and characterization of activated carbon from the pyrolysis of physic nut (*Jatropha curcas* L.) waste," *Energy Fuels* 22(1), 31-37.
- Srinath, T., Verma, T., Ramteke, P. W., and Garg, S. K. (2002). "Chromium(VI) biosorption and bioaccumulation by chromate resistant bacteria," *Chemosphere* 48, 427-435.
- Srinivasan, K., and Hema, M. (2009). "Nickel removal from wastewater by using activated carbon prepared from agro industrial wastes," *Res. J. Chem. Env.* 13(3), 54-65.
- Srivastava, S. K., Singh, A. K., and Sharma, A. (1994). "Studies on the uptake of lead and zinc by lignin obtained from black liquor a paper industry waste material," *Environ. Technol.* 15(4), 353-361.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2006a). "Equilibrium modelling of single and binary adsorption of cadmium and nickel onto bagasse fly ash," *Chem. Eng. J.* 117(1), 79-91.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2006b). "Modelling individual and competitive adsorption of cadmium(II) and zinc(II) metal ions from aqueous solution onto bagasse fly ash," *Separ. Sci. Technol.* 41(12), 2685-2710.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2006c). "Characterization of mesoporous rice husk ash (RHA) and adsorption kinetics of metal ions from aqueous solution onto RHA," *J. Hazard. Mater. B* 134(1-3), 257-267.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2007). "Adsorption thermodynamics and isosteric heat of adsorption of toxic metal ions onto bagasse fly ash (BFA) and rice husk ash (RHA)," *Chem. Eng. J.* 132(1-3), 267-278.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2008a). "Removal of cadmium(II) and zinc(II) metal ions from binary aqueous solution by rice husk ash," *Colloids Surf. A – Physicochem. Eng. Aspects* 312(2-3), 172-184.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2008b). "Adsorption of toxic metal ions onto activated carbon - Study of sorption behaviour through characterization and kinetics," *Chem. Eng. Proc.* 47(8), 1275-1286.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2009a). "Equilibrium modeling of ternary

- adsorption of metal ions onto rice husk ash,” *J. Chem. Eng. Data* 54(3), 705-711.
- Srivastava, V. C., Mall, I. D., and Mishra, I. M. (2009b). “Competitive adsorption of cadmium(II) and nickel(II) metal ions from aqueous solution onto rice husk ash,” *Chem. Eng. Proc.* 48(1), 370-379.
- Srivastava, S., and Thakur, I. S. (2006). “Biosorption potency of *Aspergillus niger* for removal of chromium (VI),” *Current Microbiol.* 53(3), 232-237.
- Stefan, D. S., Belcu, M., Stefan, M., and Marinescu, I. A. (2010). “Sorption of Hg^{2+} and Pb^{2+} ions from aqueous solutions on corn cobs biomaterials,” *Revista de Chimie* 61(1), 31-35.
- Stone, J. E., and Scallan, A. M. (1966). “Influence of drying on the pore structures of the cell wall,” in *Consolidation of the Paper Web*, Trans. Symp. Cambridge, Sept. 1965, F. Bolam (ed.), Tech. Sec. British Paper and Board Makers’ Assoc. Inc, London, Vol. 1, 145-174.
- Sud, D., Mahajan, G., and Kaur, M. P. (2008). “Agricultural waste material as potential adsorbent for sequestering heavy metal ions from aqueous solutions - A review,” *Bioresour. Technol.* 99, 6017-6027.
- Sudha, B. R., and Abraham, E. (2003). “Studies on chromium (VI) adsorption using immobilized fungal biomass,” *Bioresour. Technol.* 87(1), 17-26.
- Suemitsu, R., Uenishi, R., Akashi, I., and Nakan, M. (1986). “The use of dyestuff-treated rice hulls for the removal of heavy metals from waste water,” *J. Appl. Polym. Sci.* 31(1), 75-83.
- Suh, J. H., Yun, J. W., and Kim, D. S. (1998). “Comparison of Pb^{2+} accumulation characteristics between live and dead cells of *Saccharomyces cerevisiae* and *Aureobasidium pullulans*,” *Biotechnology Letters* 20(3), 247-251.
- Suhas, Carrott, P. J. M., and Carrott, M. M. L. R. (2007). “Lignin-from natural adsorbent to activated carbon: A review,” *Bioresour. Technol.* 98(12), 2301-2312.
- Suksabye, P., Nakajima, A., Thiravetyan, P., Baba, Y., and Nakbanpote, W. (2009). “Mechanism of Cr(VI) adsorption by coir pith studied by ESR and adsorption kinetic,” *J. Hazardous Mater.* 161(2-3), 1103-1108.
- Suksabye, P., Thiravetyan, P., Nakbanpote, W., and Chayabutra, S. (2007). “Chromium removal from electroplating wastewater by coir pith,” *J. Hazard. Mater.* 141(3), 637-644.
- Sumathi, K. M. S., Mahimairaja, S., and Naidu, R. (2005). “Use of low-cost biological wastes and vermiculite for removal of chromium from tannery effluent,” *Bioresour. Technol.* 96(3), 309-316.
- Sun, G., and Shi, W. X. (1998). “Sunflower stalks as adsorbents for the removal of metal ions from wastewater,” *Ind. Eng. Chem. Res.* 37(4), 1324-1328.
- Sundman, O., and Öhman, L. O. (2006). “Acid/base and metal adsorption properties of CMC-type softwood Kraft pulps of different charge,” *Nordic Pulp Paper Res. J.* 21(3), 372-381.
- Sundman, O., Persson, P., and Ohman, L. O. (2008). “A multitechnique study of the interactions between H^+ , Na^+ , Ca^{2+} and Cu^{2+} , and two types of softwood Kraft fibre materials,” *J. Colloid Interface Sci.* 328(2), 248-256.

- Sungur, S., and Babaoglu, S. (2005). "Synthesis of a new cellulose ion exchanger and use for the separation of heavy metals in aqueous solutions," *Separation Sci. Technol.* 40(10), 2067-2078.
- Suryavanshi, U. S., and Shukla, S. R. (2009). "Adsorption of Ga(III) on oxidized coir," *Ind. Eng. Chem. Res.* 48(2), 870-876.
- Svecova, L., Spanelova, M., Kubal, M., and Guibal, E. (2006). "Cadmium, lead and mercury biosorption on waste fungal biomass issued from fermentation industry. 1. Equilibrium studies," *Sep. Purif. Technol.* 52(1), 142-153.
- Tabakci, M., Erdemir, S., and Yilmaz, M. (2007). "Preparation, characterization of cellulose grafted with calix[4]arene polymers for the adsorption of heavy metals and dichromate anions," *J. Hazard. Mater.* 148(1-2), 428-435.
- Tandel, M. A., and Oza, B. N. (2005). "Adsorption and regeneration studies for the removal of chromium(VI) from the wastewater of electroplating industry using granular activated carbon," *Asian J. Chem.* 17(4), 2524-2530.
- Tangsathitkulchai, C., Ngernyen, Y., and Tangsathitkulchai, M. (2009). "Surface modification and adsorption of eucalyptus wood-based activated carbons: Effects of oxidation treatment, carbon porous structure and activation method," *Kor. J. Chem. Eng.* 26(5), 1341-1352.
- Tan, L., Zhu, D., Zhou, W., Mi, W., Ma, L., and He, W. (2008). "Preferring cellulose of *Eichhornia crassipes* to prepare xanthogenate to other plant materials and its adsorption properties on copper," *Bioresour. Technol.* 99(10), 4460-4466.
- Tan, W. T., Ooi, S. T., and Lee, C. K. (1993). "Removal of chromium (VI) from solution by coconut husk and palm pressed fibers," *Environ. Technol.* 14(3), 277-282.
- Tangaromsuk, J., Pokethitiyook, P., Kruatrachue, M., and Upatham, E. S. (2002). "Cadmium biosorption by *Sphingomonas paucimobilis* biomass," *Bioresour. Technol.* 85(1), 103-105.
- Tangjuank, S., Insuk, N., Udeye, V., and Tontrakoon, J. (2009). "Chromium (III) sorption from aqueous solutions using activated carbon prepared from cashew nut shells," *Intl. J. Phys. Sci.* 4(8), 412-417.
- TAPPI (1993). "Carboxyl content of pulp," In: *TAPPI Test Methods*, Technical Association of the Pulp and Paper Industry, Atlanta, GA, USA, method T237 om-93.
- Tarley, C. R. T., and Arruda, M. A. Z. (2004). "Biosorption of heavy metals using rice milling byproducts. Characterization and application for removal of metals from aqueous effluents," *Chemosphere* 54(7), 987-995.
- Tashiro, T., and Shimura, Y. (1982). "Removal of mercuric ions by systems based on cellulose derivatives," *Journal of Applied Polymer Science* 27(2), 747-756.
- Taty-Costodes, C. V., Fauduet, H., Porte, C., and Delacroix, A. (2003). "Removal of Cd(II) and Pb(II) ions, from aqueous solutions, by adsorption onto sawdust of *Pinus sylvestris*," *J. Hazard. Mater.* B105, 121-142.
- Tazrouti, N., and Amrani, M. (2009). "Chromium (VI) adsorption onto activated kraft lignin produced from alfa grass (*Stipa tenacissima*)," *BioResources* 4(2), 740-755.
- Temkin, M. J., and Pyzhev, V. (1940). "Kinetics of ammonia synthesis on promoted iron catalysts," *Acta Physiochim. URSS* 12, 217-222.
- Tewari, N., Vasudevan, P., and Guha, B. K. (2005). "Study on biosorption of Cr(VI) by *Mucor hiemalis*," *Biochem. Eng. J.* 23(2), 185-192.

- Texier, A.C., Andrès, Y., and Le Cloirec, P. (1999). "Selective biosorption of lanthanide (La, Eu, Yb) ions by *Pseudomonas aeruginosa*," *Environ. Sci. Technol.* 33, 489-495.
- Texier, A. C., Andres, Y., and Le Cloirec, P. (2000). "Selective biosorption of lanthanide (La, Eu, Yb) ions by an immobilized bacterial biomass," *Water Sci. Technol.* 42(5-6), 91-94.
- Tiemann, K. J., Gardea-Torresdey, J. L., Gamez, G., Dokken, K., Cano-Aguilera, I., Renner, J. W., and Furenlid, L. R. (2000). "Effects of oxidation state on metal ion binding by *Medicago sativa* (alfalfa): Atomic and X-ray absorption spectroscopic studies with Fe(II) and Fe(III)," *Environ. Sci. Technol.* 34(4), 693-698.
- Tiemann, K. J., Gardea-Torresdey, J. L., Gamez, G., Dokken, K., and Sias, S. (1999). "Use of X-ray absorption spectroscopy and esterification to investigate chromium(III) and nickel(II) ligand in alfalfa biomass," *Environmental Science & Technology* 33, 150-154.
- Tiemann, K. J., Rascon, A. E., Gamez, G., Parsons, J. G., Baig, T., Cano-Aguilera, E., and Gardea-Torresdey, J. L. (2002). "Heavy metal binding by inactivated tissues of *Solanum elaeagnifolium*: Chemical and subsequent XAS studies," *Microchem. J.* 71(2-3), 133-141.
- Tiwari, D., Mishra, S. P., Mishra, M., and Dubey, R. S. (1999). "Biosorptive behaviour of mango (*Mangifera indica*) and neem (*Azadirachta indica*) bark for Hg^{2+} , Cr^{3+} , and Cd^{2+} toxic ions from aqueous solutions: A radiotracer study," *Appl. Radiat. Isot.* 50(4), 631-642.
- Tobin, J. M., Cooper, D.G., and Neufeld, R. J. (1984). "Uptake of metal ions by *Rhizopus arrhizus* biomass," *Appl. Environ. Microbiol.* 47(4), 821-824.
- Tobin, J. M., and Roux, J. C. (1998). "Mucor biosorbent for chromium removal from tanning effluent," *Water Res.* 32(5), 1407-1416.
- Toles, C. A., Marshall, W. E., and Johns, M. M. (1997). "Granular activated carbons from nutshells for the uptake of metals and organic compounds," *Carbon* 35(9), 1407-1414.
- Toles, C. A., Marshall, W. E., and Johns, M. M. (1998). "Phosphoric acid activation of nutshells for metals and organic remediation. Process optimization," *J. Chem. Technol. Biotechnol.* 72(3), 255-263.
- Toles, C. A., Marshall, W. E., and Johns, M. M. (1999). "Surface functional groups on acid-activated nutshell carbons," *Carbon* 37(8), 1207-1214.
- Townsley, C. C., and Ross, I. S. (1986). "Copper uptake in *Aspergillus niger* during batch growth and in non-growing mycelial suspensions," *Experimental Mycology* 10(4), 281-288.
- Tsezos, M., and Volesky, B. (1981). "Biosorption of uranium and thorium," *Biotechnology and Bioengineering* 23(3), 583-604.
- Tsezos, M., and Volesky, B. (1982). "The mechanism of uranium biosorption by *Rhizopus arrhizus*," *Biotechnology and Bioengineering* 24(2), 385-401.
- Tshabalala, M. A., Karthikeyan, K. G., and Wang, D. (2004). "Cationized milled pine bark as an adsorbent for orthophosphate anions," *J. Appl. Polymer Sci.* 93(4), 1577-1583.
- Tsui, M. T. K., Cheung, K. C., Tam, N. F. Y., and Wong, M. H. (2006). "A comparative study on metal sorption by brown seaweed," *Chemosphere* 65(1), 51-57.

- Tunali, S., Kiran, I., and Akar, T. (2005). "Chromium(VI) biosorption characteristics of *Neurospora crassa* fungal biomass," *Miner. Eng.* 18, 681-689.
- Tupkanjana, P., and Phalakornkule, C. (2007). "Development of activated carbons from sunflower seed husk for metal adsorption," *J. Chem. Eng. Japan* 40(3), 222-227.
- Tuzen, M., Sari, A., Mendil, D., and Soylak, M. (2009). "Biosorptive removal of mercury(II) from aqueous solution using lichen (*Xanthoparmelia conspersa*) biomass: Kinetic and equilibrium studies," *J. Hazardous Mater.* 169(1-3), 263-270.
- Ucer, A., Uyanik, A., and Aygün, Ş. F. (2006). "Adsorption of Cu(II), Cd(II), Zn(II), Mn(II), and Fe(III) ions by tannic acid immobilised activated carbon," *Sep. Purif. Technol.* 47, 113-118.
- Ucer, A., Uyanik, A., Cay, S., and Ozkan, Y. (2005). "Immobilisation of tannic acid onto activated carbon to improve Fe(III) adsorption," *Separ. Purif. Technol.* 44(1), 11-17.
- Ucun, H., Aksakal, O. and Yildiz, E. (2009). "Copper(II) and zinc(II) biosorption on *Pinus sylvestris* L," *Journal of Hazardous Materials* 161(2-3), 1040-1045.
- Ugurlu, M., Kula, I., Karaoglu, M. H., and Arslan, Y. (2009). "Removal of Ni(II) ions from aqueous solutions using activated-carbon prepared from olive stone by ZnCl₂ activation," *Environ. Prog. Sustain. Energy* 28(4), 547-557.
- Ulmanu, M., Marañón, E., Fernández, Y., Castrillón, L., Anger, I., and Dumitriu, D. (2003). "Removal of copper and cadmium ions from diluted aqueous solutions by low cost and waste material adsorbents," *Water, Air, Soil Pollut.* 142(1-4), 357-373.
- Uluozlu, O. D., Sari, A., Tuzen, M., and Soylak, M. (2008). "Biosorption of Pb(II) and Cr(III) from aqueous solution by lichen (*Parmelina tiliaceae*) biomass," *Bioresour. Technol.* 99(8), 2972-2980.
- Unnithan, M. R., and Anirudhan, T. S. (2001). "The kinetics and thermodynamics of sorption of chromium(VI) onto the iron(III) complex of a carboxylated polyacrylamide-grafted sawdust," *Ind. Eng. Chem. Res.* 40(12), 2693-2701.
- Unnithan, M. R., Vinod, V. P., Anirudhan, T. S. (2004). "Synthesis, characterization, and application as a chromium(VI) adsorbent of amine-modified polyacrylamide-grafted coconut coir pith," *Indus. Eng. Chem. Res.* 43(9), 2247-2255.
- Upendra, K., and Manas, B. (2006). "Sorption of cadmium from aqueous solution using pretreated rice husk," *Bioresour. Technol.* 97(1), 104-109.
- Valdman, E., Leite, S. G. F. (2000). "Biosorption of Cd, Zn and Cu by *Sargassum* sp. waste biomass," *Bioprocess Engineering* 22, 171-173.
- Valix, M., Cheung, W. H., and Zhang, K. (2006). "Role of heteroatom in activated carbon for the removal of hexavalent Cr from wastewater," *J. Hazard. Mater.* 135(1-3), 395-405.
- Valix, M., Cheung, W. H., and Zhang, K. (2008). "Textural and surface chemistry of activated bagasse and its role in the removal of chromium ions from solution," *Adsorp. J. Intl. Adsorp. Soc.* 14(4-5), 711-718.
- Vaughan, T., Seo, C. W., and Marshall, W. E. (2001). "Removal of selected metal ions from aqueous solution using modified corncobs," *Bioresour. Technol.* 78(2), 133-139.
- Veglio, F., and Beolcini, F. (1997). "Removal of metals by biosorption: A review," *Hydrometallurgy* 44, 301-316.

- Verma, V. K., Tewari, S., and Rai, J. P. N. (2008). "Ion exchange during heavy metal bio-sorption from aqueous solution by dried biomass of macrophytes," *Bioresour. Technol.* 99(6), 1932-1938.
- Vianna, L. N. L., Andrade, M. C., and Nicoli, J. R. (2000). "Screening of waste biomass from *Saccharomyces cerevisiae*, *Aspergillus oryzae* and *Bacillus lentus* fermentations for removal of Cu, Zn and Cd by biosorption," *World J. Microbiol. Biotechnol.* 16(5), 437-440.
- Vieira, M. G. A., Oisiovici, R. M., Gimenes, M. L., and Silva, M. G. C. (2008). "Biosorption of chromium(VI) using a *Sargassum* sp. packed-bed column," *Bioresour. Technol.* 99(8), 3094-3099.
- Viera, R. H. S. F., and Volesky, B. (2000). "Biosorption: A solution to pollution?" *Internatl. Microbiol.* 3(1), 17-24.
- Vijayaraghavan, K., Lee, M. W., and Yun, Y. S. (2008). "Evaluation of fermentation waste (*Corynebacterium glutamicum*) as a biosorbent for the treatment of nickel(II)-bearing solutions," *Biochem. Eng. J.* 41(3), 228-233.
- Vijayaraghavan, K., Padmesh, T. V. N., Palanivelu, K., and Velan, M. (2006a). "Biosorption of nickel (II) ions onto *Sargassum wightii*: Application of two-parameter and three parameter isotherm models," *J. Hazard. Mater.* 133(1-3), 304-308.
- Vijayaraghavan, K., and Yun, Y. S. (2008). "Bacterial biosorbents and biosorption," *Biotechnol. Adv.* 26(3), 266-291.
- Villaescusa, I., Fiol, N., Martinez, M., Miralles, N., Poch, J., and Serarols, J. (2004). "Removal of copper and nickel ions from aqueous solutions by grape stalk wastes," *Water Research* 38(4), 992-1002.
- Villaescusa, I., Martinez, M., and Miralles, N. (2000). "Heavy metal uptake from aqueous solutions by cork and *Yohimber* bark wastes," *J. Chem. Tech. Biotechnol.* 75(9), 812-816.
- Vinopal, S., Ruml, T., and Kotrba, P. (2007). "Biosorption of Cd^{2+} and Zn^{2+} by cell surface-engineered *Saccharomyces cerevisiae*," *Int. Biodeter. Biodegrad.* 60(2), 96-102.
- Volesky, B. (1994). "Advances in biosorption of metals: Selection of biomass types," *FEMS Microbiol. Rev.* 14(4), 291-302.
- Volesky, B. (2001). "Detoxification of metal bearing effluents: Biosorption for next century," *Hydrometallurgy* 59(2-3), 203-216.
- Volesky, B., and Holan, Z. R. (1995). "Biosorption of heavy metals," *Biotechnol. Prog.* 11(3), 235-250.
- Volesky, B., May, H., and Holan, Z. R. (1993). "Cadmium biosorption by *Saccharomyces cerevisiae*," *Biotechnol. Bioeng.* 41(8), 826-829.
- Volesky, B., and Prasetyo, I. (1994). "Cadmium removal in the biosorption column," *Biotechnology & Bioengineering* 43, 1010-1015.
- Volesky, B., Weber, J., and Park, J. M. (2003). "Continuous-flow metal biosorption in a regenerable *Sargassum* column," *Water Res.* 37(2), 297-306.
- Volpe, A., Lopez, A., and Pagano, M. (2003). "Olive husk - An alternative sorbent for removing heavy metals from aqueous streams," *Appl. Biochem. Biotechnol.* 110(3), 137-149.

- Wafwoyo, W., Chung, W. S., and Marshall, W. E. (1999). "Utilization of peanut shells as adsorbents for selected metals," *J. Chem. Tech. Biot.* 74(11), 1117-1121.
- Wan Ngah, W. S., and Hanafiah, M. A. K. M. (2008b). "Removal of heavy metal ions from wastewater by chemically modified plant wastes as adsorbents: A review," *Bioresour. Tech.* 99(10), 3935-3948.
- Wang, J. L., and Chen, C. (2006). "Biosorption of heavy metals by *Saccharomyces cerevisiae*: A review," *Biotechnol. Adv.* 24(5), 427-451.
- Wang, J. L., and Chen, C. (2009). "Biosorbents for heavy metals removal and their future," *Biotechnol. Advances* 27(2), 195-226.
- Wang, J. L., Zhan, X. M., Ding, D. C., and Zhou, D. (2001). "Bioadsorption of lead(II) from aqueous solution by fungal biomass of *Aspergillus niger*," *J. Biotechnol.* 87(3), 273-277.
- Wang, X. S., Li, Z. Z., and Sun, C. (2009). "A comparative study of removal of Cu(II) from aqueous solutions by locally low-cost materials: Marine macroalgae and agricultural by-products," *Desalination* 235(1-3), 146-159.
- Wang, X. S., Tang, Y. P., and Tao, S. R. (2008). "Removal of Cr (VI) from aqueous solutions by the nonliving biomass of alligator weed: Kinetics and equilibrium," *Adsorption – J. Intl. Adsorp. Soc.* 14(6), 823-830.
- Wang, X. S., Tang, Y. P., and Tao, S. R. (2009). "Kinetics, equilibrium and thermodynamic study on removal of Cr(VI) from aqueous solutions using low-cost adsorbent alligator weed," *Chem. Eng. J.* 148(2-3), 217-225.
- Wang, Y. H., Lin, S. H., and Juang, R. S. (2003). "Removal of heavy metal ions from aqueous solutions using various low-cost adsorbents," *Journal of Hazardous Materials* 102(2-3), 291-302.
- Wartelle, L. H., and Marshall, W. E. (2000). "Citric acid modified agricultural by-products as copper ion adsorbents," *Adv. Environ. Res.* 4(1), 1-7.
- Wartelle, L. H., and Marshall, W. E. (2005). "Chromate ion adsorption by agricultural by-products modified with dimethyldihydroxyethylene urea and choline chloride," *Water Res.* 39(13), 2869-2876.
- Wase, J., and Forster, C. (1997). *Biosorbents for Metal Ions*, Taylor and Francis, 238 pp.; Chapters of particular note: Forster, C. F., and Wase, D. A J., "Biosorption of heavy metals: An introduction," Ch. 1, pp. 1-10; Garnham, G. W., "The use of algae as metal biosorbents," Ch. 2, pp. 11-37; Urrutia, M. M., "General bacterial sorption processes," Ch. 3, pp. 39-66; Kapoor, A., and Viraraghavan, T., "Fungi as biosorbents," Ch. 4, pp. 67-85.
- Williams, C. J., Aderhold, D., and Edyvean, G. J. (1998). "Comparison between biosorbents for the removal of metal ions from aqueous solution," *Water Res.* 32(1), 216-224.
- Wing, R. E. (1996). "Corn fibre citrate: Preparation and ion exchange properties," *Ind. Crops Prod.* 5(4), 301-305.
- Wing, R. E. (1997). "Cellulosic citrates: Preparation and ion exchange properties," *J. Polymer Mater.* 14(4), 303-309.

- Wong, K. K., Lee, C. K., Low, K. S., and Haron, M. J. (2003). "Removal of Cu and Pb from electroplating wastewater using tartaric acid modified rice husk," *Proc. Biochem.* 39(4), 437-445.
- Wu, Y., Zhang, S. Z., Guo, X. Y., and Huang, H. L. (2008). "Adsorption of chromium(III) on lignin," *Bioresour. Technol.* 99(16), 7709-7715.
- Xie, J. Z., Chang, H. L., and Kilbane, J. J. (1996). "Removal and recovery of metal ions from wastewater using biosorbents and chemically modified biosorbents," *Bioresour. Technol.* 57(2), 127-136.
- Xiu, G. H., and Li, P. (2000). "Prediction of breakthrough curves for adsorption of lead(II) on activated carbon fibers in a fixed bed," *Carbon* 38(7), 975-981.
- Xu, T., and Liu, X. Q. (2008). "Peanut shell activated carbon: Characterization, surface modification and adsorption of Pb^{2+} from aqueous solution," *Chinese J. Chem. Eng.* 16(3), 401-406.
- Xuan, Z. X., Tang, Y. R., Li, X. M., Liu, Y. H., and Luo, F. (2006). "Study on the equilibrium, kinetics and isotherm of biosorption of lead ions onto pretreated chemically modified orange peel," *Biochem. Eng. J.* 31(2), 160-164.
- Yan, G. Y., and Viraraghavan, T. (2001). "Heavy metal removal in a biosorption column by immobilized *M. rouxii* biomass," *Bioresour. Technol.* 78(3), 243-249.
- Yan, G., and Viraraghavan, T. (2003). "Heavy-metal removal from aqueous solution by fungus *Mucor rouxii*," *Water Research* 37, 4486-4496.
- Yang, J., and Volesky, B. (1999a). "Biosorption of uranium on *Sargassum* biomass," *Water Res.* 33 (15), 3357-3363.
- Yang, J., and Volesky, B. (1999b). "Cadmium biosorption rate in protonated *Sargassum* biomass," *Environ. Sci. Technol.* 33(5), 751-757.
- Yang, J., and Volesky, B. (1999c). "Modeling uranium—proton ion exchange in biosorption," *Environ. Sci. Technol.* 33(22), 4079-4085.
- Yang, L., and Chen, J. P. (2008). "Biosorption of hexavalent chromium onto raw and chemically modified *Sargassum* sp.," *Bioresour. Technol.* 99(2), 297-307.
- Yang, T., and Lua, A. C. (2006). "Textural and chemical properties of zinc chloride activated carbons prepared from pistachio-nut shells," *Mater. Chem. Phys.* 100(2-3), 438-444.
- Yi, W., Sakamoto, Y., and Kamiya, Y. (2009). "Remediation of actual groundwater polluted with nitrate by the catalytic reduction over copper-palladium supported on active carbon," *Appl. Catal. A Gen.* 361(1-2), 123-129.
- Yin, H., He, B., Peng, H., Ye, J., Yang, F., and Zhang, N. (2008). "Removal of Cr(VI) and Ni(II) from aqueous solution by fused yeast: Study of cations release and biosorption mechanism," *J. Hazard. Mater.* 158(2-3), 568-576.
- Yin, P., Yu, Q., Jin, B., and Ling, Z. (1999). "Biosorption removal of cadmium from aqueous solution by using pretreated fungal biomass cultured from starch wastewater," *Water Res.* 33(8), 1960-1963.
- Yoon, S., Han, S. S., and Rana, S. V. S. (2008). "Molecular markers of heavy metal toxicity - A new paradigm for health risk assessment," *J. Environ. Biol.* 29(1), 1-14.
- Youssef, A. M., El-Nabarawi, T., and Samra, S. E. (2004). "Sorption properties of chemically activated carbons. 1. Sorption of cadmium (II) ions," *Colloid Surf. A* 235(1-3), 153-163.

- Yu, B., Zhang, Y., Shukla, S. S., and Dorris, K. L. (2000). "The removal of heavy metal from aqueous solutions by sawdust adsorption – Removal of copper," *J. Hazard. Mater. B* 80(1-3), 33-42.
- Yu, B., Zhang, Y., Shukla, A., Shukla, S., and Dorris, K. L. (2001). "The removal of heavy metals from aqueous solutions by sawdust adsorption – Removal of lead and comparison of its adsorption with copper," *J. Hazard. Mater.* 84(1), 83-94.
- Yu, H., Covey, G. H., and O'Connor, A. J. (2008). "Innovative use of silvichemical biomass and its derivatives for heavy metal sorption from wastewater," *Int. J. Environ. Pollut.* 34(1-4), 427-450.
- Yu, J. X., Tong, M., Sun, X. M., and Li, B. H. (2007). "A simple method to prepare poly(amic acid)-modified biomass for enhancement of lead and cadmium adsorption," *Biochem. Eng. J.* 33(2), 126-133.
- Yu, L. J., Shukla, S. S., Dorris, K. L., Shukla, A., and Margrave, J. L. (2003). "Adsorption of chromium from aqueous solutions by maple sawdust," *J. Hazard. Mater.* 100(1-3), 53-63.
- Yu, Q. M., Matheickal, J. T., Yin, P. H., and Kaewsarn, P. (1999). "Heavy metal uptake capacities of common marine macro algal biomass," *Water Res.* 33(6), 1534-1537.
- Yue, Z. R., Bender, S. E., Wang, J. W., and Economy, J. (2009). "Removal of chromium Cr(VI) by low-cost chemically activated carbon materials from water," *J. Hazard. Mater.* 166(1), 74-78.
- Yun, Y. S., Park, D., Park, J. M., and Volesky, B. (2001). "Biosorption of trivalent chromium on the brown seaweed biomass," *Environ. Sci. Technol.* 35(21), 4353-4358.
- Yun, Y. S., and Volesky, B. (2003). "Modeling of lithium interference in cadmium biosorption," *Environ. Sci. Technol.* 37(16), 3601-3608.
- Zafar, M. N., Nadeem, R., and Hanif, M. A. (2007). "Biosorption of nickel from protonated rice bran," *J. Hazardous Mater.* 143(1-2), 478-485.
- Zagorodni, A. A. (2007). *Ion Exchange Materials: Properties and Applications*, Elsevier, Amsterdam.
- Zahra, N. (2010). "Arsenic contamination in water and its removal by using different low cost adsorbents," *J. Chem. Soc. Pakistan* 32(2), 259-264.
- Zatta, P. (ed.) (2003). *Metal Ions and Neurodegenerative Disorders*, World Scientific, River Edge, NJ, USA.
- Zhang, K., Cheung, W. H., and Valix, M. (2005). "Roles of physical and chemical properties of activated carbon in the adsorption of lead ions," *Chemosphere* 60(8), 1129-1140.
- Zhang, L. N., Cai, J., Zhou, J. P., and Tang, Y. R. (2004). "Adsorption Cd^{2+} and Cu^{2+} on ion-exchange beads from cellulose/alginate acid blend," *Separation Sci. Technol.* 39(5), 1203-1219.
- Zhang, L., Zhao, L., Yu, Y., and Chen, C. (1998). "Removal of lead from aqueous solution by non-living *Rhizopus nigricans*," *Water Res.* 32(5), 1437-1444.
- Zhang, Y., and Banks, C. (2006). "A comparison of the properties of polyurethane immobilised *Sphagnum* moss, seaweed, sunflower waste and maize for the biosorption of Cu, Pb, Zn and Ni in continuous flow packed columns," *Water Res.* 40(4), 788-798.

- Zhang, Z. H., Wu, Q. L., Cai, Z. T., Yan, C., Song, H. Y., and Pan, D. (2009). "Effect of alkali metal salt on the macropore structure of rayon-based activated carbon fibers," *New Carbon Mater.* 24(3), 265-269.
- Zhao, B-X., Wang, P., Zheng, T., Chen, C.-Y., and Shu, J. (2006). "Preparation and adsorption performance of a cellulosic-adsorbent resin for copper(II)," *J. Applied Poly. Sci.* 99(6), 2951-2959.
- Zhao, M., and Duncan, J. R. (1997a). "Batch removal of hexivalent chromium by *Azolla filiculoides*," *Biotechnol. Appl. Biochem.* 26, 179-182.
- Zhao, M., and Duncan, J. R. (1997b). "Use of formaldehyde cross-linked *Saccharomyces cerevisiae* in column bioreactors for removal of metals from aqueous solutions," *Biotechnol. Lett.* 19(10), 953-955.
- Zhao, M., and Duncan, J. R. (1998a). "Removal and recovery of nickel from aqueous solution and electroplating rinse effluent using *Azolla filiculoides*," *Proc. Biochem.* 33(3), 249-255.
- Zhao, M., and Duncan, J. R. (1998b). "Column sorption of Cr(VI) from electroplating effluent using formaldehyde cross-linked *Saccharomyces cerevisiae*," *Biotechnol. Lett.* 20(6), 603-606.
- Zhao, M., Duncan, J. R., and Van Hille, R. P. (1999). "Removal and recovery of zinc from solution and electroplating effluent using *Azolla filiculoides*," *Water Res.* 33(6), 1516-1522.
- Zheng, J. C., Feng, H. M., Lam, M. H. W., Lam, P. K. S., Ding, Y. W., and Yu, H. Q. (2009). "Removal of Cu(II) in aqueous media by biosorption using water hyacinth roots as a biosorbent material," *J. Hazard. Mater.* 171, 780-785.
- Zheng, L. C., Dang, Z., Yi, X. Y., and Zhang, H. (2010). "Equilibrium and kinetic studies of adsorption of Cd(II) from aqueous solution using modified corn stalk," *J. Harard. Mater.* 176(1-3), 650-656.
- Zheng, W., Li, X. M., Wang, F., Yang, Q., Deng, P., and Zeng, G. M. (2008). "Adsorption removal of cadmium and copper from aqueous solution by areca - A food waste," *J. Hazardous Mater.* 157(2-3), 490-495.
- Zhou, D., Zhang, L., Zhou, J., and Guo, S. (2004). "Cellulose/chitin beads for adsorption of heavy metals in aqueous solution," *Water Research* 38(11), 2643-2650.
- Zhou, J. L. (1999). "Zn biosorption by *Rhizopus arrhizus* and other fungi," *Appl. Microbiol. Biotechnol.* 51(5), 686-693.
- Zhou, J. L., Huang, P. L., and Lin, R. G. (1998). "Sorption and desorption of Cu and Cd by macroalgae and microalgae," *Environ. Pollution* 101(1), 67-75.
- Zhou, J. L., and Kiff, R. J. (1991). "The uptake of copper from aqueous solution by immobilized fungal biomass," *J. Chem. Technol.* 52(3), 317-330.
- Zhou, M., Liu, Y. G., Zeng, G. M., Li, X., Xu, W. H., and Fan, T. (2007). "Kinetic and equilibrium studies of Cr(VI) biosorption by dead *Bacillus licheniformis* biomass," *World J. Microbiol. Biotechnol.* 23(1), 43-48.
- Zhu, C. S., Wang, L. P., and Chen, W. B. (2009a). "Removal of Cu(II) from aqueous solution by agricultural by-product: Peanut hull," *J. Hazardous Mater.* 168(2-3), 739-746.

- Zhu, H. J., Jia, Y. F., Wu, X., and Wang, H. (2009b). "Removal of arsenic from water by supported nano zero-valent iron on activated carbon," *J. Hazard. Mater.* 172(2-3), 1591-1596.
- Ziagova, M., Dimitriadis, G., Aslanidou, D., Papaioannou, X., Tzannetaki, E. L., and Kyriakides, M. L. (2007). "Comparative study of Cd(II) and Cr(VI) biosorption on *Staphylococcus xylosus* and *Pseudomonas* sp. in single and binary mixtures," *Bioresour. Technol.* 98(15), 2859-2865.
- Zouboulis, A. I., Matis, K. A., and Hancock, I. C. (1997). "Biosorption of metals from dilute aqueous solutions," *Separation Purification Methods* 26(2), 255-295.
- Zoumpoulakis, L., and Simitzis, J. (2001). "Ion exchange resins from phenol/formaldehyde resin-modified lignin," *Polymer Internat.* 50(3), 277-283.
- Zulkali, M. M. D., Ahmad, A. L., and Norulakmal, N. H. (2006). "*Oriza sativa* husk as heavy metal adsorbent: Optimization with lead as model solution," *Bioresour. Technol.* 97(1), 21-25.
- Zvinowanda, C. M., Okonkwo, J. O., Agyei, N. M., Forbes, P., Mpangela, V., Phaleng, J., Shabalala, P. N., Dennis, T., and Ozoemena, K. I. (2008a). "Biosorption of toxic metals: The potential of maize tassel for the removal of Pb (II) from aqueous solutions," *Fresen. Environ. Bull.* 17(7), 814-818.
- Zvinowanda, C. M., Okonkwo, J. O., Agyei, N. M., Sekhula, M. M., and Sadiku, R. (2009a). "Application of maize tassel for the removal of Pb, Se, Sr, U and V from borehole water contaminated with mine wastewater in the presence of alkaline metals," *J. Hazard. Mater.* 164(2-3), 884-891.
- Zvinowanda, C. M., Okonkwo, J. O., Shabalala, P. N., and Agyei, N. M. (2009b). "A novel absorbent for heavy metal remediation in aqueous environments," *Int. J. Environ. Sci. Tech.* 6(3), 425-434.

APPENDIX

Table A. Tabulation of Research Publications for Removal of Metal Ions from Dilute Aqueous Solution by Use of Raw or Modified Lignocellulosic Materials

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
TREE MATERIALS						
WOOD						
Hardwood						
<i>Fagus (beech)</i>	Sawdust	Cr(VI)	16	.031	80 min. optimum at pH 1.0; Langmuir fit	Acar and Malkoc 2004
<i>Mangifera indica</i>	Sawdust	Cu(II)	10	.016	Langmuir fit ; regen. with acid	Ajmal et al. 1998
<i>Quercus</i> (oak sawdust)	HCl	Cu(II), Ni(II), Cr	3.2,3.3, 1.7	.05,.06, 0.033	Pseudo 2 nd order rate; Langmuir fit	Argun et al. 2007
Neem biomass		Zn(II)	140	2.1	Best pH 4-5; 2 nd order rate; Langmuir fit	Arshad et al. 2008
Beech, linden, Poplar sawdust		Cu(II)	—	—	Best pH 3.5-5; ion exchange; Langmuir fit	Bozic et al. 2009
Walnut sawdust		Cd(II), Ni(II)	—	—	Pb(II) and Cd(II) adsorbed in preference to Ni(II); ion exchange ; Langmuir fit	Bulut & Tez 2007b
Rosewood	CH ₂ O	Cr(VI)	15-23	.29-.44	Best pH 3; Treatment increased uptake; first-order rate	Garg et al. 2004
<i>Betula sp.</i>		Cu(II)	5	0.079	Sawdust less effective than algal biomass	Grimm et al. 2008
<i>Casia f</i> biomass		Ni(II)	20-173	.34-2.9	Best pH 6; bark more effective than pods, stem, leaves; smaller particles more effective; 2 nd order rate; Langmuir fit	Hanif et al. 2007
Aspen	Bleach, hydrolys.	Cu(II)	0.9-2.2	.01-.04	Higher pH favored to 5.5; Langmuir fits; Bleached>untreated>hydrolyzed>>lignin; carboxyl groups key; competition (Ca, Na, Al); ion exchange & complexation	Huang et al. 2009
Papaya	Hybrid w fungal	Cd(II)	18, 142	.16,1.3	The hybrid adsorbed much more than the sum of the components; 2 nd order rate; Langmuir fit.	Iqbal et al. 2007

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Beech sawdust	Aromatic CH ₂ O res	Cd(II), Zn(II), Co(II), Ni(II)	—	—	Mutual sorption binary mixtures; 2.4 meq/g; regenerated with HCl	Miyauchi et al. 2007
Papaya		Cu(II), Cd(II), Zn(II)	—	—	Best pH 5; 2 nd order rate; Langmuir fit; regen. with HCl	Saeed et al. 2005a
Oak, locust	CH ₂ O, NaOH	Cu(II), Zn(II)	4-6, 4-7	.06-.09, .06-.11	NaOH boosted adsorption; CH ₂ O did not	Sciban et al. 2006a
Poplar		Cu(II), Zn(II), Cd(II)	4-6, 6, 0.7	.06-.09, .09,.01	Multilayer adsorption fit; hindrance from other ions	Sciban et al. 2007
Carpenter's dust		Cr(VI)	40	0.77	Best pH 2; Langmuir fit	Sharma & Forster 1994a
Maple sawdust		Ni(II)	—	—	Higher pH favored to 5; chelation ion exchange; regen. with acid	Shukla et al. 2005
Maple sawdust		Cu(II)	61	0.96	Ion exchange	Yu et al. 2000
Sawdust		Pb(II), Cu(II)	1-3,1-2	.01,.03		Yu et al. 2001
Maple sawdust		Cr(VI)	5	0.10	Tested at pH 6; Langmuir fit; ion exchange	Yu et al. 2003
Softwood						
Cryptomeria jap		Cr(VI)	72-91	1.4-1.6	Tests at pH 3; Langmuir fit	Aoyama et al. 2004
Spruce sawdust	Phosph- orylated	Pb(II), Cd(II), Ni(II)	224, 56, 26	1.08, .50,.44	Pb > Cd > Ni	Holan & Volesky 1995
Spruce sawdust		Cd(II), Cu(II), Ni(II), Pb(II), Zn(II)	—	—	2.1 to 4.3x10 ⁽⁻²⁾ meq g ⁽⁻¹⁾ ; ion exchange; calcium solution can be used for regeneration	Marin & Ayele 2002
Spruce sawdust		Cd(II), Cu(II), Ni(II), Pb(II), Zn(II)	—	—	Column experiments; competition	Marin & Ayele 2003
Juniper fibers	NaOH	Cd(II)	9-30	.08-.27	Pseudo 2 nd order rate; Langmuir fit	Min et al. 2004
Juniper wood		Cd(II)	3	0.027	The bark performed much better	Shin et al. 2007
<i>Pinus sylvestr.</i>		Cd(II), Pb(II)	9, 10	.08, .05	Best pH 5.5; pseudo 2 nd order rate; Langmuir fit; pore diffusion control; ion exchange;	Taty-Costodes et al. 2003

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Unspecified						
Sawdust, unsp.		Cr(VI)	9.6	0.18	Best pH 4.5-6.5; 2 nd order rate; Langmuir fit; exothermic	Baral et al. 2006
Sawdust		Cr(VI)	16	0.31	Best pH 2; Langmuir fit	Dakiki et al. 2002
Sawdust, mill		Cu(II)	—	—	Langmuir fit; ion exchange	Larous et al. 2005
Wood		Cu(II), Pb(II)	3, 8	.05, .04	Citric acid treatment increased adsorption by about 10X; 2 nd order rate	Low et al. 2004
Cellulose beads		W, Mo, V, Ge, Sb oxoanions	—	—	Tungstate, molybdate adsorption successful; higher pH favored to 5.5	Mistova et al. 2007
Wood pulp		Na(I), Mg(II), Ca(II), Mn(II), Ba(II)	—	—	Ion exchange selectivity can be calculated	Rudie et al. 2006
Three sawdusts		Cu(II)	—	—	Softwoods effective at low conc; hardwoods effective at high conc.	Sciban & Kalasnja 2004a
Poplar, various sawdusts		Cu(II)	2-3	.03-.05	Tests at pH 4; Langmuir fit; higher pH favored for Cu(II), Zn(II), Ni(II), Cd(II)	Sciban & Kalasnja 2004b
Oak sawdust, Black locust SD	NaOH	Cu(II), Zn(II)	4-6, 4-7	.06-.09, .06-.11	NaOH treatment boosted Cu uptake 2.5-5X; Ni 15X; also reduces further leaching	Sciban et al. 2006b
Sawdust, Rice husk, Coir pith		Cr(VI)	1.5, 0.6, 0.2	0.029, 0.012, 0.004	Freudlich fits	Sumathi et al. 2005
Mechan. fibers						
Newsprint		Cu(II)	30	0.47	Higher pH best ; 2 nd order rate; Langmuir fit ; endothermic	Chakravarty et al. 2008
Kraft fibers						
Kraft pulp fibers		Fe(III), Cr(III), Pb(II), Cd(II)	—	—	Metal adsorption ↑ with ↑ pH	Abdel-Aal et al. 2006
Unbleached kraft		Ca(II)	1-2	.02-.05	Donnan theory with carboxyl and phenol groups; higher pH favored; bleaching reduces Ca uptake, especially at high pH	Duong et al. 2004

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
BARK						
Pine bark, (also cones, needles)		Cd(II), Cu(II), Ni(II), Pb(II)	9-38, 6-16, 3-13, 10-29	.08-.34, .09-.25, .05-.22, .05-.14	Higher pH favored to 7; smaller particles higher uptake; binary competition; adsorption mainly in cell wall ; ion exchange; free radicals play role, Langmuir fit; partial regen. with HCl	Al-Asheh & Duvnjak 1998
Larch bark		Cr(VI)	31	0.60	Tests at pH 3; Langmuir fit	Aoyama & Tsuda 2001
Pine bark	Fe ²⁺ , H ₂ O ₂	Cd(II)	10-13	.09-.12	Results depended on the ratio of Fe ²⁺ to H ₂ O ₂ . 1 st order rate; Langmuir fit; exothermic	Argun & Dursun 2008a
Pine bark	HCl	Cu(II)	—	—	Best at pH 5	Argun et al. 2005a
Pine bark		Ni(II)	21	0.36		Argun et al. 2005b
Pine bark	Various	Cd(II), Pb(II), Cu(II), Ni(II)	12-20	.11-.18	NaOH > Fenton reag. > polymerization	Argun et al. 2009
Cork		Cu(II), Zn(II), Ni(II)	40, 50, 20	.63,.76, .34	Higher pH better; ion exchange less important for Zn(II); role of carboxylate groups	Chubar et al. 2003
<i>Pinus radiata</i>	CH ₂ O + H ₂ SO ₄ or NNO ₃	U	37	0.16	Treatments enhanced uptake, with nitric acid preferred; formaldehyde prevented color bleed	Freer et al. 1989
Tree barks		Cu(II), Cd(II), Cr(III), Fe(II), Fe(III), Pb(II), Hg(II), Ni(II), Zn(II)	22-44, 47, 0.4, 35, 19, 90, 50, 33-43, 44	.35-.69, .42,.01, .63,.34, .43,.25, .56-.83, 0.67	Uniform metal distribution; binding to acidic sites; higher pH favored; regen. with acid; inverse correlation of molar uptake with atomic radius; metal recovery by pyrolysis	Gaballah & Kilbertus 1998
Eucalyptus		Cd(II)	15	0.13	Pseudo 2 nd order rate; Langmuir fit	Ghodbane & Hamdaoui 2007
Eucalyptus		Hg(II)	33	0.16	Pseudo 2 nd order rate; Langmuir fit	Ghodbane & Hamdaoui 2008
<i>Picea, pinus, larix, pseudotsuga, tectona, afzelia</i>	CH ₂ O	Pb(II), Zn(II), Cr(III), Fe(II), Cu(II)	—	—	Pectins and tannins important; grain size; regeneration with HCl	Gloaguen & Morvan 1997

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Azadirachta indica</i>		Zn(II)	33.5	0.51	Particle size important; best pH 6; pseudo 2 nd order rate; Langmuir fit;	King et al. 2008a
Guava		Hg(II)	3.4	0.016	Best pH 9; 2 nd order rate; Freundlich fit	Lohani et al. 2008
Cork powder		Cr(III)	6.3	0.21	Tested at pH 4; Langmuir fit	Machado et al. 2002
Mango & neem		Cs(I)	—	—	First order rate; Freundlich fit; endothermic; irreversible	Michra et al. 2007
Pine bark	Pelletize, citric acid	Cu(II), Zn(II), Cd(II), Ni(II)	75, 53, 50, 27	2.1, .81, .44, .46	Langmuir fit	Oh & Tshabalala 2007
Pine bark, tannins		V(V), Re(VII), Mo(VI), Ge(6), As(V), Cd(II), Hg(II), Al(III), Pb(II), Fe(II), Fe(III), Cu(II)	346	0.78	Eval at pH 2; bark was more effective than the tannins from the bark	Palma et al. 2003
Eucalyptus	CH ₂ O	Cu(II), Cr(III), Cd(II), Ni(II)	166, 37, 252, 44	2.6, .71, 1.2, .75		Saliba et al. 2002b
Eucalyptus bark & other materials		Cr(VI), Cr(III), Mg(II), Ca(II)	45	0.87	Eucalyptus bark best for Cr(VI) removal; best pH for Cr(VI) was 2; Freundlich fit;	Sarin & Pant 2006
Coniferous (15)		Cd(II)	10-14	.19-.27	Barks varied considerably for different ions; Freundlich fit	Seki et al. 1997
Juniper bark		Cd(II)	10	0.19	Higher pH favored to 6; bark uptake 3-4 X higher than then wood; approximate stoichiometry with Ca release	Shin et al. 2007
Mango & neem		Hg(II), Cr(III),	172, 35	0.86, 0.67	Hg(II) sorbed, but not Cd(II); first order rate; Freudlich fit; competition by anions & cations	Tiwari et al. 1999
Cork, yohimber		Cu(II), Ni(II)	3-8, 4-8	.05-.13, .07-.14	Best pHs 6-7; salt competition; Langmuir fits; regen. with HCl	Villaescusa et al. 2000
Bark	CH ₂ O	Cd(II), Cu(II), Pb(II), Zn(II), Ni(II), Co(II), Mn(II)	28, 18, 68, 2, 2, 2, 2	.25, .29, .33, .03, .03, .04	Formaldehyde treatment reduced color leaching; ion exchange mechanism	Randall et al. 1974

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
FOLIAGE						
Eucalyptus leaves		Cu(II), Zn(II), Cd(II), Pb(II)	—	—	Ratio, pH, contact time, concentration; 2 hr to max. adsorp.; effective for mixed systems	Abdel-Ghani et al. 2008
Conifer needles		U(VI), Cu(II), Cd(II)	40-90, 4-12, 8-18	.17-.38, .06-.19, .07-.16	$UO^{2+} > Cu^{2+} > Cd^{2+} = Zn^{2+} > Co^{2+} = Ni^{2+} > Mn^{2+}$	Aoyama et al. 1991
Conifer needles		Cr(VI)	6.3	0.12	Tests at pH 3; Freundlich fit	Aoyama et al. 1999
London plane tree		Cr(VI)	68-76	1.3-1.5	Tests at pH 3; Langmuir fit	Aoyama 2003
Yerba mate leaf stems		Cd(II)	4.8	0.042	The pure lignin sample showed higher uptake; Langmuir fit	Basso et al. 2004
Pine needles		Cr(VI)	22	0.42	Best pH 2; Langmuir fit	Dakiki et al. 2002
Palm flower	Acid	Cr(VI), Cr(III)	7, 6	.13, .12	2 nd order rate; acid treatment helped Cr(VI) uptake, hurt Cr(III)	Elangovan et al. 2008b
Rubber leaf		Cu(II)	8.4	0.13	Langmuir fit; ion exchange/complexation	Hanafiah & Ngah 2009
Petiolar sheath		Pb(II), Ni(II), Cd(II), Cu(II), Cr(III), Zn(II)	11, 7, 11, 8, 5, 6	.05, .12, .10, .13, .10, .09	$Pb^{2+} > Cd^{2+} > Cu^{2+} > Zn^{2+} > Ni^{2+} > Cr^{3+}$; best pH 4; regenerable	Iqbal et al. 2002
Petiolar sheath		Cd(II), Cu(II), Zn(II)	See above	See above	$Cd > Cu > Zn$; Langmuir fit; regenerable	Iqbal & Saeed 2002
Teak leaves		Cu(II)	95	1.5	Best pH 5.5; pseudo 2 nd order rate; Langmuir fit	King et al. 2006
<i>Syzygium cumini</i>		Pb(II)	32	0.15	Langmuir fit	King et al. 2007
<i>Syzygium cumini</i>		Zn(II)	36	0.55	Langmuir fit	King et al. 2008b
<i>Tectona grandis</i>		Cu(II)	15	0.24	2 nd order rate; Langmuir fit; exothermic	Kumar et al. 2006a
<i>Tectona grandis</i>		Zn(II)	16	0.24	2 nd order rate; Langmuir fit; exothermic	Kumar et al. 2006b
<i>Rosa c. petals</i>	NaOH	Pb(II), Zn(II)	88, 74	.42, 1.1	Best pH 5; pseudo 2 nd order rate; Langmuir fit	Nasir et al. 2007
<i>Hevea b.</i> leaf pdr		Cu(II)	9	0.14	Best pH 4-5; pseudo 2 nd order rate; Langmuir fit; exothermic	Ngah & Hanafiah 2008a
<i>Hevea b.</i> leaf pdr		Cu(II)	15	0.24	Pseudo 2 nd order rate; diffusion control; Langmuir fit best	Ngah & Hanafiah 2008b

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Hevea b.</i> leaf pdr	CH ₂ O	Cu(II)	8-9	.12-.14	Pseudo 2 nd order rate; Langmuir fit; ion exchange/complexation; regenerate with HCl or EDTA	Ngah & Hanafiah 2009
<i>Ficus religiosa</i>		Pb(II), Cr(VI)	17, 6	.08, .12	Ion exchange; pseudo 2 nd order rate; Langmuir fit	Qaiser et al. 2007
<i>Ficus religiosa</i>		Pb(II)	37	0.18	Pseudo 2 nd order rate; Langmuir fit; ion exchange; regen. with HNO ₃	Qaiser et al. 2009
Tobacco dust		Pb(II), Cu(II), Cd(II), Zn(II), Ni(II)	40, 36, 30, 25, 24	.19, .57, .27, .38, .41	Surface acidity; ion exchange and surface complexation; regen. with HCl	Qi & Aldrich 2008
Teak leaves		Cd(II)	30	0.27	Best pH 5.5; pseudo 2nd order rate; Langmuir fit	Rao et al. 2010
Palm frond (also bark, EFB)	NaOH	Cu(II), Zn(II)	8-14, 6-130	.13-.22, .09-2.0	Freundlich uptake ; Regeneration with NaOH, EDTA, HCl, HNO ₃ ; binding sites damaged	Salamantinia et al. 2007
Beech leaves		Cd(II)	—	—	Freundlich fit	Salim et al. 1992
Saltbush, <i>Atriplex</i>		Cu(II), Pb(II), Zn(II)	68,300, 33	1.1, 1.4, 0.50	Freundlich fit	Sawalha et al. 2007
4 organic wastes		Cr(VI)	3-30	.06-.58	Best pH 1.5-3; anaerobically digested biomass was more effective	Sharma & Forster 1994a
Leaf mold	Fungal decay	Cr(VI)	20-40	.38-.76	Best pH 2, 2 nd order rate	Sharma & Forster 1994b
Leaf mold	Fungal decay	Cr(VI)	26	0.50	Very little reduction took place when using leaf mold; activated carbon caused reduction	Sharma & Forster 1996a
CONES						
Nordmann fir		Ni(II)	—	—	Best pH 6.5; Langmuir fit.	Aksakal et al. 2008
Pine cone	HCl	Cu(II)	—	—	Best at pH 3	Argun et al. 2005a,b
Pine cone	Fenton	Cd(II), Pb(II)	2-11, 2-10	.02-.10, .01-.05	Fenton oxidation greatly increased uptake; 1 st order rate; exothermic; Langmuir fit	Argun et al. 2008
<i>Thuja</i>		Ni(II)	12.4	0.21	Pseudo 2 nd order rate; Langmuir fit	Malkoc 2006

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Cupressus</i> cones		Cr(VI)	119	2.3	Best pH 0.2-0.5; higher temperature favored; Langmuir fit; irreversible by NaOH, etc.	Murugan & Subramanian 2003
<i>Thuja orientalis</i>		Cu(II)	19	0.30		Nuhoglu & Oguz 2003
<i>Thuja orientalis</i>		Cr(VI)	49	0.94	Best pH 1.5	Oguz 2005
<i>Pinus sylvest</i>		Cu(II), Zn(II)	25, 16	.39, .24	2 nd order rate; Langmuir fit	Ucun et al. 2009
NUT SHELLS						
Coconut, almond, ground nut, walnut	-	Cr(VI),	90+, 2.4-22, 6, 2.3-18	1.7+, .05-.42, .12, .04-.35	Tamarindus seed outperformed nut shells; lower pH favored; Langmuir fits	Agarwal et al. 2006
Walnut, hazelnut, almond shells	-	Cu(II)	4-7	.06-.11	Best pH 6; chelation & ion exchange	Altun & Pehlivan 2007
Coconut coir	Amino, PAM graft, Fe(III)	Cr(VI)	143	2.8	The grafted, Fe ³⁺ -treated coir adsorbed Cr(VI); Pseudo 2 nd order rate; Langmuir fit; NaOH regeneration	Anirudhan et al. 2010
<i>Brazil nut shells</i>		Cd(II), Ni(II)	19	0.17	Sorbents favored different metals; Langmuir fit	Basso et al. 2002a
Hazelnut, almond		Ni(II), Cd(II), Pb(II)	1.6, 0.9, 3.5, 1.5, 4.4, 2.5	.03, .02, .03, .01, .02, .01	Selectivity: Pb(II) > Cd(II) > Ni(II); pseudo 2 nd order rate ; ion exchange ; Langmuir fit ; exothermic	Bulut & Tez 2007a
Hazelnut shells		Cd(II), Zn(II), Cr(III), Cr(VI)	5, 3, 2, 18	.04, .05, .04, .35	Best pH 2.5-3.5 for Cr(VI); Langmuir fits; HSAB model; anionic removal mechanism	Cimino et al. 2000
Almond shell		Cr(VI)	11	.21	Best pH 2; Langmuir fit	Dakiki et al. 2002
Coconut coir		Cr(VI)	6-27	.12-.52	Phenolic sites; organic matter oxidation; recovered by calcination	Gonzalez et al. 2008
Coconut copra		Cd(II)	1.8-4.5	.02-.04	Higher pH favored to 5; Langmuir fit; exothermic	Ho & Ofomaja 2006a
Coconut copra		Pb(II)	36-47	.17-.23	Langmuir fit	Ho & Ofomaja 2006b
Coconut fiber	Unmod, thiolated	Hg(II), As(III), Pb(II)	—	—	Pb (II) > Hg (II) > As (III); seudo 2 nd order rate; particle diffusion model	Igwe et al. 2008

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Pecan shells	Oxygen level	Cu(II)	83	1.30	Oxygen addition increased affinity but decreased yield of carbon	Klasson et al. 2009
Acorn		Cr(VI)	31.5	0.60	Best pH 2; pseudo 2 nd order rate; Langmuir fit	Malkoc & Nuhoglu 2007a
Acorn		Cr(VI)	12-63	.23-1.2	Best pH 2; smaller particles increased uptake;	Malkoc et al. 2006a
Coir pith	CTAB	Cr(VI)	76	1.5	Best pH 2; 2 nd order rate; slight proportion of reduction; Langmuir fit	Namasivayam & Sureshkumar 2008
Coir pith	CTAB	Mo(VI)	58	0.60	Best pH 3; 2 nd order rate; Langmuir fit	Namasivayam & Sureshkumar 2009
Coconut copra		Cd(II)	1.7	0.015	Higher pH favored to 5.5; pseudo 2 nd order; ion exchange equilibria	Ofomaja & Ho 2007
Coconut copra		Cd(II)	3	0.03	Langmuir fit	Ofomaja & Ho 2008
Coir pith		U	90-220	.38-.92	Best pH 4-6.6; Langmuir fit	Parab et al. 2005
Coir pith		Co(II), Cr(III), Ni(II)	13, 12, 16	.22, .23, .27	Pest pHs 4.3, 3.3, 5.3; pseudo 2 nd order rates; Langmuir fits	Parab et al. 2006
Coir pith		Co(II)	—	—	Best pH 4-7; 2 nd order rate; Langmuir fit; regen. with HCl	Parab et al. 2010
Hazelnut, almond		Pb(II)	28, 8	.14, .04	Best pH 6-7; Langmuir fit; ion exchange/complexation	Pehlivan et al. 2009a
Green coconut		Cd(II), Cr(III), Cr(VI)	236,62, 42	2.1,1.2, .81	Langmuir fit best for Cd(II); Freundlich best for Cr(III)	Pino et al. 2006
<i>Delonix regia</i>		Cr(VI)	12	0.23	Best pH <3; reduction & sorption; pseudo 2 nd order rate; Langmuir fit;	Prasad & Abdullah 2010
Coir	Oxidation	Cu(II)	3-7	.05-.11	Oxidation increased uptake; Langmuir fit; regen. with HCl; ion exchange	Shukla et al. 2009
Coir, jute, sawdust, nut s.	Dye	Pb(II)	26	0.13	Monochlorozine dye enhanced Pb uptake; 2 nd order rate ; Langmuir fit	Shukla & Pai 2005b
Groundnut shells		Cu(II), Ni(II), Zn(II)	8, 10, 18	.12, .17, .28	Reactive orange dye moderately enhanced uptake; Langmuir fits	Shukla & Pai 2005c
Coir fibers	H ₂ O ₂	Ni(II), Zn(II), Fe(II)	4, 8, 7	.07, .12, .12	Oxidation more than doubled uptake; higher pH favored; Langmuir fits; regen. with NaOH	Shukla et al. 2006

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Coir pith		Cr(VI)	138-318	2.7-6.1	Best pH 2; Langmuir fit; endothermic; adsorbed mainly in reduced form	Suksabye et al. 2007
Coir pith		Cr(VI)	43	0.83	ESR study at pH 2; pseudo 2 nd order rate; lignin sites reduced Cr(VI) to Cr(III); but cellulose reduced it to Cr(V)	Suksabye et al. 2009
Coir	Oxidized	Ga(III)	19 (14)	0.27	Oxidation increased uptake; higher pH favored to 3; pseudo 2 nd order rate; Langmuir fit; regen. with HCl	Suryavanshi & Shukla 2009
Coconut husk & palm press fibers		Cr(VI)	29, 14	.56, .27	Best pHs 1.5 to 5 or 3;	Tan et al. 1993
CROP RESIDUALS						
Husk						
Rice husk		Pb(II)	—		Metal adsorption ↑ with ↑ pH; Fit the Temkin isotherm model	Abdel-Ghani et al. 2007
Rice husk	PO ₄ ³⁻	Cd(II)	90	0.80	Column operation effective; Langmuir fits	Ajmal et al. 2003
Rice husk		As(III), As(V)	—	—	Tests below saturation; KOH regeneration worked.	Amin et al. 2006
Bengal gr. husk		Cr(VI)	92	1.8	Best at pH 2; Agitation helped; Langmuir fit	Ahalya et al. 2005
Cajus cajan husk		Fe(III), Cr(VI)	—	—	Best pH 2 & 2.5; Involvement of carboxyl, OH, amide; Langmuir fit	Ahalya et al. 2007
Rice husk	Boiling, CH ₂ O	Cr(VI)	6-10	.11-.19	Best pH 2; minor enhancement due to CH ₂ O; functional groups; not Langmuir fit	Bansal et al. 2009
Groundnut husk	Ag	Cr(VI)	7	0.13	Uptake favored by oxidation of substrate by Ag; Freundlich fit	Dubey & Krishna 2007
Rice husk		Cr(VI)	55-210	1.1-4.0	Best pH 1.8-2.8; Reductive adsorption at pH 2; rate laws;	El-Shafey 2005
Rice husk	H ₂ SO ₄	Cd(II), Se(IV)	24-27, 17-20	.21-.24, .22-.25	Pseudo 2 nd order rates; Low pH preferred for Se(IV); above 4 for Cd(II); ion exchange (Cd); Langmuir fits	El-Shafey 2007b
Rice husk		Pb(II)	—	—	Effective adsorption; Freundlich fit	Khalid et al. 1998a
Rice husk		Cd(II)	—	—	Effective adsorption; Freundlich fit	Khalid et al. 1998b

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Rice husk		Hg(II)	1.3	0.0065	Effective adsorption; Freundlich fit; endothermic	Khalid et al. 1999
Rice husk	Ca, Mg	Pb(II), Hg(II), Cu(II), Co(II), Mn(II), Cd(II), Zn(II), Ni(II),	58, 58, 11, 10, 8, 8, 8, 6	.28,.29, .17,.17, .15,.07, .12,.10	Calcium and magnesium originally present were displaced	Krishnani et al. 2008b
Rice husk	Epichlor, NaOH, NaHCO ₃	Cd(II)	8-20	.07-.18	Pseudo 2 nd order rate; Langmuir fit	Kumar & Bandyopadhyay 2006a
Rice husk	Na ₂ CO ₃	Cd(II)	12	0.11	Column; breakthrough; regeneration with HCl	Kumar & Bandyopadhyay 2006b
Cocoa shell		Pb(II)	74	0.36	Cocoa shells more effective than cedar bark	Meuneir et al. 2002
Rice husk	Phos- phate	Pb(II), Cu(II), Zn(II), Mn(II)	No eval	No eval	Column tests; benefits of phosphate treatment	Mohan & Sreelakshmi 2008
<i>Lathyrus s.</i> husk		Cd(II)	35	0.31	95% uptake; pseudo 2 nd order rate; Langmuir fit; ion exchange; Cd present as micro-precipitate; regen. with acid	Panda et al. 2006
Black gram husk		Cd(II)	39	0.35	Regen. with HCl	Saeed & Iqbal 2003
Black gram husk		Pb(II), Cd(II), Zn(II), Cu(II), Ni(II)	50, 40, 34, 26, 20	.24,.36, .52,.41, .34	Pb > Cd > Zn > Cu > Ni; Langmuir fits; best pH 5 ; little competition ; regen. with HCl	Saeed et al. 2005b
Mung bean husk		Cd(II)	36	0.32	Pseudo 2nd order rate; Langmuir fit; ion exchange release of alkaline earth metals	Saeed et al. 2009
Rice husk		Cd(II), Pb(II), Al(III), Cu(II), Zn(II)	1.5, 5, - , - , -	.01,.02	To meet EPA limits; smaller particles had much higher capacity	Tarley & Arruda 2004
Rice husk	Epichlor- ohydrin; base	Cd(II)	9-20	.08-.18	Pseudo 2nd order rate; Langmuir fit	Upendra and Manas 2006
<i>Oriza sativa</i>		Pb(II)	7	0.034	Best pH 5	Zulkali et al. 2006
Maize tassel		Pb(II)			Best pH 7; diffusion control	Zvinowanda et al. 2008a

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Maize tassel		Pb(II), Se, Sr, U, V	2.6, - , -, -	0.01	Pseudo 2nd order rate; Langmuir fit; competition	Zvinowanda et al. 2009a
Maize tassel		Cr(VI), Cd(II)	4.5-9, 135	.09-.17, 1.2	Best pHs 2, 5-6, resp.	Zvinowanda et al. 2009b
Stalks, etc.						
Cassava waste	Thioglyco- llic acid	Cu(II), Cd(II), Zn(II)	95	1.5	Thioglycollic acid treatment enhanced binding.; 20-30 minutes mixing sufficient.	Abia et al. 2003
Cicer arietinum		Fe(III)	72	1.3	Langmuir fit; regeneraton possible	Ahalya et al. 2006
Olive stone		Cd(II)	5-10	.04-.09	Higher temperature favored; Langmuir fit best	Calero de Hoces et al. 2006
Grape waste	Sulfuric	Cr(VI); also Cr(II), Fe(III), Zn(II), Cd(II), Pb(II)	99	1.9	Cross-linked grape waste was effective for all of the ions; Langmuir fit	Chand et al. 2009
Grape stalk, coffee waste	EDTA	Cu(II), Ni(II)	2, 1.5; 2.5, 3	.03,.03; .04,.05	Best pH 5.5; severe competition by EDTA; pseudo 2 nd order rate; Langmuir fit;	Escudero et al. 2008
Pomegranate		Cr(VI)	11	0.21	Best pH 1, pseudo 2 nd order rate, Langmuir fit	El Nemr 2007
Grape bagasse		Cd(II), Pb(II)	54, 42	.48,.20	Best pHs 7 & 3; Langmuir fits	Farinella et al. 2007
Grape bagasse		Cd(II), Pb(II)	87, 89	.77,.43	Best pHs 7 & 3; Langmuir fits; Pb tended to win competition; column removal	Farinella et al. 2008
Grape stalk, bark, olive stone		Cr(VI)	60, 35, 15, 8	1.2,.67, .29, .15	Best pH 2-3, salt-tolerant; Langmuir fit	Fiol et al. 2003
Grape stalk	Alginate	Cr(VI)	—	—	Second order rate; diffusion control; Langmuir fit	Fiol et al. 2004
Casava waste	Raw; Acid-treat	Cd(II), Zn(II)	87, 56; 647, 559	.77,.86; 5.8,8.5	Best pH 4.5-5.5; diffusion control; sulfhydryl-metal bonds preclude regeneration	Horsfall & Abia 2003
<i>Caladium bicolor</i>		Pb(II), Cd(II)	88, 66	.42,.59	Best pH 7; Langmuir fit	Horsfall & Spiff 2004
Casava tuber waste		Pb(II)	86	0.41	Ion exchange	Horsfall et al. 2005
<i>Caladium bicolor</i>		Pb(II), Cd(II)	49, 52	.24,.46	Sticking probability model	Horsfall & Spiff 2005a

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Fluted pumpkin	Mercapto ethanoic	Ni(II)	13, 42	.22,.72	The treatment enhanced uptake; Langmuir fit; exothermic	Horsfall & Spiff 2005b
Fluted pumpkin	Sulfanyl acetic	Pb(II), Cd(II), Zn(II)	—	—	Pseudo 2 nd order rate; exothermic	Horsfall & Spiff 2005c
Casava tuber bark waste		Cd(II), Cu(II), Zn(II)	6-26, 33-91, 22-83	.05-.23, .05-1.4, .34-1.3	Pseudo-2 nd order rate; Langmuir fit; exothermic	Horsfall et al. 2006
Olive waste		Cr(VI)			Best pH 2; endothermic	Malkoc et al. 2006b
Grape stalk		Pb(II), Cd(II)	50, 28	.24,.25	Best pH 5.5; pseudo 2 nd order rate; Langmuir fit; interference by NaCl, NaClO ₄ ; regeneration by HCl or EDTA	Martínez et al. 2006a
Olive waste		Pb(II), Cd(II)	14-19	.07-.09	Higher pH favored to 7; sorbent judged to be only moderately good; regeneration possible	Martínez et al. 2006b
Olive pomace	H ₃ PO ₄ , H ₂ O ₂	Cu(II), Cd(II)	30, 11	.47,.10	Phosphoric acid treatment best ; carboxylic acids important; Langmuir fit	Martin-Lara et al. 2008
Olive waste		Pb(II)	6-23	.03-.11	Carboxylic acids important; Langmuir fit	Martin-Lara et al. 2009
Rice straw, cotton stalks, bagasse	Phospho- rylation; NaOH	Cd(II), Co(II), Cr(III), Cu(II), Fe(III), Ni(II), Pb(II), Zn(II)	—	—	NaOH treatment increased uptake	Nada et al. 2002a
Rice straw, cotton stalks, bagasse	Phospho- rylation; NaOH	Cd(II), Co(II), Cr(III), Cu(II), Fe(III), Ni(II), Pb(II), Zn(II)	—	—	Optimum phosphorylation reaction	Nada et al. 2002b
Cotton stalks	Chloro- sulfonic, phos oxy chloride	Sr(II), As(III), Cu(II), Ni(II)	16, 4, 4, 9	.18,.05, .06,.15	Best pH 3; having both phosphate & sulfonate groups promoted metal uptake.	Nada et al. 2006
Cotton stalks	Phosph orylated	Pb(II), Cu(II), Ni(II), Co(II), Cr(III), Cd(II)	52, 20, 18, 27, 39, 27	.25,.31, .31,.46, .75,.24	Not as high sorption as phosphorylated lignin	Nada & Hasan 2003

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Grape waste	HCl media	Au(III)	1900	9.6	First order rate; reduction; Au particles formed on substrate; endothermic	Parajuli et al. 2008
Wheat, soybean straws, corn	1% NaOH	Cu(II), Ni(II), Cd(II), Pb(II)	—	—	Certain combinations of biomass and metal worked better; 1% NaOH treatment much better than CH ₂ O, acid, or 4% NaOH	Sciban et al. 2008
Sunflower stalks		Cu(II), Zn(II), Cd(II), Cr(III)	29, 31, 42, 27	.46,.47, .37,.52	Uptake fell with temperature, except for Cr(III)	Sun & Shi 1998
Grape stalk		Cu(II), Ni(II)	10-16, 11-18	.16-.25, .19-.31	Best pH 5.5-6; Langmuir fit	Villaescusa et al. 2004
Olive husk		Pb(II), Cd(II), Cu(II), Zn(II)	33, 17, 3.4, 3.3	.16,.15, .05,.05	Freundlich fits; severe competition with Cu(II) as the clear winner	Volpe et al. 2003
Corn stalk		Cd(II)	3.4	0.030	Best pH 7; pseudo 2 nd order rate; Freundlich fit	Zheng et al. 2010
FOOD RESIDUALS						
Bagasse						
Sugar cane	Triethyle ne- tetramine	Cu(II), Cd(II), Pb(II)	60-222	.94-3.5	Succinylation after 2X mercerization, then derivatized with triethylenetetramine; Langmuir fits	Alves Gurgel & Gil 2009
Sugar cane, oil cake		Cr(VI)	6, 12	0.12, 0.23	Best pH 2; Langmuir fit	Garg et al. 2007
Sugar cane		Ni(II)	No eval	No eval	Best pH 7.5	Garg et al. 2008a
Sugar cane, corn cob, oil cake		Cd(II)	69-106	0.61	Best pH 6; Langmuir fit	Garg et al. 2008b
Sugar cane		Cr(VI)	—	—	Best pH 2	Garg et al. 2009
Sugar cane	Anearo- bic dig.	Zn(II), Cd(II)	—	—	Increased adsorption capacities; biogas as biprodukt	Joseph et al. 2009
Sugar bagasse	5N NaOH, EDTA	Cu(II), Cd(II), Pb(II)	39-93, 88-149, 192- 333	.61-1.5, .07-1.3, .93-1.6	Mercerization greatly increased adsorption capacities.	Karnitz et al. 2009

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Sugar bagasse	NaOH, EDTA dianhydr	Ca(II), Mg(II)	16-54, 14-43	0.4-1.4, .58-1.8	Modified sugarcane bagasse showed higher adsorption than modified pure cellulose.	Karnitz et al. 2010
Sugar bagasse	H ₂ SO ₄ , drying	Cr(VI)	—	—	Saline waters, brackish conditions; best results with H ₂ SO ₄ charring	Krishnani et al. 2004
Sugar bagasse, soy bean hull	Epichloro hydrin	Ca(II)	36, 52	0.9, 1.3	Idea of single use	Laxzlo & Dintzis 1994
Bagasse	Phospho-sulfonat.	Cr, Fe, Cu(II), Zn(II), Cd(II), Pb(II), Ni(II), Co(II)	3, 4, 0.9, 0.7 1.1, 3.3, 0.4, 0.5	.06-.07, .01, .01, .01, .02, .01, .01	On a molar basis Cu(II) and Pb(II) were favored over other divalent cations	Nada et al. 2003
Bagasse	Various COO Rx	Cu(II), Ni(II), Cr(III), Fe(III)	99-381, 80-470, 440, 84-469	1.6-6.0, 1.4-8.0, 8.46, 1.5-8.4	Carboxymethylated bagasse > periodote oxidized > succinylated .	Nada & Hassan 2006
Sugar bagasse	Micro-wave rad	Cu(II), Hg(II)	76, 481	1.2, 2.4	Best pH 6	Orlando et al. 2002
Sugar bagasse		Cr(VI)	13	0.25	Best pH 2; Langmuir fit	Sharma & Forster 1994a
Soy bean hull, etc.	Citric ac	Cu(II)	91	1.43	Best results with low lignin, low density materials, high anionic charge	Wartelle & Marshall 2000
Agricultural waste		Cr(VI)	58-103	1.1-2.0	Langmuir fits	Wartelle & Marshall 2005
Areca food waste		Cd(II), Cu(II)	1, 3	.01, .05	Best pH 5.6; Langmuir fit; regen with HNO ₃	Zheng et al. 2008
Sugar beet pulp						
Sugar beet		Cu(II)	16-29	.25-.46	Best pH 4; Langmuir fit; activation energy.	Aksu & Isoglu 2005
Sugar beet	FeCl ₃ loaded	Cr(VI)	5	0.10	Evaluated at pH 4.4; Langmuir fit	Altundogan 2005
Sugar beet	NaOH, citric acid	Cu(II)	55-204	.87-3.2	Pretreatment increased adsorption greatly; ion exchange pseudo 2 nd order rate; exothermic, Langmuir fit	Altundogan et al. 2007
Sugar beet		Cd(II), Cu(II), Ni(II), Pb(II), Zn(II)	53, 39, 21, 120, 32	.47, .61, .36, .58, .49	Cu≈Pb>>Cd≈Zn>Ni>Ca; Langmuir fits except Ca; ion exchange/chelation	Dronnet et al. 1997

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Sugar beet		Cu(II), Ni(II), Pb(II)	30, 12, 60	.47, .20, .29	Hlgher pH favored ; diffusion control	Gerente et al. 2000
Sugar beet		Cu(II), Zn(II)	31, 36	.49, .55	60-97% uptake; best pH 5.5; Freundlich fit	Pehlivan et al. 2006
Sugar beet		Cd(II), Pb(II)	46, 44	.41, .21	Best pH 5; ion exchange/complexation; limited regeneration by acid	Pehlivan et al. 2008
Sugar beet pulp		Cu(II), Zn(II), Cd(II), Ni(II)	21	0.33	Three different pKa sites; surface complexation; competition: Cu ²⁺ > Zn ²⁺ > Cd ²⁺ > Ni ²⁺	Reddad et al. 2002a
Sugar beet pulp		Pb(II), Cu(II), Zn(II), Cd(II), Ni(II)	49, 12, 10, 17, 8	.24, .19, .15, .19, .14	Langmuir fit; molar affinities: Cu ²⁺ > Zn ²⁺ > Cd ²⁺ > Ni ²⁺	Reddad et al. 2002b
Sugar beet pulp	Hot HCl, NaOH	Ni(II), Cu(II)	12-21; 21-29	.20-.36, .33-.46	Saponification and base extraction increased uptake; 2 nd order rate; Langmuir fit	Reddad et al. 2002d
Sugar beet pulp		Cr(III), Cr(VI)	—	—	Strong pH effects; reduction of Cr(VI)	Reddad et al. 2003
Sugar beet pulp		Cr(VI)	17	0.33	Best pH 2; Langmuir fit	Sharma & Forster 1994a
Other						
Soya cake		Cr(VI)	32	0.62	The biomass reduced Cr(VI) at pH 1, high adsorption	Daneshvar et al. 2002
Wheat bran extract		Cr(VI)	35	0.67	Best pH 2.1; Langmuir fit; adsorption consumes protons, consistent with reduction to Cr(III)	Dupont & Guillon 2003
<i>Avena m</i> (oat)		Cr(VI)	2.5-3.4	.05-.07	Tests at pH 2; binding increased with temperature; Langmuir fit; regen. with HCl; reduction to Cr(II) occurred	Gardea-Torresdey et al. 2000a
Hop byproducts	Dried, ground	Pb(II)	74	0.36	Hlgher pH favored to 5; regen. with citrate	Gardea-Torresdey et al. 2002
Carrot residues		Mn(II), Ni(II), Co(II), Cu(II)	5, 6.5, 6.3, 12	.09, .11, .11, .19	First-order rates; Langmuir fits	Guzel et al. 2008
Rice polish		As(III), As(V)	0.07-0.08	0.0009-0.0011	Regen. with NaOH	Hasan et al. 2009a
Coffee beans	degrease	Cd(II)	6.7	0.06	Best pH 3-5; Langmuir fit; ion exchange; regen. by HCl or HNO ₃	Kaikake et al. 2007

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Corn cobs		Cu(II)	26	0.41	Pseudo 1 st order rate; Langmuir fit; anionic complexes not removed at all; regenerable with acidic H ₂ O ₂	Khan and Wahab 2007
Apple residue		Cu(II)	9-34	.14-.54	Chemical mod increased uptake 5X; best pH 5.5-7; competition (Pb); Langmuir fit	Lee & Yang 1997
Apple residue	Phosph oxychlor	Cu(II), Pb(II), Cd(II)	No eval	No eval	Regenerable	Lee et al. 1998
Apple residue		Cu(II), Pb(II), Cd(II)	No eval	No eval	Esterificaiton of carboxyl groups decreased adsorption	Lee et al. 1999
Corn cobs	Citric ac., nitric ac. oxidized	Cd(II)	—	—	Oxidation by citric, nitric acids increased uptake by 11X, 3.8X, resp.; higher pH favored to 6; ion exchange; carboxylic sites; regen. by lowering pH	Leyva-Ramos et al. 2005
Wine waste		Cr(III)	10-16	.19-.31	Higher temperature favored; Langmuir fits	Li et al. 2004
Banana pith		Cu(II); Cu(II), Ni(II), Cr(III), Zn(II)	9-14	.14-.22	Pb(II) > Cu(II) > Ni(II) > Cr(III) > Zn(II); best pH 5; Langmuir fit	Low et al. 1995a
Rice hull	EDTA	Cu(II), Cr(III), Ni(II), Pb(II)	9,10, 9,29	.14,.19, .15,.14	Higher pH favored	Low et al. 2000
Apple residue	P(V) oxy- chloride	Cu(II), Zn(II), Ni(II)	25-102, 20-72, 18-65	.39-1.6, .31-1.1, .02-1.1	Greatest affinity for copper; enhanced uptake by P oxychloride; regenerated with HCl	Maranon & Sastre 1991a
Apple residue	Xanthat., phosph.	Cu(II), Zn(II), Ni(II)	—	—	Langmuir fits	Maranon & Sastre 1991b
Apple residue	Xanthat., phosph.	Cu(II), Zn(II), Ni(II)	—	—	Langmuir fits	Maranon & Sastre 1991b
Apple residue	Oxidation Crosslink Carbxym Xanthat Phospha		—	—	The treatments increased structural stability and decreased swelling	Maranon et al. 1991

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Apple residue	Acidic groups	Cu(II), Zn(II), Ni(II)	25-102, 20-72, 18-65	.39-1.6, .31-1.1, .31-1.1	Flow-through; regeneration with HCl	Maranon & Sastre 1992a
Apple residue	P(V) oxy-chloride	Cu(II), Zn(II), Ni(II)	—	—	Preconcentration; regeneration with HCl	Maranon & Sastre 1992b
Rice bran, cotton hulls, soy hulls		Zn(II); Cu(II), Ni(II).	7-41 (Zn)	.11-.63	Extrusion stabilized materials had higher performance than expander-stabilized; great loss of capability on HCl regeneration	Marshall & Johns 1996
Soybean hulls	NaOH, citric ac,	Cu(II)	25, 43-155	.39,.68-2.4	Citric acid treatment increased uptake by 6X	Marshall et al. 1999
Soybean hulls	NaOH, citric ac,	Cu(II), Cr(VI)	25-155, 14-46	.39-2.4, .27-.88	Citric acid treatment increased uptake by 6X	Marshall & Wartelle 2006
Cococa shells		Pb(II), Cu(II)	18	0.09	Lead and copper removed from acid leachate from soil; affinity decreased in following order: ion exchange; Pb>>Cu>Fe>Al>Cr>>Co>Zn>Mn>Cd>Ni	Meunier et al. 2003a
Cococa shells		Pb(II)	33	0.16	Competition with hardness ions; ion exchange; carboxyl & amine groups involved	Meunier et al. 2003b
Rice hulls		Hg(II), Cr(III)	—	—	First order rate; Freundlich fit; endothermic	Mishra et al. 1998
Rice hulls		Cs(I)	24	0.18	Higher pH favored; Freundlich fit; ion exchange/complexation	Mishra et al. 2007
Cotton	LiCl, NaOH, acid	Mg(II), Mn(II), Sr(II)	1, 1, 1	.04,.02, .01	Alkali and activating agents decreased crystallization and increased uptake	Nada et al. 2009a
Cotton linters	Phosphorylation	Cu(II), Fe, Mn(II), Ni(II), Pb(II), Zn(II)	—	—	Phosphorous shown by spectrophotometry	Nada et al. 2005
Carrot residues		Cr(III), Cu(II), Zn(II)	45, -, -	0.87	Langmuir fit	Nasernehad et al. 2005
Rice bran		Cr(VI), Cr(III), Ni(II)	0.07, 0.1, -	0.0013, 0.0019	Pseudo 2nd order rate; Freundlich fits	Oliveira et al. 2005

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Coffee husks		Cu(II), Cd(II), Zn(II), Cr(VI)	4-7, 3-6, 3.5-4.5, 3-6	.06-.11, .03-.05, .05-.07, .06-.05	Tests at pH 4; 48-98% uptake; pH optima; pseudo 2nd order rates; Langmuir fits	Oliveira et al. 2008
Bean wastes		Pb(II)	427	2.06	Langmuir fit; endothermic	Ozcan et al. 2009
Wheat bran	H ₂ SO ₄	Pb(II)	83	0.40	Best pH 6; Langmuir fit; exothermic	Ozer 2007
Wide assortment		Cr(VI)	—	—	Reductive adsorption mechanism shown	Park et al. 2007
Hops: <i>Humulus l</i>		Cu(II), Zn(II), Cr(III), Cr(VI)	No eval	No eval	Cr(VI) was reduced to Cr(III) for adsorption; surface complexes	Parsons et al. 2002
Rice polish		As(III), As(V)	0.14, 0.15	0.0018, 0.0020	Pseudo 2 nd order rates; Langmuir fits; exothermic	Ranjan et al. 2009a
Rice polish		As(III), As(V)	0.067, 0.079	0.0009, 0.0010	Flow column tests; regen. with 10% NaOH	Ranjan et al. 2009b
Tomato root; Tobacco root		Sr(II)	24; 13	0.27; 0.15		Scott et al. 1998
Corn cobs		Cu(II), Cd(II)	7-12, 3-6	.11-.19, .03-.05	Langmuir fits; Competitive sorption; Cu had stronger binding; interaction factors	Shen & Duvnjak 2004
Corn cobs		Cu(II), Cd(II)	1-7, 3-7	.02-.11, .03-.06	Modified Langmuir fit; thermodynamics	Shen & Duvnjak 2005a
Corn cobs		Cu(II)	—	—	Surface reaction model; mass transfer control	Shen & Duvnjak 2005b
Corn cobs		Cu(II), Cd(II)	6, 9	.09,.08	Kinetic modeling; diffusion control	Shen & Duvnjak 2005c
Jute	Dye, H ₂ O ₂	Cu(II), Ni(II), Zn(II)	8, 5, 6	.13,.09, .09	Both treatments increased uptake moderately; higher pH favored; Langmuir fit	Shukla & Pai 2005a
Jute, sawdust, groundnut shells	Dye	Pb(II)	19	0.09	Monochlorozine dye enhanced Pb uptake; 2 nd order rate ; Langmuir fit	Shukla & Pai 2005b
Rice bran		Cr(VI)	286	5.5	Best pH 2; Langmuir fit; desorption at high pH	Singh et al. 2005a
Rice polish		Cd(II)	10	0.09	Langmuir fit	Singh et al. 2005b
Wheat bran		Cd(II)	48-63	.43-.96	Langmuir fit; exothermic	Singh et al. 2006
Corn cob		Hg(II), Pb(II)	—	—	Langmuir fits; ion exchange	Stefan et al. 2010
Rice hulls	Dye	Pb(II), Hg(II), Cd(II)	22, 30, -	.11,.15, -	Regen. with acid	Suemitsu et al. 1986

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Corn cob	Citric ac, H ₃ PO ₄	Cd(II), Cu(II), Pb(II), Ni(II), Zn(II)	47-66, 35-45, 85-149, 28-38, 29-35	.42-.58, .55-.71, .41-.72, .48-.65, .44-.54	Adsorption capacities favorable to ion exchange resins	Vaughan et al. 2001
SEEDS						
Tamerindus	-	Cr(VI)	55-98	1.1-1.9	Decreasing pH favored; Langmuir fit	Agarwal et al. 2006
Mustard oil cake		Ni(II)	85-92	1.4-1.6	Cu(II) > Zn(II), Cr(VI), Mn(II), Cd(II), Ni(II) and Pb(II); 2nd order rate; higher temperature favored; endothermic	Ajmal et al. 2005
Wheat shells		Cu(II)	—	—	Best pH 5-6	Basci et al. 2003
<i>Mirabilis jalapa</i>		Cd(II)	22	0.20	The pure lignin sample showed higher uptake; Langmuir fit	Basso et al. 2004
Peanut shell	Pelletiz.	Cu(II), Cd(II), Zn(II), Pb(II)	8	0.13	Pelletization did not hurt uptake	Brown et al. 2000
Peanut shell	NaoH wash, heat acid	CD(II), Cu(II), Ni(II), Pb(II), Zn(II)	—	—	Outperformed commercial resins	Chamarthy et al. 2001
Peanut shell	Wet, dry	Se(IV)	12-17	.15-.22	Wet sorbent worked better; first-order rate; higher pH favored to 7; Langmuir fit; elemental metal found on substrate; substrate becomes oxidized	El-Shafey 2007a
Taramind	H ₂ SO ₄	Cr(VI)	30	0.58	Best pH 1-3; 2 nd order rate; Langmuir fit; regeneration by acid or base	Gupta & Babu 2009
Peanut shell	Citric ac	Co(II), Ni(II)	29-270	.49-4.6	140 °C, minor moisture esterification; major enhancement; best pH 7 for adsorption; Langmuir fit	Hashem et al. 2005a
Palm kernel fiber		Pb(II)	50	0.24	Pseudo 2 nd order rate; Langmuir fit; endothermic	Ho & Ofomaja 2005
Palm kernel fiber		Cu(II)	4-13	.06-.20	Pseudo 2 nd order rate	Ho & Ofomaja 2006c
Peanut husk, sawdust		Pb(II), Cr(III), Cu(II)	4-5, 2.5-3.5, 2.5-3.5	.02-.03, .05-.07, .04-.06	2 nd order rate; Langmuir fit	Li et al. 2007

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Ocimum basilica</i> .		Cr(VI)	205	3.9	Best pH 1.5; Langmuir fit	Melo & D'Souza 2004
		Cu(II)	—	—	Best pH 6; Freundlich fit	Mohammad et al. 1997
Wheat bran		Cd(II)	10-25	.09-.22	Pseudo 2 nd order rate; Langmuir fit	Nouri et al. 2007
Goundnut husk	EDTA Rx	Cd(II), Pb(II)	40, 39	.36,.19	Particle diffusion control	Okiemen et al. 1991
Sago waste		Cu(II), Pb(II)	12, 47	.19,.23	Best pHs 4-5.5; 2 nd order rate; Langmuir fits	Quek et al. 1998
Peanut shell	Wash, citric ac., H ₃ PO ₄		—	—	Acid treatments increased uptake;	Waywoyo et al. 1999
Peanut hull		Cu(II)	21	0.33	Best pH 5.5; pseudo 2 nd order rate; Langmuir fit; ion exchange; exothermic	Zhu et al. 2009
FRUIT STONE						
Olive stone	H ₂ SO ₄	Cd(II)	128	1.14	Time required 15 min ; ion exchange	Aziz et al. 2009
Olive stone		Cd(II)	—	—	Neutral pH best, smaller size, more effective; pseudo 2 nd order rate	Blazquez et al. 2005
Olive stone		Cr(III), Cr(VI)	—	—	Best pH 4-6 and 2, resp. ; reductive adsorp.	Blazquez et al. 2009
Olive stone		Cd(II), Cr(III), Pb (II)	3, 7, 10	.03,.13, .05	Pseudo 2nd order rate; Cr>Cd>Pb takeup;	Calero et al. 2009
Olive waste		Cr(III), Cu(II), Zn(II)	—	—	Humic-like fraction polymerin; uptake Cr(III) > Cu > Zn; ion exchange; some specificity	Capasso et al. 2004
Olive cake		Cr(VI)	33	0.63	Compared vs. sawdust, pine needles, almond shell, cactus leaves, charcoal at pH 2; wool best, most selective first-order; Langmuir fits	Dakiky et al. 2002
Olive cake		Pb(II), Cd(II)	18-28, 11	.09-.14, .10	Regeneration with acids	Doyurum & Celik 2006
Olive stone		Pb(II), Ni(II), Cu(II), Cd(II)	9, 2, 2, 8	.04,.03, .03,.07	Best pH 5.5-6; pseudo 2nd order rate; Langmuir fit; adsorption-complexation	Fiol et al. 2006
Olive stone		Cd(II), Cr(III), Pb(II)	—	—	Pseudo 2nd order rate; Sips fit; endothermic	Hernainz et al. 2008
Olive stone, wastes, prunings	Cr(III) presence	Pb(II), Cr(III)	4-8, 3-4	.02-.04, .03-.04	Affinity for Pb(II) > Cr(III); site competition; multicomponent isotherms; Sips fit	Hernainz et al. 2009

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Olive stone		Cd(II)	0.2	0.002	Higher pH favored to 6; pseudo 2 nd order rate; Langmuir fit	Kula et al. 2008
Olive pomace		Pb(II), Cu(II), Cd(II)	2-15, 1-5, 1-7	.01-.07, .02-.08, .01-.06	Best pH for Cd(II) is 6.5; Langmuir fits; carboxylic an phenolic groups involved	Pagnanelli et al. 2003
Olive pomace		Cu(II), Cd(II)	No eval	No eval	Competition; Langmuir fit; specific sites	Pagnanelli et al. 2005a
FRUIT PEEL						
Orange peel		Ni(II)	86-96	.47-1.6	Ni(II) > Cu(II) > Pb(II) > Zn(II) > Cr(II); First-order kinetics; enothermic, higher temperature favored; regeneration possible	Ajmal et al. 2000
Bael fruit	H ₃ PO ₄	Cr(VI)	17	0.33	Phosphoric acid developed pores; best pH 2; pseudo 2 nd order; Langmuir fit	Anandkumar & Mandal 2009
Banana, orange		Cu(II), Co(II), Ni(II), Zn(II), Pb(II)	8	0.12	Best with increasing pH to 7; effective for trace removal	Annadurai et al. 2003
Pea, bean, fig, Medlar peels		Cd(II)	98-148	.87-1.3	Pseudo 2nd order rate; Langmuir fit	Benaissa 2006
Pomegranate peel	Act. Carb	Pb(II), Cu(II)	—	—	2 nd order rates; Langmuir fits	El-Ashtoukhy et al. 2008
Orange waste	Phospho	Pb(II), In(III), Ga(III), Zr(IV), Cu(II), Fe(III)	238,80, 49,105, 62,171	1.1,.70, .70,1.2, 1.0,3.1	Effective to concentrate metals.	Ghimire et al. 2008
Mango peel		Cu(II), Ni(II), Zn(II)	46, 40, 28	.72,.68, .43	Cu ²⁺ >Ni ²⁺ >Zn ²⁺ ; best pH 5-6 ;	Iqbal et al. 2009a
Mango peel		Cd(II), Pb(II)	69, 99	.61,.48	Pseudo 2 nd order rate ; 75% due to carboxyl and 25% due to OH groups ; ion exchange ; regenerable	Iqbal et al. 2009b
Orange peel	Alkalis, crosslink	Cd(II)	47	3.8	Citric acid treatment had biggest benefit; best pH 6; regen. with HCl	Li et al. 2007
Orange peel	Alkalis, acids	Cd(II), Zn(II), Co(II), Ni(II)	59, 79, 72, 72	.52,1.2, 1.3,1.2	Pretreatments increased uptake moderately; Langmuir fit	Li et al. 2008
Banana skin, etc.		Cr(VI), Cr(III)	No eval	No eval	Best pH 1.5-4; Complete reduction by biomass (more effective than FeSO ₄	Park et al. 2008a

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Fruit gum powder		Cr(VI)	218	4.2	Tested at pH 1.0; Freundlich fit	Samantanai et al. 1997
Orange peel	Saponif., citric ac.	Pb(II)	253	1.22	Best pHs 4.5-6, pseudo 1 st order rates;	Xuan et al. 2006
Cobs						
Maize					Increasing pH; Fit the Temkin isotherm fit	Abdel-Ghani et al. 2007
Maize	Phosphat Sulfonate Carboxyl	Zn(II), Pb(II), Ni(II), Fe, Cr	14, 19, 21	0.21, 0.09, 0.36	Sodium binding capacities increased with negative groups and crosslinking	Nada et al. 2009b
Maize		Cr(VI)	14	0.27	Best pH 2; Langmuir fit	Sharma & Forster 1994a
Tea leaves						
Waste tea leaves	Dried	Pb > Fe > Zn > Ni	73 (Pb)	0.35	Carboxyls bind Pb, Fe; -OH binds Ni, Zn; Langmuir fit	Ahluwalia and Goyal 2005a
Tea wastes		Cu(II), Cd(II)	9, 11	.14,.10	Competition; not Langmuir fit	Cay et al. 2004
Tea wastes		Ni(II)	15	0.26	Langmuir fit; sl. endothermic; irreversible	Malkoc & Nuhoglu 2005
Tea wastes	Bed, flow	Cr(VI)	34-56	.65-1.1	Best pH lowest; smaller particles increased capacity	Malkoc & Nuhoglu 2006a
Tea wastes	Bed, flow	Ni(II)	7-11	1.1-1.9	Smaller particles increased capacity	Malkoc & Nuhoglu 2006b
Tea wastes		Cr(VI)	55	1.1	Best pH 2; Langmuir fit; endothermic	Malkoc & Nuhoglu 2007b
Tea, coffee, nut shells		Cr(VI), Cd(II), Al(III)	1.5, 1.3	.03,.01	Al uptake noted; first order rate; Freundlich fit	Orhan & Buyukgungor 1993
Tea wastes, coffee wastes		Cr(VI)	45, 39	.87,.75	Reduction to Cr(III) by phenolics in the tea, then adsorption; Toth fit better than Langmuir	Prabhakaran et al. 2009
STRAW, GRASSES						
Wheat straw, grass		Cr(III)	20	0.38	Low cost; pseudo 2 nd order rate; Langmuir fit; regeneration vs. ashing	Chojnacka 2006
Wheat straw		Cd(II), Cu(II)	15, 11	.13,.17	Higher pH favored; 2 nd order rate; Langmuir fits; chemisorption proposed	Dang et al. 2009
Wheat straw		Zn(II), Ni(II)	—	—	High pH favored; no effect of particle size; little competition	Doan et al. 2008

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Wheat bran		Cr(III), Hg(II), Pb(II), Cd(II), Cu(II), Ni(II)	93, 70, 62, 21, 15, 12	1.8,.35, .30,.19, .24,.20	Ion exchange, complexation, size exclusion	Farajzadeh & Monji 2004a
Wheat bran	NaCl	Cr(III), Hg(II),	—	—	The salt treatment helped adsorption	Farajzadeh & Monji 2004b
Rice straw	tartaric	Cr(VI)	3.2	0.06	Best pH 2; smaller particle size better; reduction promoted by sulfate, inhibited by nitrate; Langmuir fit	Gao et al. 2008
Sorghum straw		Cr(III)	7-13	.13-.25	Carboxyl and OH groups; Regenerated with nitric acid; desorbed by EDTA	Garcia-Reyes et al. 2009
Straw xanthate; Alkali-treated straw		Cr(III)	1.9; 3.9	0.037, 0.075	Best pH 3.6-3.9; Langmuir fit	Kumar et al. 2000
Steam expl. wheat	Fe-mod.	Cr(VI)	9	0.17	Langmuir fit	Li et al. 2004a
Spent grain		Cd(II), Pb(II)	17, 36	.15,.17	Pseudo 2 nd order rates; Langmuir fits; EDTA prevented sorption	Low et al. 2000
Spent grain		Cu(II)	10.5	0.17	Pseudo 2 nd order rate; Langmuir fit	Lu & Gibb 2008
Wheat bran	H ₂ SO ₄	Cr(VI)	91-133	1.8-2.6	Best pH 1.5; first order rate; Langmuir fit; exothermic	Ozer & Ozer 2004
Wheat bran	Dehyd- rated	Cu(II)	52-65	.82-1.0	Best pH 5; exothermic	Ozer et al. 2004b
Wheat bran	H ₂ SO ₄	Cd(II)	43-101	.38-.90	Best pH 5.4; first order rate; Langmuir fit	Ozer & Pirincci 2006
Rice bran		Cd(II), Cu(II), Pb(II), Zn(II)	1, 0.4, 4, 0.1	.01,.01, .02,.00	Freundlich fit	Montanher et al. 2005
Alfalfa		U	No eval	No eval	Higher pH favored to 4.5; carboxyl groups dominant	Parsons et al. 2006
Barley straw		Cu(II), Pb(II)	4, 23	.06,.11	Higher pH favored to 6; Langmuir fit	Pehlivan et al. 2009b
Rice bran	H ₃ PO ₄	Ni(II)	102	1.7	Higher pH favored to 6; pseudo 2 nd order rate; Langmuir fit; ion exchange	Zafar et al. 2007
WEEDS, PLANTS						
<i>Parthenium hyst.</i>		Cd(II)	—	—	Best at pH 3-4; 2 nd order rate; Langmuir fit; endothermic; 82% recovery by HCl	Ajmal et al. 2006

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Paspalum notatum</i>	Acid	Ni(II), Cu(II), Al(III), Fe(III)	3-6, 2-4, 3-14, 3-8	.05-.10, .03-.06, .11-.52, .05-.14	Acid pretreatment increased sorption on the root material	Araujo et al. 2007
<i>Salvinia cucullata</i>		Cr(VI)	232	4.5	Lower pH best; 2 nd order rate; diffusion control; Langmuir fit	Baral et al. 2007
<i>Arundo donax</i>		Cd(II), Ni(II)	—	—		Basso et al. 2002a
Cactus		Cr(VI)	7	0.13	Best pH 2; Langmuir fit	Dakiki et al. 2002
Cactus		Cu(II), Cd(II), Fe(III), Ni(II), Zn(II), Pb(II)	10, 0.4, 0.2, 8, 1.5, 3	.16,.03, .00,.14, .02,.01	Oxalate formation was involved, not just ion exchange	Davila-Jimenez et al. 2003
Alfalfa biomass		Ni(II)	4	0.07	Best pH 5-6; regen. with HCl	Gardea-Torresdey et al. 1996b
Alfalfa biomass		Cd(II), Cr(III), Cr(VI), Pb(II), Zn(II)	7, 8, 0, 43, 5	.06,.15, 0, .21, .08	Best pHs ca. 5; recoverable by HCl	Gardea-Torresdey et al. 1998
Alfalfa biomass		Au(III)	No eval	No eval	Accumulation involves reduction to elemental; favored by low pH; bioreduction	Gardea-Torresdey et al. 2000b
Alfalfa biomass		Cr(III)	No eval	No eval	Carboxyl ligands involved; bidentate complex	Gardea-Torresdey et al. 2002
<i>Convolvulus arv.</i>		Cd(II), Cr(VI), Cu(II)	4, 1.5, 0.6	.04,.03, .01		Gardea-Torresdey et al. 2004b
Moss		Cu(II)	23	0.36	Pseudo 2 nd order rate; Langmuir fit	Grimm et al. 2008
Tree fern		Zn(II), Cu(II), Pb(II)	8, 11, 40	.12,.17, .19	Decreased size beneficial; Langmuir fit	Ho et al. 2002
Tree fern		Cu(II)	12	0.19	Pseudo 2 nd order rate; Langmuir fit; endothermic	Ho 2003
Tree fern		Cd(II)	12	0.11	Pseudo 2 nd order rate; non-linear kinetic model	Ho 2004
Tree fern		Pb(II)	35	0.17	Best pH 4-7; Pseudo 2 nd order rate; ion exchange	Ho 2005

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Coriandrum sativ.</i>		Hg(II), CH ₃ Hg ⁺	2, 2	0.01 0.01	Carboxylic acid groups involved	Karunasagar et al. 2005
Sunflower stem		Cr(III)	83	1.6	Exothermic; selective; suppressed by anions, cations, Fe(II), Fe(III), Y(III); Dubinin-Radushkevich fit	Malik et al. 2005
Sunflower stem		Hg(II)	58	0.29	Dubinin-Radushkevich fit; enhancements and suppressions by anions, cations	Malik et al. 2006
Saltbush, <i>Atriplex</i>		Cr(VI), Cr(III)	0-4, 6-27	0-0.08, .12-.52	Tests at pH 5, which is unfavorable for Cr(VI); Langmuir fits	Sawalha et al. 2005
Saltbush, <i>Atriplex</i>		Cd(II), Cr(III), Cr(VI)	36, 30, 30	.32,.58, .58	Freundlich fits; ion exchange	Sawalha et al. 2006
Alfalfa biomass		Cu(II), Pb(II)	20, 43	.31,.21		Tiemann et al. 1999
Alfalfa biomass		Fe(II), Fe(III)	3	.05	Best pH 5	Tiemann et al. 2000
<i>Solanum elaeag.</i>		Cu(II), Pb(II), Cr(III), Zn(II), Ni(II)	46, 32, 43, 12, 13	.72,.15, .83,.18, .22	Esterification used to confirm binding by carboxylic acid groups	Tiemann et al. 2002
AQUATIC PLANT						
Fresh water						
<i>Eichhornia c</i>	Live	Cd(II), Zn(II)	1-10, 1-12	.02-.19, .01-.18	Metals at high levels inhibited growth; competition; slow uptake with time	Hasan et al. 2007
<i>Eichhornia c</i>	Dried powder	Cr(VI)	92	1.8	Best pH 2; Langmuir fit	Hasan et al. 2010
<i>Eichhornia c</i> roots		Eu(III)	13	0.086	Binding to carboxylate groups of root hairs	Kelley et al. 1999
<i>Ceratophyllum d.</i>		Cu(II), Pb(II), Zn(II)	6, 45, 14	.09,.22, .21		Keskinkan et al. 2004
<i>Eichhornia c</i> roots		Cu(II)	21	0.33	Batch tests, agitated; best pH ca. 5; Langmuir fit; EDTA prevents uptake by biomass	Low et al. 1994
<i>Eichhornia c</i>		Cr(VI)	—	—	Pseudo 2 nd order rate; hydroxyl group; Freundlich fit	Mohanty et al. 2006
<i>Agave lechuguilla</i>		Cr(III)	26-36	.50-.69	Langmuir fit	Romero-Gonzalez et al. 2005

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Agave lechuguilla</i>		Cr(III)	14	0.27	Langmuir fit; interactions with carboxyl groups	Romero-Gonzalez et al. 2006
<i>Azolla filiculoides</i>		Pb	93	0.45	Best pH 3.5-4.5	Sanyahumbi et al. 1998
<i>Eichhornia c</i>	Dried				Biomass can be placed in bags for use	Schneider et al. 1995
<i>Phragmites</i> reed		Cu(II), Cd(II), Ni(II), Pb(II), Zn(II)	0.5,0.4, 0.5,0.7, 0.6	.01,.00, .01,.00, .01	Best pH neutral, except acidic for Pb(II); Langmuir fits; regen. with acid	Southichak et al. 2006a
<i>Phragmites</i> reed	pH	Pb(II)	17	0.08	Langmuir fit; carboxyl groups involved	Southichak et al. 2006a
<i>V. spiralis</i> , <i>Eichhornia c.</i> , etc.	Dried	Cd(II), Ni(II), Zn(II), Cu(II), Cr(III), Pb(II)	2.6,2.1, 4.1,3.0, 2.8,1.0	.02,.04, .06,.05, .05,.00	Langmuir & Freundlich fits; non-competition; ion exchange	Verma et al. 2008
Alligator weed		Cr(VI)	20-24	.38-.46	Best pH 1; pseudo 2 nd order rate	Wang et al. 2008
Alligator weed		Cr(VI)	—	—	Best pH 1; pseudo 2 nd order rate; Langmuir fit; endothermic	Wang et al. 2009
<i>Azolla filiculoides</i>	Cross- linked	Cr(VI)	71-120	1.4-2.3	Best pH 2; Langmuir fit	Zhao & Duncan 1997a
<i>Azolla filiculoides</i>	Dried	Ni(II)	43	0.73	Best pH 6.5; regen. with acid	Zhao & Duncan 1998a
<i>Azolla filiculoides</i>		Zn(II)	45	0.69	Best pH 6; regen. with acid	Zhao & Duncan 1999
Water hyacinth roots		Cu(II)	23	0.36	Best pH 5.5; mesoporous; ion exchange	Zheng et al. 2009
Seaweed						
Various sp.	Species	Cu(II), Ni(II), Pb(II), Zn(II), Cd(II)	No eval	No eval		Aderhold et al. 1996
<i>Turbinaria ornate</i>		Cr(III)	31	0.60	Tests at pH 3.5; Langmuir fit	Aravindhan et al. 2004a
<i>Sargassum wight.</i>		Cr(VI)	35	0.67	Tests at pH 3.5-3.8; Langmuir fit	Aravindhan et al. 2004b
<i>Ascophyllum nod.</i>		Ni(II), Zn(II), Al(III), Sb(III)	—	—	Competition shown; participation of weak and strong acid groups	Bakir et al. 2009
<i>Cystoseira indica</i>	Epichlor	Cr(VI)	18-24	0.35	Best pH 3; cross-linking with epichlorohydrin; ion exchange; not Langmuir fit	Basha et al. 2008
<i>Cystoseira indica</i>	Epichlor	Cu(II), Ni(II)	—	—	Best pH 6; 2 nd order rate; Ion exchange; Langmuir fit; HCl regeneration successful	Basha et al. 2009

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Sargassum</i> sp.	Acid, base, Ca, CH ₂ O, glutaral.	Cu(II), Pb(II), Zn(II), Cd(II), Ni(II)	57-114, 210, 43, 71, 26	.90-1.8, 1.0, .66, .63, .44	Pb>Cu>Zn>Cd>Ni; Higher pH better; ion Exchange; regen. with HCl (90%); functional groups	Chen & Yang 2005
<i>Sargassum</i> sp.	CH ₂ O	Cu(II), Pb(II)	57-76, 144	.90-1.2, 0.69	CH ₂ O increased uptake 20%; functional groups; coordination model; ion exchange	Chen & Yang 2006
<i>Sargassum</i> sp.		Cr(III)	136	2.6	Emphasis on rates; Langmuir fit	Cossich et al. 2004
<i>Sargassum</i> sp.		Cd(II), Zn(II)	120	1.1	Pseudo 2 nd order rate; Langmuir fit	De Britto et al. 2007
<i>Sargassum</i> sp.		La(III), Eu(III), Yb(III)	118, 129, 138	0.85, 0.85, 0.80	Favored by higher pH; Eu > La > Yb; confirmed by Ca release	Diniz & Volesky 2005
Reed, water lily	Acid	Cr(VI), Cr(III)	9, 7	.17, .13	2 nd order rate; Cr(VI) was reduced by tannins, phenolics, etc.; acid treatment enhanced uptake; alkali treatment hurt Cr(VI) uptake	Elangovan et al. 2008a
<i>Sargassum</i> fl.		Cd(II), Pb(II)	103, 219	0.92, 1.06	Strong, weak acid groups, sulfonate vs. carboxylate; bidentate complex of Cd(II)	Fourest & Volesky 1996
<i>Posidonia</i> oc.	EDTA	Cu(II)	—	—	Not as effective as activated carbon	Gabaldón et al. 2007
<i>Porphyra</i> & <i>Ulva</i>		Pb(II)	139	0.67	Can be separated from zinc by this sorbent	Ghimire et al. 2007
<i>Laminaria japon.</i>	Epichlor	Pb(II), Fe(III), Cd(II), La(III), Ce(III)	279, 85, 124, 121, 122	1.4, 1.5, 1.1, .87	Concentration factor 74 for Pb(II) with Zn(II)	Ghimire et al. 2008
<i>Posidonia ocean.</i>		Cu(II)	57-86	.90-1.4	Seagrass; Langmuir fit; regen. with HCl	Izquierdo et al. 2010
<i>Laminaria japon.</i>	Ca load	Pb(II), Cu(II)	—	—	Kelp had higher affinity for Pb; ion exchange	Lee & Suh 2000
5 brown seaweed			64-95	—	Pseudo 2 nd order rate; Langmuir fit	Lodeiro et al. 2005
<i>Sargassum</i> sp., orange peel, bracken fern		Cr(III)	—	—	Carboxyl group content correlated with uptake; Langmuir fit; regeneration with sulfuric acid and sodium citrate	Lodeiro et al. 2008
<i>Ascophyllum n.</i>		W, Mo, V, Ge, Sb metal oxo-anions	—	—	Tungstate, molybdate, and vanadate adsorbed effectively	Mistova et al. 2007

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Various species	Acetone	Cu(II), Cr(III), Cr(VI)	27-65, -, -	.42-1.0	Blocking carboxyl, amino groups hurt uptake; some reactions suppressed reduction to Cr(III)	Murphy et al. 2009a
Various species		Cr(VI)	—	—	Reduction was an important part of mechanism; ion exchange	Murphy et al. 2009b
<i>Sargassum glau.</i>	Protonat	Pb(II), Cd(II)	244, 27	1.2,.24	Bed; ion exchange; partial regeneration by HCl (60%)	Naddafi et al. 2007
<i>Ecklonia</i> sp.	Thermal	Cr(VI), Cr(III)	15-38	.29-.73	Thermal treatment made biomass a better reductant but with less affinity for the Cr(III)	Park et al. 2004a
<i>Ecklonia</i> sp.	Proton- ated	Cr(VI)	234	4.5	Tests at pH 2.5; complete reduction to Cr(III) by biomass, with some of the latter appearing in solution	Park et al. 2004b
<i>Ecklonia</i> sp.	Acid treatment	Cr(VI)	No eval	No eval	Amination helped adsorption, whereas esterification of carboxyls had a smaller effect	Park et al. 2005d
<i>Ecklonia</i> sp.	Cr(III), other metals	Cr(VI)	No eval	No eval	Most metals did not affect Cr(VI) reduction by the biomass	Park et al. 2006a
<i>Ecklonia</i> sp.	Two- stage pH	Cr(VI), Cr(III), Zn(II)	No eval	No eval	Reductive adsorption of Cr(VI); ion exchange of the others; start at pH 1.5-2.5, then raise the pH to 4-5	Park et al. 2006b
<i>Ecklonia</i> sp.		Cr(VI)	No eval	No eval	Flow column; neural network modeling	Park et al. 2006c
<i>Ecklonia</i> sp.		Cr(VI)	No eval	No eval	Complete surface reduction; was Cr(III) in bound state	Park et al. 2008d
<i>Sargassum</i> sp.	Drying	Cr(VI)	—	—	Drying reduced porosity	Rocha et al. 2006
Seaweed waste		Cd(II)	60-140	.53-1.3	Best pH 6-8; two pKa sites correspond to carboxyls and thiols or amines. Esterification reduced uptake markedly; ion exchange	Romero-Gonzalez et al. 2001
<i>Sargassum fluit.</i>	Dead	Cd(II), Cu(II), Zn(II)	34-302, 171, 174	.30-2.7, 2.7, 2.7	Multicomponent Langmuir fit; ion and proton exchange; 2-site model; competition for sites	Scheiwer & Volesky 1995

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Sargassum</i> sp.		Cu(II)	133	2.1	Ion exchange; carboxyl and sulfate sites; Donnan analysis	Scheiwer 1999
Four species		Cu(II), Ni(II)	64-197, 65-170	1.0-3.1, 1.1-2.9	Cu binding 10X stronger than Ni; brown algae had much higher uptake; stoichiometric binding	Scheiwer & Wong 1999
Marine algae		Cu(II), Ni(II)	171, 135	2.7, 2.3	Site characterization	Scheiwer & Wong 2000
<i>Sargassum</i> f		U	8	0.03	In presence of other ions; spent biomass was calcined for storage	Silva et al. 2009
<i>Sargassum</i>		Ag(I), Cd(II), Co(II), Cu(II), Mn(II), Ni(II), Pb(II), Zn(II), Cr(III)	43-65, 56-79, 35, 57-67, 22-33, 18-37, 248, 26-39, 68	0.4-0.6, 0.5-0.7, 0.6-0.6, 0.9-1.1, 0.4-0.6, 0.4-0.6, 1.1-1.2, 0.4-0.6, 1.3	Langmuir fits; Cr(III) > Pb ≈ Cu > Ag ≈ Zn ≈ Cd > Ni ≈ Co >> Cr(VI) > As(V) low salt; salt inhibited sorption; ion exchange	Tsui et al. 2006
<i>Ecklonia</i> m		Cu(II), Ni(II), Cd(II)	No eval	-	Copper wins the competitions	Williams et al. 1998
<i>Ecklonia</i>		Cr(III)	35	0.7	Higher pH preferred; carboxyl binding sites; hydrolysis reactions at higher pH	Yun et al. 2001
<i>Sargassum</i> p		Cd(II)	146	1.3	Carboxyl groups binding; complexation	Yun & Volesky 2003
Brown seaweed, other biomass		Multi-metal: Cu(II), Pb(II), Zn(II), Ni(II) Alone: Cu(II), Pb(II), Zn(II), Ni(II)	2-117 23, 41, 13, 12	0.2 0.4, 0.2, 0.2, 0.2	Chromatographic effect due to differing affinities of metals	Zhang & Banks 2006

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Loofa						
Loofa alone		Ni(II)	6	0.10	Not as effective as when coated by bacterium	Akhtar et al. 2004
<i>Chlorella sorokin.</i>	Immob.	Ni(II)	48-60	0.8-1.0	Immobilized <i>Chlorella sorokin.</i> on Loofa worked best at pH 4+; HCl regeneration	Akhtar et al. 2004
<i>Sargassum fluit.</i>	Proton	Cu(II)	62, 54	1.0, 0.8	Elution of the exchanged ions	Kratochvil et al. 1995
<i>Sargassum fluit.</i>	Acid or Ca ²⁺	Cu(II)	75	1.2	Ion exchange; how to regenerate not critical	Kratochvil et al. 1997
<i>Sargassum fluit.</i>	Proton	Cr(III), Cr(VI)	38, 60	0.73, 1.2	Best pH 2 for Cr(VI); simultaneous anion exchange & reduction;	Kratochvil et al. 1998
<i>Sargassum fluit.</i>		U(VI)	560		Higher pH favored to 4; Langmuir fit; hydrolyzed U species; regen. w. HCl	Yang & Volesky 1999a
<i>Sargassum fluit.</i>		Cd(II)	75	1.45	Langmuir fit; ion exchange; diffusion control	Yang & Volesky 1999b
<i>Sargassum fluit.</i>	Proton-ated	U(VI)	430	1.8	Higher pH favored ; ion exchange ; model	Yang & Volesky 1999c
<i>Sargassum</i> sp.	HCl, NaOH, CaCl ₂ , CH ₂ O, glutarald	Cr(VI)	31-58	0.6-1.1	Treatments reduced leaching, did not hurt metal uptake; best pH 2; redox control	Yang & Chen 2008
Microbiota						
Algae						
<i>Fucus serratus</i>		Cu(II)	102	1.61	Effective pH 5; ion exchange; Langmuir fit; alginate mucilage may be key	Ahmady-Asbchin et al. 2008
<i>Oscillatoria angu.</i>		Zn	641	10		Ahuja et al. 1999
<i>Chlorella sorokin.</i>	Immob. on loofa	Ni(II)	48-60	0.82-1.02	Immobilized <i>Chlorella sorokin.</i> on loofa worked best at pH 4+; HCl regeneration	Akhtar et al. 2004
<i>Chlorella vulgaris</i>		Cr(VI)	6-28	0.1-0.5	Simultaneous removal of Cr(VI) and Cu(II)	Aksu & Açikel 1999
<i>Chlorella vulgaris</i>		Cr(VI)	27	0.52	Simultaneous removal of Cr(VI) and Fe	Aksu & Açikel 2000
<i>Chlorella vulgaris</i>		Cu(II)	43	0.68	Best pH 4-4.5	Aksu et al. 1992
<i>Chlorella vulgaris</i>		Fe(III), Cr(VI)	21, 25	0.4, 0.5	Best pH 2; metals compete; Langmuir fit.	Aksu et al. 1997
<i>Chlorella vulgaris</i>		Cu(II), Cr(VI)	17-28, 27	0.3-0.5, 0.52	Competitive adsorption of the two metals.	Aksu et al. 1999

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Chlorella vulgaris</i>		Cd(II)	111	1.00		Aksu (2001)
<i>Chlorella vulgaris</i>	Dried	Cd(II), Ni(II)	87, 58	0.78, 0.89	Competition shown; Langmuir fit	Aksu & Donmez 2006
		Cd(II)	28	0.53	Desorption by HCl and pH 1 worked by ion exchange for concentration & regeneration	Aldor et al. 1995
<i>Caulerpa lentillif.</i>		Cu(II), Cd(II), Pb(II)	4.4, 6.7, 11	0.07, 0.06, 0.055	Binary sorption; some mutual sites exist; better at higher pH	Apiratikul & Pavasant 2006
<i>Chlamydomonas</i>	Heat, acid	Cr(VI)	18- 26	0.34- 0.5	Best pH 2; 2 nd order rate; Langmuir fit; NaOH regeneration (96%)	Arica et al. 2005
<i>F. vesiculosus</i> , <i>A. nodosum</i>		Zn(II), Cu(II), Ni(II)	2-25, 4-9, 0.7-3	.02-.39, .06-.14, .01-.05	Bacteria, yeast, fungi, activated sludge, and marine algae were effective; biomass types were suited for different metals.	Bakkaloglu et al. 1998
<i>Spirogyra</i> spp.	NaOH, CaCl ₂ , CH ₂ O	Cr(III)	30	0.6	Best pH 5; Langmuir fit OK	Bishnoi et al. 2007
<i>Sargassum siliq.</i>		Cr(VI)	60	1.2	Best pH 2; reduction in parallel with adsorption; reduction is a first step in regeneration	Cabtingan et al. 2001
<i>Fucus</i>		Cu(II)	115	1.8	Pseudo 2 nd order rate; Langmuir fit	Cochrane et al. 2006
<i>Fucus spiralis</i>		Cd	64	0.57		Cordero et al. 2004
<i>Sargassum</i> sp.		Cd(II)	120	1.1		Cruz et al. 2004
Various algae		Cr(VI)	79-154	1.5-3.0	Tested at pH 2; Langmuir fits	Dönmez et al. 1999
<i>Dunaliella</i> strains		Cr(VI)	46-102	0.9-2.0	Best pH 2; strong competition by salt; pseudo 2 nd order rate; Langmuir fit	Dönmez & Aksu 2002
<i>Ulva lactuca</i>		Cr	11	0.2	Best pH 1; not sensitive to salt; pseudo 2 nd order rate; Langmuir fit	El-Sikaly et al. 2007
<i>Fucus vesiculosus</i>		Cu(II)	75	1.2		Fourest & Volesky 1997
<i>Spirulina platensis</i> <i>Chlorella vulgaris</i>	Fresh & spent	Cr(VI)	68-76	1.3-1.5	Best pH 1.5; also OK pH 4-5; fresh or spent worked equally; Langmuir fit	Gokhale et al. 2008
<i>Fucus vesiculosus</i>		Cu(II)	23	0.4	Pseudo 2 nd order rate; Langmuir fit; regenerated with HCl	Grimm et al. 2008
<i>Spirogyra</i> sp.		Cr(VI)	15	0.3	Best pH 2; Langmuir fit	Gupta et al. 2001

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Oedogonium</i> sp., <i>Nostoc</i> sp	Dried	Pb(II)	93-145	0.4-0.7	Best pH 5; 2 nd order rate; Langmuir fit; carboxyl and amino groups; endothermic; regenerated with HCl (90%)	Gupta & Rastogi 2008a
<i>Oedogonium</i> sp.,	Dried, NaOH	Cd(II)	80-89	0.7-0.8	NaOH enhancement; 2 nd order rate; Langmuir fit; functional groups; regenerable	Gupta & Rastogi 2008b
<i>Oedogonium</i> h.,	Raw, acid treat	Cr(VI)	31-35	0.6-0.7	Acid treatment helped; best pH 2; first order rate; Langmuir fit; groups; regenerated with NaOH (75%)	Gupta & Rastogi 2009
<i>Fucus</i> spp.	Dead	Cd(II)	90	0.8	Higher pH favored to 5; Pseudo 2 nd order rate; multi-site model	Herrero et al. 2006
Three algal sp.; <i>Ascophyllum</i> n. <i>Fucus spiralis</i> <i>Sargassum</i> nat.	CH ₂ O	Cd(II)	100, 215, 73, 135	0.9, 1.9, 0.6, 1.2	Best pH 3.5; regen. with HCl	Holan et al. 1993
<i>Ascophyllum</i> n. <i>Fucus vesiculos.</i> <i>Sargassum</i> nat.		Ni(II), Pb(II) Ni(II), Pb(II) Ni(II), Pb(II)	30, 270- 360; 17,220- 371; 24-44, 70-220	0.5, 1.3-1.7; 0.3, 1.1-1.8; 0.4-0.9, 0.3-1.1		Holan & Volesky 1995
<i>Chlorella vulgaris</i>	Lyophil- ized	Au(0)	No eval	No eval	Gold powder and ionic; at least three adsorption sites involved	Hosea et al. 1986
<i>Aphanothece</i> h		Zn(II)	133	2.0		Incharoensakdi & Kitjahn 2002
Algal biomass	Varieties	Pb(II)	40-270	0.2-1.3	Higher pH favored; regen. at pH<1 (95%) or CaCl ₂	Jalali et al. 2002
Algal biomass	Ferro- cyanide	Cs(I)	10- 100	0.08- 0.8	Best pH 4; ferrocyanide enhanced uptake; Langmuir fit; regen. w base	Jalali-Rad et al. 2004
<i>Undaria pinnat.</i>		Cu(II)	200	3.2	Uptake of Cu(II) increased 4.5X by oxime; highly selective vs. Ca(II), Cd(II), Pb(II)	Kim et al. 1996
<i>Undaria pinnat.</i>		Pb(II)	340	1.6	Surface complexation model demonstrated	Kim et al. 1998

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Undaria pinnat.</i>		Pb(II), Cu(II), Cd(II)	340	1.6	Xanthation increased adsorption capacity 3X; selective adsorption possible (compared to Ni(II), Zn(II), and Co(II))	Kim et al. 1999
30 strains		Cd(II), Pb(II), Ni(II), Zn(II)	34, 93-270, 22-26, 20-29	0.3, .45-1.3, .37-.45, .32-.45	Langmuir fits; different selectivities, different optimum pHs; phosphorylation beneficial in some cases	Klimmek et al. 2001
<i>Ulva fasciata</i>		Cu(II), Zn(II)	27, 14	0.4, 0.2	Higher pH favored to 5; Langmuir fit	Kumar et al. 2006c
<i>Ascophyllum n</i>		Co(II)	156, 100	2.65, 1.7		Kuyucak & Volesky 1989
<i>Pachymeniopsis</i>		Cr(VI)	225	4.3		Lee et al. 2000
3 brown algae	Dead	Cu(II), Pb(II), Zn(II)	164, 538, 136	2.6, 2.6, 2.1	Best pHs 3-6; severe competition	Lee et al. 2002
2 marine algae	CH ₂ O, glutarald	Pb(II), Cd(II), Cu(II), Ni(II), Zn(II)	378, 130, 85, 89, 60	1.8, 1.2, 1.3, 1.4, 0.9	Modification effectiveness : GA > FA > PEI ; Langmuir fits	Leusch et al. 1995
<i>Cystoseira bacc.</i>		Cd(II); Pb(II)	101, 186	0.9, 0.9	Higher pH favored to 4; pseudo 2 nd order rate; Langmuir fit; carboxyl group involvement	Lodeiro et al. 2006
<i>Laminaria japon.</i>	Epichlor; KMnO ₄	Pb(II)	250- 346	1.2- 1.7	Best pH 5.3; Langmuir combination fit	Luo et al. 2006
Marine algae		Pb(II), Cu(II)	250, 78	1.2, 1.2	Electrostatic and coordination binding	Malik et al. 2002
<i>Ulothrix zonata</i>		Cr(VI)			Freundlich fit	Malkoc & Nuhoglu 2003
<i>Fucus vesicul.</i>		Cd(II), Pb(II), Cu(II)	108, 211, 106	0.96, 1.00, 1.67	Pseudo 2 nd order rate; ion exchange/complexation; Langmuir fit	Matta et al. 2008
Marine algae		Pb(II), Cu(II)	331, 83	1.6, 1.3	Modification was effective; best pH 4.5	Matheickal & Yu 1999
Marine algae	CaCl ₂ , heat	Cd(II)	124	1.1	Modification was effective; best pH 5	Matheickal et al. 1999

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Various	Dried	Cu(II)	6-22	0.10-0.35	Carboxyl & amino groups prominent; acidic sites most important	Murphy et al. 2007
Various	Dried	Cr(III), Cr(VI)	63, 46	1.2, 0.8	Langmuir fits	Murphy et al. 2008
<i>Chlorella vulgaris</i> , <i>Cladophora crisp.</i> <i>Rhizopus arrhizus</i>		Cr(VI)	2.5-3.5, 2-3, 2.5-4.5	0.07, 0.06, 0.08	Best pHs 1-2; Freundlich fits	Nourbakhsh et al. 1994
<i>Ulothrix zonata</i>		Cu(II)	160	2.5	Langmuir fit	Nuhoglu et al. 2002
Two species		Cr(III)	12-14	0.23-0.27	Best pH 5; competition; carboxyl groups important; Langmuir fit; regen. with H ₂ SO ₄	Onyancha et al. 2008
<i>Cladophora crisp.</i>		Cu(II)	60	1.0	Best pH 4.5; pseudo 2 nd order rate; Langmuir fit	Ozer et al. 2004a
<i>Microcystis</i>		Fe(III), Ni(II), Cr(VI)	260, 95, 65	4.6, 1.6, 1.2	Iron adsorbed preferentially with Langmuir fit; Ni and Cr Freundlich fits; carboxyl & amino groups important	Pradhan et al. 2007
<i>Fucus vesiculosus</i>	HCl, Ca, CH ₂ O, Na ₂ CO ₃ , NaOH	Cu(II), Cd(II), Pb(II), Ni(II)	223, 337, 248, 141	0.9-3.8, 0.5-3.0, 0.9-1.2, 0.4-2.4	Treatments with Na ₂ CO ₃ and NaOH increased uptake greatly; calcium was the only metal that improved sorption capacities; Langmuir fits	Rincón et al. 2005
<i>Chlorella vulgaris</i>		U	4	0.017		Sakaguchi & Nakajima 1991
<i>Ceramium virgat.</i>		Cr(VI)	26	0.50	Best pH 1.5; pseudo 2 nd order rate; Langmuir fit best	Sari & Tuzen 2008
<i>Padina pavonica</i>		Al(III)	77	2.8	Pseudo 2 nd order rate; Langmuir fit; ion exchange; endothermic; regen. with HCl	Sari & Tuzen 2009b
<i>Sargassum sp.</i> , <i>Padina sp.</i>		Cd(II), Cr(III), Cr(VI)	64, 15, 10	0.57, 0.28, 0.2	Best pH Cr(VI) at 2; for Cr(III) 3.8; for Cd(II) 5.5; Langmuir fits; simultaneous reduction and adsorption	Sheng et al. 2004a
Several species		Pb(II), Cu(II), Cd(II), Zn(II), Ni(II)	259 Pb 37-72 Cu	1.25 Pb 0.6-1.1 Cu	Best pHs 5.5-6'; chelating by carboxyls with participation by ether, ROH, amino groups	Sheng et al. 2004b
<i>Sargassum sp.</i>		Pb(II), Cu(II), Cd(II)	180, 65, 31	0.85, 1.0, 0.6	Higher pH favored; Langmuir fits (competitive); correlations with electronegativities & stability of hydroxides; competition & hogging	Sheng et al. 2007

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Sargassum sp.</i>	PVA gel	Cu(II)	57	0.9	The beads showed slower uptake than free <i>Sargassum</i>	Sheng et al. 2008
<i>Sargassum sp.</i>		Cd(II), Zn(II), Cu(II)	157, 118, 77	3.0, 1.8, 1.2	Langmuir fits	Valdman & Leite 2000
<i>Sargassum sp.</i>		Cr(VI)	19	0.36	Column dynamics	Vieira et al. 2008
<i>Ascophyllum n.</i>		Cd(II)	30	0.28	Column studies	Vlosky & Prasetyo 1994
<i>Sargassum sp.</i>		Cu(II)	38	0.60	Column long-term use	Volesky et al. 2003
Micro-algae, etc.		Cu(II)	4-10	.06-.16	Pseudo 2 nd order rate; Langmuir fits	Wang et al. 2009
<i>Chlorella fusca</i>		Pb(II)	293	1.4		Wehrem & Wattern 1994
Common marine		Cd(II), Cu(II), Pb(II)	90-123, 51-76, 207- 330	0.8-1.1, 0.8-1.2, 1.0-1.6	0.8 to 1.6 mmol/g (dry)	Yu et al. 1999
Alginic acid with cellulose		Cd(II), Cu(II)	79, 32	0.70, 0.50	Best pHs 2-3; competition; regen. with HCl	Zhang et al. 2004
Algae & micro- algae sp.		Cu(II), Cd(II)	21-23, 22-24	0.35, 0.20	Best pHs 4-5 & 6.7, resp.; competition; Freundlich fit; regen by HCl or EDTA	Zhou et al. 1998
BACTERIAL						
<i>Streptomyces</i>	NaOH	Zn(II)	2.9	0.04	NaOH pretreatment increased binding; continuous flow system demonstrated; HCl regeneration successful	Addour et al. 1999
Various		Pb, Zn, Cd, Cr, Cu, Ni	5 to 641	Mass listed	Review article: Fermentation byproducts were effective.	Ahluwalia et al. 2005b
<i>Zoogloea ramig.</i>		Cu	29	0.46		Aksu et al. 1992
<i>Thiobacillus fero.</i>		Cr(III)	509	9.8	Tolerant of Cr(III); best pH 1.4;	Baillet et al. 1998
<i>Streptomyces rim.</i>	NaOH	Ag(I)	63	0.58	Mass transfer control; poor Langmuir fit	Bakhti et al. 2008
<i>Bacillus subtilis</i>		Mn(II), Fe(III), Ni(II), Cu(II), Au(III)	0.8, 3.6, 0.1, 3.0, 0.36	0.01, 0.06, 0.002, 0.05, 1.8	Removal of carboxyl groups precluded metals uptake; removing amines had no effect.	Beveridge & Murray 1980

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Phormidium lam.</i>	In resin	Cu(II), Fe(II), Ni(II), Zn(II)	20-21, 17-18, 13-16, 18-19	.31-.33, .30-.33, .22-.27, .28-.29	Smaller bead size increased rate; regeneration with HCl	Blanco et al. 1999
<i>Rhodococcus</i>		Pb(II)	94	0.45	Competition; 2 nd order rate; Langmuir fit	Bueno et al. 2009
<i>Pseudomonas a.</i>	Inactivat.	Hg(II)	180	0.90	Effects of pH, salt, phosphate; Langmuir fit	Chang & Hong 1994
<i>Pseudomonas a.</i>	Live vs. inactivat.	Pb(II), Cu(II), Cd(II)	70-110, 20-24, 30-60	0.3-0.5, 0.3-0.4, 0.2-0.5	Both live & inactivated cells were effective; Higher pH better, eventually has hydroxides; regeneration effective	Chang et al. 1997
Bacterial cellulose	CMC	Cu(II), Pb(II)	13, 60	0.2, 0.3	Good pH 4.5; carboxylation greatly increased uptake	Chen et al. 2009
<i>Pseudomonas p.</i>	Living, non	Cu(II), Zn(II)	13-24, 12-27	0.2-0.4, 0.2-0.4	Living cells adsorbed more; Best pH 4.5-5; Langmuir fits; Regen. By HCl (84%)	Chen et al. 2005
<i>Streptomyces r.</i>	NaOH	Cu(II), Zn(II), Cr(VI)	30, 27, 27	0.5,0.4, 0.5	Poor Langmuir fit	Chergui et al. 2007
<i>Corynebacterium</i>	Protonat.	Pb(II)	568	2.7	Ion exchange with H	Choi & Yun 2004
<i>Streptococcus l.</i>		Pb(II), U	100, 440	0.48, 1.8		Friis & Myers-Keith 1986
<i>Streptococcus e.</i> , <i>Saccharomyces</i> , <i>Aspergillus niger</i>	Nutrients (living)	Cr(VI), Fe(III)	58, 22; 35, 22; 13, 20	1.1,0.4; 0.7,0.4, 0.2,0.4	Higher temperature favored moderately, regeneration with NaOH	Goyal et al. 2003
<i>Aeromonas hydro.</i>	Dead, p- suflone	Cr(VI)	45-42	0.9-0.8	Regenerable with moderate loss of effectiveness	Hasan et al. 2009b
Ten bacterial,	Living	U	22-53	0.1-0.2	actinomycetes > bacteria, yeasts > fungi; Freunlich isotherm; bio activity not needed	Horikoshi et al. 1981
Cyanobacteria	Live, salts	Cr(VI)	17-18	0.35	Best pH 3; moderate repression by salt; pseudo 2 nd order rate; Langmuir fit	Kiran et al. 2007
Cyanobacteria	Live	Cr(VI)	111	2.1	Immobilization greatly decreased uptake; regenerable with HCl	Kiran & Kaushik 2008
<i>Pseudomonas a.</i>	Matrices, epichlor, chitosan	Pb(II)	28-34	0.1-0.2	Regeneration with HCl (capacity values multiplied by 1000 factor)	Lin & Lai 2006

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Aeromonas cavi.</i>		Cd(II)	124-155	1.1-1.4	Langmuir fit	Loukidou et al. 2004a
<i>Aeromonas cavi.</i>		Cr(VI)	169-284	3.2-5.5	Pseudo 2 nd order rate; higher uptake at lower temperature; Langmuir fit	Loukidou et al. 2004b
<i>Streptomyces r.</i>	NaOH	Zn(II)	30, 80	.45-1.2	NaOH treatment greatly increased capacity	Mameri et al. 1999
<i>Streptomyces n.</i>		Cd(II), Cu(II), Ni(II), Pb(II), Zn(II), Ag(I), Co(II), Cr	3.4, 9, 0.8, 55, 1.6, 38, 1.2, 2.0	.003, 0.14, 0.013, 0.26, 0.024, 0.35, 0.020, 0.038		Mattuschka & Straube 1993
<i>Micrococcus lut.</i>	Hot H ₂ O, NaOH, CH ₂ O & mixture	Cu(II)	33+	0.5+	KOH treatment most effective; N and O sites important	Nakajima et al. 2001
<i>Micrococcus lut.</i>		Th, U	18-74, 2-71	.08-.32, .01-.30	Langmuir binary fits	Nakajima & Tsuruta 2004
<i>Zoogloea ramig.</i>		Cr(VI)	2	0.04		Nourbakhsh et al. 1994
<i>Pseudomonas a.</i> on activated C		Cr(VI), Ni(II), Cu(II), Zn(II), Cd(II)	No report	No report	42-84% uptake; Langmuir fits	Orhan et al. 2006
<i>Pantoea sp.</i>		Cr(VI), Cd(II), Cu(II)	54-204, 54, 30	1-4, 0.5,0.5	Best pHs: 3, 6, 5 for Cr(VI), Cd(II), Cu(II); Langmuir fits	Ozdemir et al. 2004
<i>Arthrobacter sp.</i>		Cu(II), Cd(II), Fe	45, 13, 56	0.71, 0.12, 1.0	Ion exchange/complexation; two kinds of acidic sites	Pagnanelli et al. 2000
<i>Pseudomonas p.</i>	Freeze dried	Cd(II), Cu(II), Pb(II), Zn(II)	8.0,6.6, 56, 6.9	.15,.10, .27,.10	Best pHs 7-7.5; 80% removal; Langmuir fit; M(OH) ⁺ complexes	Pardo et al. 2003
<i>Corynebacterium</i>		Cr(VI)	5.7	0.11	Reductive adsorption	Park et al. 2008b
<i>Streptomyces pim.</i>	Ethanol	Cd(II)	5-30	0.04- 0.26	Higher pH favored to 5; Langmuir fit; resorbed with EDTA	Puranik et al. 1995

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Streptovercillium</i>	Boiling water	Pb(II), Zn(II)	58, 21	0.28, 0.32	Boiling water increased uptake by 41-52%; best pHs 3.5-4.5 and 5-6; Langmuir fit; more than one bonding site; regen. HCl, NaHCO ₃	Puranik & Paknikar 1997
<i>Streptovercillium</i>		Pb(II), Zn(II), Cd(II), Cu(II) Ni(II), Co(II)	62, 9, 18, 6, 4, 4	0.3+, 0.14, 0.16, 0.10, 0.07, 0.07	Preferential Pb(II) uptake; Langmuir fits predict multi-metal adsorption; Pb ²⁺ > Zn ²⁺ = Cu ²⁺ > Cd ²⁺ > Ni ²⁺ > Co ²⁺	Puranik & Paknikar 1999
<i>Bacillus thuring.</i>		Cr(VI)	29-34	.55-.65	Langmuir fit	Şahin & Öztürk 2005
<i>Bacillus firmus</i>		Pb(II), Cu(II), Zn(II)	467, 381, 418	2.2, 1.8, 2.0		Salehizadeh & Shojaosadati 2003
Microbial bomass		Sr(II)	13-24	.15-.27	On roots; Langmuir fit; regen. by acid	Scott 1992
<i>Streptomyces r</i>	NaOH	Cd(II)	63	0.56	Mass transfer control; Langmuir fit	Selatnia et al. 2004a
<i>Streptomyces r</i>	NaOH	Fe(III)	122	2.18	Langmuir fit	Selatnia et al. 2004b
<i>Streptomyces r</i>	NaOH	Pb(II))	135	0.65	Langmuir fit	Selatnia et al. 2004c
<i>Streptomyces r</i>	NaOH	Ni(II))	33	0.56	Langmuir fit	Selatnia et al. 2004c
<i>Bacillus coagul.</i> ; <i>Bacillus megater.</i>		Cr(VI)	40, 31	.77, .60	Dead cells were more effective	Srinath et al. 2002
<i>Sphingomonas p</i>	Living	Cd(II)	No eval	No eval	Living cells adsorbed more	Tangaromsuk et al. 2002
<i>Mucor hiemalis</i>		Cr(VI)	47-54	.90-1.0	Langmuir fit	Tewari et al. 2005
<i>Pseudomonas a.</i>	Drying	La(III),Eu(III), Yb(III)	129,61, 56	.93,.40, .32	Batch; BET fit; drying did not affect uptake; Al(III) antagonism	Texier et al. 1999
<i>Pseudomonas a.</i>	Drying	La(III),Eu(III), Yb(III)	74, 35, 33	.53,.23, .19	Column; Competition: Eu ³⁺ > Yb ³⁺ > La ³⁺	Texier et al. 2000
<i>Pseudomonas f.</i>		Th, U	15, 6	.06,.02		Tsezos & Volesky 1981
<i>Mucor meihei</i>		Cr	60	1.15	Best pH zero	Tobin & Roux 1998
<i>Saccharomyces c.</i> , <i>Aspergillus oryzae</i> <i>Bacillus lentus</i>	Fermen- tation byprods.	Cu(II), Zn(II), Cd(II)	10-30, 5-13, 4-80	.16-.47, .08-.20, .04-.71	Nonprotonated biomass had higher uptake; Langmuir fits	Vianna et al. 2000
<i>Corynebacterium</i>	Biomass origin	Ni(II)	102- 111	1.7-1.9	Best pH 6	Vijayaraghavan et al. 2008

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
From mine extract	Poly-sulfone	Cd(II)	10-60	.09-.53	3-fold higher uptake than many other candidates; uptake increased greatly by carboxylation, CS ₂ , thiosulfate; various regeneration solutions	Xie et al. 1996
<i>Bacillus licheni.</i>	Dead	Cr(VI)	60	0.12	Pseudo 2 nd order rate; Langmuir fit	Zhou et al. 2007
<i>Staphylococcus, Pseudomonas</i>		Cd(II), Cr(VI)	164, 95-143	1.46, 1.8-2.8	Langmuir fit; Cd wins competition	Ziagova et al. 2007
<i>Actinomyces</i> , fungi	Living or dead	Cd(II)	—	—	Non-living biomass showed greater uptake	Zouboulis et al. 1997
YEAST						
Yeast biomass	Acetone	Pb(II)	49	0.24	Blocking carboxyl groups hurt adsorption; complexation	Ashkenazy et al. 1997
<i>Saccharomyces c.</i>		Sr(II), Mn(II), Zn(II), Cu(II), Cd(II), Ti(I)	1.3, 0.82, 0.92, 1.3, 2.8, 0.33	0.015, 0.015, 0.014, 0.028+, 0.025+, 0.007	Covalent & electrostatic contributions; explained by hard/soft ion theory; metal complexes can interfere with adsorption	Avery & Tobin 1993
<i>S.rimosus</i> , yeast		Zn(II), Cu(II), Ni(II)	2-26, 4-9, 1-3	.03-.39, .06, .14, .01-.05	Bacteria, yeast, fungi, activated sludge, and marine algae were effective; biomass types were suited for different metals.	Bakkaloglu et al. 1998
Yeast	Hot NaOH	Fe(III), Cu(II), Cr(III), Hg(II), Pb(II), Cd(II), Co(II), Ag(I), Ni(II), Fe(II)	—	—	Selective adsorption: Cu ²⁺ > Cr ³⁺ > Cd ²⁺ and Cu ²⁺ > Pb ²⁺ > Ni ²⁺ >> Cr(VI)	Brady et al. 1994
Distillary		Cu(II), Zn(II), Fe(II), Pb(II), Ag(I)	5, 12, 14, 180, 55	.08, .18, .25, .87, 0.51	Pb > U > Ag > Zn greater than or equal to Fe > Cu	Bustard & McHale 1998
<i>Saccharomyces c.</i>		Pb(II)	30	0.14	Immobilized bacterium biomass on pine cone; best pH 5; Langmuir fit	Cabuk et al. 2007
<i>Saccharomyces c.</i>		Cu(II)	No eval	No eval	Biocatalytic reduction by immobilized microbe	Chandran et al. 2002

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Brewer's waste		Pb(II), Ag(I), Cs(I), Sr(II)	86, 43, 1, 8	.42,.40, .01-.09	Langmuir fit; uptake correlated with covalent index and electroneativity, opposite to dissociation constant	Chen & Wang 2008b
<i>Saccharomyces c.</i>		Zn(II)	5-43	.08-.66	Ion exchange	Chen & Wang 2007a
<i>Saccharomyces c.</i>		Pb(II), Ag(I), Cr(II), Cu(II), Zn(II), Cd(II), Co(II), Sr(II), Ni(II), Cs(II)	85,41, 12,10, 10,16, 8,11, 6,12	.41, .38 .24,.16, .15,.14, .13,.12, .11,.09	SQAR model; selectivity vs. hard or soft ions shown; Pb(II) and Ag(I) were high outliers	Chen & Wang 2007b
<i>Saccharomyces c.</i>		Pb(II), Ag(I), Cr(III), Cu(II), Zn(II), Cd(II), Co(II), Sr(II), Ni(II), Cs(I)	85, 42, 13, 10, 10, 15, 8, 10, 6, 12	.41,.39, .25,.16, .15,.13, .14,.11, .10,.09	Langmuir fits; uptake increased with increasing covalent character of binding	Chen & Wang 2007c
<i>Saccharomyces c</i>		Zn(II)	20	0.3	Ion exchange demonstrated; binding with oxygen	Chen & Wang 2008a
<i>Saccharomyces c.</i>		Pb(II), Ag(I), Cu(II), Zn(II), Co(II), Sr(II), Cs(I)	87,30, 11, 7, 5, 5, 8	.42,.28, .17,.11, .08,.06, .06	Pb>Ag>Cu>Zn>Co>Sr>Cs; 2nd order rate; Langmuir fit; soft ions preferred; covalent content	Chen & Wang 2010
Ten yeasts	Living	U	16-40	0.1-0.2	actinomycetes > bacteria, yeasts > fungi; Freunlich isotherm; bio activity not needed	Ten bacterial,
<i>Saccharomyces c.</i>		U(VI)	2082	8.7	UO ₂ ²⁺ ions; the cells were destroyed & broken open by the uranyl nitrate	Popa et al. 2003
<i>Rhodotorula rubra</i>		Cd(II), Pb(II)	13, 6.0	0.12, 0.03	Dead biomass preferred; best pHs 4-6; Langmuir fit; desorp. with EDTA or HCl	Salinas et al. 2000
<i>Saccharomyces c</i>	Genetic fusions	Cd(II), Zn(II)	2-3, 1.3-2.0	.02-.03, .02-.03	30% increased uptake due to genetic engineering	Vinopal et al. 2007
<i>Saccharomyces c</i>	Living vs. dead	Cd(II)	70	0.62	Living cells were more effective	Volesky et al. 1993
<i>Candida fused</i>	Live	Cr(VI), Ni(II)	No eval	No eval	Reduction of Cr(VI) involves metabolism; Ni uptake is passive	Yin et al. 2008

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Saccharomyces c</i>	CH ₂ O	Cu(II), Zn(II), Cd(II)	8, 7, 7	.12, .11, .06	Best pHs 5.3, 6, 6.7; regen. with HCl	Zhao & Duncan 1997b
<i>Saccharomyces c</i>	CH ₂ O	Cr(VI)	63	1.2	Low pH best; regen. with HCl	Zhao & Duncan 1998b
FUNGAL						
<i>Aspergillus flavus</i>	Deterg., NaOH, DMSO	Pb(II), Cu(II)	13, 11	.06, .17	Deterg., NaOH, DMSO enhanced sorption.	Akar & Tunali 2006
<i>Aspergillus parasi.</i>		Pb(II)	10-38 (55 at 70 min)	.05-.18	Higher pH favored to 6; lower temp. better; ion exchange/complexation; Langmuir fit; regeneration possible	Akar et al. 2007
<i>Rhizopus arrhizus</i>	NaCl	Cr(VI)	65-80	1.2-1.5	Best pH 2; salt repressed adsorption; Langmuir fit	Aksu & Balibek 2007
<i>Aspergillus niger</i>	Alkali	Ag(I)	10,000	92	Ion exchange; can be regenerated.	Akthar et al. 1995
<i>Lactarius scrobic.</i>		Pb(II), Cd(II)	56, 53	.27, .47	Best pH 5.5; ion exchange; 2 nd order rate; exothermic; regen. 95% with acid treatment.	Anayurt et al. 2009
<i>Lentinus sajor-c</i> ; CMC alone; <i>L. sajor-c</i> on CMC		Cr(VI)	19, 5, 32	0.37, 0.10, 0.62	Tested at pH 2; Langmuir fits	Arica & Byramoğlu 2005
<i>Rhizopus oligo.</i>		Pb(II)	126	0.61	Best pH 5; Langmuir fit; ion exchange	Ariff et al. 1999
<i>Rhizopus oligo.</i>		Cd(II)	17	0.15		Aloysius et al. 1999
<i>Rhizopus arrhizus</i>		Cr	11	.21	Best pHs 2-7	Bai & Abraham 1998
<i>Rhizopus nigric.</i>		Cr, Pb(II)	47	0.90	Best pH 2; smaller particles better	Bai & Abraham 2001
Four strains	Acetic anhydr., cationics	Cr(VI)	46-200	0.9-3.8	Best pH 2; acetic anhydride rx. with amino groups hurt adsorption; cationic compounds enhanced adsorption; Langmuir fit	Bai & Abraham 2002
<i>Rhizopus nigric.</i>	Support	Cr(VI)	21-119	.40-2.3	Effect of matrix to hold the biomass; regeneration by carbonate or NaOH	Bai & Abraham 2003
<i>S.cerevisiae</i>		Zn(II), Cu(II), Ni(II)	3.4, 3.9, 1.5	0.052, 0.061, 0.025	Bacteria, yeast, fungi, activated sludge, and marine algae were effective; biomass types were suited for different metals.	Bakkaloglu et al. 1998

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Trametes versic.</i>	Live, inactiv.	Cu(II), Pb(II), Zn(II)	117, 230, 109	1.8, 1.1, 1.7	Best pH 4-6; slightly higher uptake on inactivated biomass; Langmuir fit; HCl regeneration 97%	Bayramoglu et al. 2003
<i>Lentinus sajor-c.</i>		Cr(VI)	20-33	.38-.63	Heat treatment enhanced uptake; HCl and NaOH less effective; Langmuir fits	Bayramoglu et al. 2005
<i>Aspergillus fumi</i>		U(VI)	423	1.8	Best pH 5; Inhibited by Al(III), but not other ions; Langmuir fit;	Bhainsa & D'Souza 1999
<i>Rhizopus arrhizus</i>		Sr(II), Cd(II), Cu(II), Mn(II), Zn(II), Pb(II)		.12,.18, .20,.12, .14,.25	Pb ²⁺ > Cu ²⁺ > Cd ²⁺ > Zn ²⁺ > Mn ²⁺ > Sr ²⁺ ; Competition; binding correlated with covalent index; hard ions such as Sr(z+) exhibited onto ionic binding to the metal	Brady & Tobin 1995
<i>Rhodotorula glut.</i>		Pb(II)	74	0.36	Best pH 4.5-5; Langmuir fit; ion exchange and precipitation	Cho & Kim 2003
<i>Aspergillus flavus</i>		Cr(VI)	0.1-0.3	.006	Autoclaving enhanced uptake; Langmuir fits	Deepa et al. 2006
<i>Penicillium c</i>	Graft PAA	Cu(II), Cd(II)	108, 210	1.7, 0.18	Pseudo 2 nd order rate; Langmuir fit; endothermic; surface groups; HCl regen.	Deng & Ting 2005a
<i>Penicillium c</i>	PEI, glutaral.	Cu(II), Pb(II) Ni(II)	92,204, 55	1.5,1.0, 0.94	Enhanced sorption; amine association; Langmuir fit	Deng & Ting 2005b
<i>Penicillium c</i>	PEI, glutaral.	Cr(VI)	279	5.4	Positive zeta potl.; effective at pH 4.3-5.5; Langmuir fit; Cr(III) detected on surface	Deng & Ting 2005c
<i>Penicillium c</i> ; modified...	PEI, glutaral.	Cr(VI)	26, 224	0.5, 4.3	Pseudo 2 nd order rate; partial reduction; some aggregation on surface	Deng & Ting 2006
<i>Aspergillus niger</i>	NaOH	Cr(II), Pb(II)	29,33	.56,.16	Langmuir fit; endothermic	Dursun 2006
<i>Aspergillus niger</i>		Cu(II), Zn(II), Ni(II), Cr(VI)	5, 4, 6, 3	.08,.06, .10,.06	Best pH 4-5 for cations; Langmuir fit; copper and zinc could be co-adsorbed	Filipovic-Kovacevic et al. 2000
Mycelial biomass	NaOH	Ni(II), Zn(II), Cd(II), Pb(II)	5, -, 19, 166	.08, -, .17,.80	Best pHs 5-7; proton exchange; Langmuir fit; controlled by acidity of substrates	Fourest & Roux 1992
<i>Rhizopus arrhizus</i>		Ni(II), Cd(II), Zn(II), Pb(II), Cu(II)	18, 27, 14, 56, 10	.31,.24, .21,.27, .16		Fourest & Roux 1992
Mycelial biomass		Ni(II), Zn(II), Cd(II), Ag(I), Pb(II)	56, 39	0.95, 0.35	Best pH 7 for Pb; cationic activation important	Fourest et al. 1994

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Phanerochaete c.</i> , <i>Saccharomyces c.</i> <i>Fomitopsis pinic.</i>		Cd(II)	84, 109, 130	0.75, 0.97, 1.16	Wood-rotting fungal pellets	Gabriel et al. 1996
<i>Aspergillus niger</i> <i>Cladosporium p.</i> ; <i>Rhizopus arrhizus</i> <i>Saccharomyces c</i>		Th, Cu, Cu, Th	162, 18, 10, 119	0.70, 0.28 0.16, 0.51		Gadd 1988
<i>Rhizopus arrhizus</i>		Th	97	0.42		Gadd et al. 1988
<i>Aureobasidium p.</i>		Cu	6	0.09		Gadd & Mowll 1995
<i>Aspergillus</i> spp.	Dried, CN ⁻	Au(III), Ag(I), Cu(II)	—	—	Metabolically active fungi worked better	Gomes & Linardi 1996
<i>Phanerochaete c.</i>	Heat , NaOH	Cd(II), Hg(II)	148, 69-79	1.32, .34-.39	NaOH-treated > heat-in activated > active; Best pH 6; Regen. HCl (98%)	Guridik et al. 2004
White rot fungus		Pb(II), Cr(III), Cr(VI), Cu(II), Zn(II)	—	—	Uptake accompanied by proton release;	Hanif et al. 2010
Various		Pb(II), Cd(II), Ni(II)	5-56, 30	.02-.27, .27	Pb > Cd > Ni	Holan & Volesky 1995
18 fungal biomass	Living	U	27-81	0.1- 0.34	actinomycetes > bacteria, yeasts > fungi; Freunlich isotherm; bio-activity not needed	Ten bacterial,
White rot (<i>Phanerochaete chrysosporium</i>)		Cd(II)	71	.63	Immobilized on loofa sponge	Iqbal et al. 2005
<i>Phanerochaete c</i>	Hybrid w papaya	Cd(II)	71, 142	0.63, 1.3	The hybrid adsorbed much more than the sum of the components; 2 nd order rate; Langmuir fit	Iqbal et al. 2007
<i>Phanerochaete c</i>	Live, heat inac	Hg(II), Cd(II)	52-115, 50-80	.29-.57, .44-.71	Heat inactivation favored adsorption; Ca alginate beads; best pH 5-6; Langmuir fit; regen. with HCl (97%)	Kacar et al. 2002
<i>Aspergillus niger</i>		Pb(II), Cd(II), Cu(II)	6.3, 3.2, 2.0	0.030, 0.028, 0.031	Modification of carboxyl and amine groups adversely affected metal uptake; phosphate groups of lipids did not seem to be involved. The ions Ca ²⁺ , Mg ²⁺ & K ⁺ were displaced.	Kapoor & Viraraghavan 1997

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Aspergillus niger</i>	NaOH, CH ₂ O, DMSO, detergent	Pb(II), Cd(II), Cu(II), Ni(II)	2-7.4, 1.3-3.4, 0.7-3.1, 1.8max	.01-.04, .01-.03, .01-.05, .03	Pretreatment significantly increased uptake of Pb, Cd, and Cu, but decreased Ni uptake.	Kapoor & Viraraghavan 1998a
Fungal biomass	Contin- uous	Pb(II), Cd(II), Cu(II), Ni(II)	10, 4, 3, 1	.05,.04, .05,.02	Immobilization in sulfone matrix beads filled with fungal biomass powder	Kapoor & Viraraghavan 1998b
<i>Aspergillus niger</i>	NaOH (boiling)	Pb(II), Cd(II), Cu(II),	8-10, 3-4, 0.3-3.6	.04,.05, .03,.04, 0-.06	Pretreatment increased uptake, except for Ni; live fungi more effective; higher pH favored; Langmuir fit; competition; regen. with HNO ₃	Kapoor et al. 1999
<i>Aspergillus niger</i>		Hg(II), CH ₃ Hg ⁺	No eval	No eval	Sorption not sensitive to other ions; esterification of substrate defeated sorption; regenerable	Karunasagar et al. 2003
<i>Undaria pinnatifida</i>		Pb	350		Best pH 3-4; acid site binding	Kim et al. 1995
<i>Rhizopus nigric.</i>	Pelleted growth	Li(I), Ag(I), Pb(II), Cd(II), Ni(II), Zn(II), Cu(II), Sr(II), Fe(II), Fe(III), Al(III)	1.2, 49, 83, 33, 12, 16, 23, 25, 26, 23, 4	0.18, 0.45, 0.40, 0.30, 0.20, 0.24, 0.36, 0.28, 0.47, 0.41, 0.16	Fe ²⁺ > Ag ⁺ > Fe ³⁺ > Pb ²⁺ > Cu ²⁺ > Cd ²⁺ > Sr ²⁺ > Zn ²⁺ > Ni ²⁺ > Li ⁺ > Al ³⁺ ; Diverse binding sites; binding correlated with covalent index of the metal ions; Langmuir fits	Kogej & Pavko 2001
<i>Aspergillus niger</i> , <i>A. s.</i> ; <i>Penicillium j.</i>		Cr(VI)	1-2	0.019	Best pH 2; Langmuir fit	Kumar et al. 2008
<i>Trichoderma k.</i> ; <i>Fusarium c</i>		Cd(II)	9-102; 12-50	.08-.91, .11-.44	Difference between the two fungal biomass samples disappeared upon autoclaving	Kurek & Majewska 2004
<i>Aspergillus niger</i>		Co, Au, U	95, 200 27	1.6,1.0, 0.11	Higher pH favored; competition demonstrated	Kuyucak & Volesky 1989
<i>Phanerochaete c</i>		Cd(II), Pb(II)	15, 12	.13,.06	Best pHs 4.5; competition; Freundlich fits	Li et al. 2004

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Penicillium simp.</i>		Pb(II), Cu(II)	153, 112	0.74, 1.76	Pseudo 2 nd order rate; Langmuir fit; regeneration with HCl	Li et al. 2008
<i>Mucro rouxii</i>		Pb(II)	769	3.7	Best pH 6; Pb wins exchange competition	Lo et al. 1999
<i>Aspergillus niger</i> , <i>Penicillium chrys.</i> , <i>Claviceps paspali</i>	NaOH	Zn(II)	800, 640, 320	12, 9.8, 4.9	Higher pH favorable to 9; regen. w HCl	Luef et al. 1991
<i>Saccharomyces c</i>		Cu(II)	10	0.16		Mattuschka et al. 1993
<i>Aspergillus n.</i>	On wheat bran	Cu(II), Zn(II)	—	—	Higher pH favored to 6; Langmuir fits; competition	Modak et al. 1996
<i>Aspergillus n.</i>	CTAB	Cr	11-14	.21-.27	2 nd order rate; Freundlich fit; exothermic; amino groups participate	Mungasavalli et al. 2007
<i>Ganoderma lucid.</i>		Cu	24	0.38		Muraleedharan & Venkobachar 1990
<i>Penicillium c.</i>		Pb(II), Cd(II), Cu(II), Zn(II), As(III)	116,11, 9, 6.5, -	.56,.05, .09,.10 -	Best pH 4-5; moderate competition	Niu et al. 1993
<i>Rhizopus arrhizus</i>		Cr	36	.69		Nourbakhsh et al. 1994
<i>Rhizopus arrhizus</i>		Cr	11	.17	Best pH 4.5	Omar et al. 1996
<i>Rhizopus arrhizus</i>		Fe(III), Pb(II), Cd(II)	68, 55, 52	1.2,.26, .46	Langmuir fits	Ozer et al. 1997
<i>Saccharomyces c.</i>		Pb(II), Ni(II), Cr(VI)	270,46, 33	1.3,.78, .63	Langmuir fits; exothermic	Ozer & Ozer 2003
<i>Aspergillus n.</i>		Cr(VI)	No eval	No eval	Cr(VI) removed, Cr(III) appears in solution and as the bound species	Park et al. 2005b
Four strains	Dead	Cr(VI)	No eval	No eval	Reduction on contact	Park et al. 2005c
Fungal	Fe oxide coated	As(III), As(V)	No eval	No eval		Pokhrel & Viraraghavan 2006
<i>Aspergillus n.</i>	Fe oxide coated	As(III), As(V)	81, 93	1.08, 1.24	Best pH 6; pseudo 2 nd order rate; Langmuir fit for As(V); Redlich-Peterson fit for As(III)	Pokhrel & Viraraghavan 2008
<i>Rhizopus arrhizus</i>	Immob.	Cr(VI)	9-11	.11-.21	Tests at pH 2; immobilization yielded moderately lower uptake; Freundlich fit	Prakasham et al. 1999
<i>Aspergillus foetid.</i>		Cr(VI)	2	0.04	Best pH 7	Prasanjit & Sumathi 2005
<i>Rhizopus arrhizus</i>		Zn(II)	—	—	98% removal; 2 nd order rate; Langmuir fit	Preetha & Dubay 2005

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Rhizopus arrhizus</i>		Cu(II)	—	—		Preetha & Viruthagiri 2007a
<i>Rhizopus arrhizus</i>		Cr(VI)	No eval	No eval	Kinetic study; Freundlich fit	Preetha & Viruthagiri 2007b
<i>Aspergillus n.</i>		Cu(II), Zn(II)	0.6-2.6, 0.1-0.2	.01-.04, 0-.003	Living fungus effective	Price et al. 2001
<i>Rhizopus arrhizus</i>		Cr(VI), Fe(III)	58	1.1	Tests at pH 2; competition; Langmuir fit	Sag & Kutsal 1996
<i>Inonotus hispidus</i>		As(III), As(V)	52, 60	0.69	Best pH As(III) was 6 & for As(V) 2; pseudo 2 nd order rate; Langmuir fit; ion exchange; regen. with acids	Sari & Tuzen 2009a
<i>Amanita rubesc.</i>		Pb(II), Cd(II)	38, 27	0.18, 0.24	Pseudo 2 nd order rates; Langmuir fit; ion exchange; regen. with acids	Sari & Tuzen 2009d
<i>Aspergillus niger</i> , <i>Rhizopus arrhizus</i> <i>Saccharomyces</i>		Co, U; Co, Co	2.4, 29; 2.9, 5.8	.04,.12, .05, .10		Sakaguchi & Nakajima 1991
<i>Phanerochaete c</i>		Pb(II), Cd(II), Cu(II)	2	0.01	Best pH 6; Langmuir fits	Say et al. 2001
<i>Penicillium p</i>		Hg(II), Cd(II), Pb(II), As(III)	70,110, 253,36	.34,.98, 1.2,.48	Higher pH favored to 5; Langmuir fits; competition; regen. with HCl	Say et al. 2003a
<i>Penicillium c</i>		Hg(II), Cd(II), Pb(II), As(III)	55, 12, 213,26	.27,.11, 1.0,.35	Higher pH favored to 5; competition; regen. with HCl	Say et al. 2003b
<i>Penicillium p</i>		Cr(VI)	36	0.69	Higher pH favored to 6 (!); Langmuir fit; regen. with HCl	Say et al. 2003c
Waste fungal	Dead	Ca(II), Fe, Ni(II), Cr(III), Cr(VI)	—, —, —, 16, —, 24	—, .31, .46	Uptake Ca > Cr(III) > Ni > Fe > Cr(VI); competition, Ni did not compete well	Sekhar et al. 1998
<i>Penicillium c</i>		Cd(II), Zn(II), Cu(II), Pb(II)	22, 13, 12, 96	.20,.25, .19,.46	Langmuir fits; tolerant of Ca	Skowronski et al. 2001
<i>Aspergillus niger</i>	NaOH	Pb(II)	93	0.45	Langmuir fit	Spanelova et al. 2003
<i>Aspergillus niger</i>		Cr(VI)	9	0.17	Study at pH 6	Srivastava & Thakur 2006
<i>Rhizopus nigric.</i>	Polymer matrices	Cr(VI)	45-119	.86-2.3	Immobilized systems had less capacity per unit mass; regen. with NaOH, carbonate, or biocarbonate; Freundlich fit	Sudha & Abraham 2003

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Aureobasidium p.</i> <i>Saccharomyces c.</i>		Pb(II)	57	0.27	Dead cells had higher capacity, slower uptake	Suh et al. 1998
<i>Penicillium oxal.</i> <i>Tolypocladium sp.</i>		Cd(II), Pb(II), Hg(II)	-, - 270	— 1.34	Langmuir fit	Svecova et al. 2006
<i>Rhizopus arrh.</i>		La(III), etc.	16 Cu	0.25	$UO_2^{2+} > Cr^{3+} > Pb^{2+} > Ag^+ > Ba^{2+} > La^{3+} > Zn^{2+} > Hg^{2+} > Cd^{2+} > Cu^{2+} > Mn^{2+} > Na^+, K^+, Rb^+, Cs^+ (=0)$; ionic radius governs	Tobin et al. 1984
<i>Aspergillus niger</i> ; <i>Penicillium spin.</i>		Cu(II), Zn	5; 0.4- 2, 0.2	.08, .01- .03, 0	Best uptake in the lag phase of growth	Townsley & Ross 1986
<i>Rhizopus arrhizus</i>		U, Th	180, 22	.76, .09	Best pH 4-5	Tsezos & Volesky 1981
<i>Aspergillus terre.</i>		U, Th	10, 60	.04, .26		Tsezos & Volesky 1981
<i>Penicillium chrys.</i>		U, Th	70, 142	.29, .61		Tsezos & Volesky 1981
<i>Rhizopus arrhizus</i>		U	180	0.76	Interference by Fe(II) and Zn(II)	Tsezos & Volesky 1982
<i>Neurospora cras.</i>		Cr(VI)	0.4-16	.01-.31	Very strong enhancements by acidic acid, heat inactivation, and NaOH; Freundlich fits	Tunali et al. 2005
<i>Xanthoparmelia c</i>		Hg(II)	83	0.41	2 nd order rate; Langmuir fit; ion exchange; exothermic; regen. with HCl	Tuzen et al. 2009
<i>Parmelina tili.</i>		Pb(II), Cr(III)	76, 52	.37, 1.0	Langmuir fits ; ion exchange	Uluozlu et al. 2008
<i>Saccharomyces c</i>		Cu(II), U, Zn	17-40, 55-140, 14-40	.27-.63, .23-.59, .21-.61		Volesky & May-Phillips 1995
<i>Aspergillus n.</i>		Pb(II)	—	—	1st order rate ; Freundlich fit ; regen. HNO ₃	Wang et al. 2001
<i>Pleurotus sapidus</i>		Cd(II), Hg(II)	127, 287	1.3, 1.4		Yalcinkaya et al. 2002
<i>Mucor rouxii</i>	Poly- sulfone immob.	Pb(II), Cd(II), Ni(II), Zn(II)	4, 4, 0.4, 1.4	.02, .08, .01, .02	Regen. with HCl	Yan & Viraraghavan 2001
<i>Mucor rouxii</i>		Pb(II), Zn(II), Cd(II), Ni(II)	54, 54, 20, 21	.26, .82, .38, .36	Similar performance living vs. dead; higher pH favored; 2 nd order rate	Yan & Viraraghavan 2003
Fungal, various	Heating, Ca	Cd(II)	31-63	.60-1.2	Heating and Ca treatment improved uptake; Pb ²⁺ > Cu ²⁺ > Cd ²⁺ > Zn ²⁺	Yin et al. 1999
<i>Rhizopus nigric</i>	dead	Pb(II)	14	0.07	Langmuir fit	Zhang et al. 1998

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Rhizopus arrhizus</i> other fungi		Zn(II)	14	0.21	Higher pH favored ; Langmuir fit ; mainly bound to the chitin	Zhou 1999
<i>Rhizopus arrhizus</i>	Immob. on foam	Cu(II)	15+	0.24+	Best pH 6.7-7; competition: $Mn^{2+} \gg Zn^{2+} > Cd^{2+} > Mg^{2+} > Ca^{2+}$; could be regenerated	Zhou & Kiff 1991
LIGNIN-RELATED						
Isolated lignin						
Organosolv lignin	-	Cu(II)	1.7	0.027	Increasing pH; decreasing temp.; 10 min.; regeneration by HCl successful	Acemioğlu et al. 2003
Lignin content		Cd(II)	48	0.76	The pure lignin sample showed higher uptake; Langmuir fit	Basso et al. 2004
Pulping lignin		Pb(II), Cd(II), Zn(II); Cu(II)	18, 8, 11, 20	.09,.07, .17,.31	Best pHs 4-5; ion exchange	Celik & Demirbas 2005
Kraft lignin		Cu(II), Pb(II)	6.4, 62	0.1, 0.3	Proton displacement/ion exchange; Pb(II)>Cu(II)>Zn(II)>Cd(II)>Ca(II)>Sr(II) ; higher pH preferred esp. low-affinity metals; biotic ligand model discussed	Crist et al. 2002
Kraft lignin		Pb(II)	104+	0.5+	Indulin AT; results as exchange constants; Pb(II)>Cu(II)>Zn(II)>Cd(II)>Ca(II)>Sr(II); exchange with protons; Langmuir fit	Crist et al. 2003
Kraft lignin	Ca(OH) ₂ , DMF, heat	Pb(II), Cd(II)	72, 52	0.35, 0.46	Ion exchange with Ca	Crist et al. 2004
Alkali glycerol lign.		Pb(II), Cd(II)	7-9	.03-.08	Higher pH favored to 5; Langmuir fit	Demirbas 2004
Alkali glycerol lign.		Cr(III), Cr(VI)	9, 25	.17,.48	Best pH for Cr(III) 4.5-5.5	Demirbas 2005
Alkali glycerol lign.		Co(II), Hg(II)	8, 5	.14,.02	Higher pH favored; Langmuir fits (batch)	Demirbas 2007
Acid hydrolysis	Quat.	Cu(II), Cr(III)	1.7-26, 0.8-12	.03-.41, .01-.23	Large enhancement by quaternization	Dizhbite et al. 1999
Wheat bran lignin		Cr(VI)	35	0.67	Oxidation of substrate consumes protons and reduces to Cr(III), also providing binding site	Dupont and Guillon 2003
Lignin model cpds		Fe(III)	No eval	No eval	Best pH 5; Stable complexes; Surface oxidation by Fe(III)	Guillon et al. 2001

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Black liquor		Pb(II), Cu(II), Cd(II), Zn(II), Ni(II)	62, 18, 18, 9, 6	.30, .28, .16, .14, .11	Pb(II) > Cu(II) > Cd(II) > Zn(II) > Ni(II); pseudo 2nd order rate; carboxylic and phenolic sites	Guo et al. 2008
Kraft & organosolv		Cu(II), Cd(II)	22, 81	.35, .72	Higher pH favored; Sips equation fit (varied affinities); competition; ion exchange	Harmita et al. 2009
Kraft lignin		Cr(VI), Cr(III)	—	—	Oxygen groups e.g. phenols sorb Cr(VI); regen. with acid	Lalvani et al. 1997
Commercial lignin		Cr(VI), Cr(III)	3.8, 7	0.07, 0.13	Tests at pH 2.5 for Cr(VI) and 3 for Cr(III); a commercial activated carbon was not able to adsorb the Cr(VI), just Cr(III)	Lalvani et al. 2000
Lignin model compounds		Fe(III), Mn(II), Cu(II)	—	—	Potentiometric titrations to determine complex stabilities	Merdy et al. 2000
Straw lignin		Cu(II)	4	0.065	Carboxylic and phenolic groups involved; relatively stable	Merdy et al. 2002
Straw lignin		Fe(III), Mn(II)	No eval	No eval	Carboxylic and phenolic groups involved; relatively stable complexes characterized	Merdy et al. 2003
Kraft lignin		Cu(II), Cd(II)	87, 137	1.4, 1.2	Pseudo 2 nd order rate; particle and film diffusion; Langmuir fit	Mohan et al. 2006
PA-, EN- lignins	Aminated HCl soln	Au(III), Pd(II), Pt(IV)	—	—	Langmuir fit; reductive adsorption of Au; but Cu(II), Fe(III), Ni(II), Zn(II) were <i>not</i> adsorbed;	Parajuli et al. 2006
Sugar bagasse	CH ₂ O	Cd(II), Pb(II)	31, 91	0.28, 0.44	Langmuir fit	Peternele et al. 1999
Oxidized lignins	Acidic media	Cd(II)	No eval	No eval	Oxidation increased capacity	Quintana et al. 2008
Kraft lignin		Cu(II)	—	—	Effective over wide concentration range	Sciban & Kalasnja 2004a
Kraft lignin		Pb(II), Zn(II)	—	—	Higher pH favored: Langmuir fit	Srivastava et al. 1994
Kraft lignin		Cr(III)	18	0.35	Pseudo 2 nd order rate; Langmuir 2-surface fit; ion exchange	Wu et al. 2008
Olive stone lignin	Phenol- CH ₂ O, H ₂ SO ₄	Co(II), Ni(II), Cu(II)	31, 28, 25	0.52, 0.48, 0.42	Sulfonated novolak resin made with lignin was more acidic and had higher metal uptake	Zoumpoulakis & Simitzis 2001

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Lignite, humic ac.						
Lignite humic ac		Cr(III)	9, 16	0.18- 0.30	Best pH 4-5; ion exchange/complexation with carboxyl groups; Langmuir fit; 90% regeneration potential	Arslan & Pehlivan 2008
Walnut expeller, Peanut skins, Rice straw, Plum pit shells, Peanut hulls Rice hulls Sugar bagasse		Hg(II)	880, 820, 280, 240, 220, 180, 180	4.4, 4.1, 1.4, 1.2, 1.1, 0.90 0.90	Ag products can be used for Hg uptake; tests at pH 3.4-3.7	Friedman & Waiss 1972
Paper mill waste, sewage, compost		Pb(II), Zn(II)	39, 8	0.19, 0.12	Compost improved uptake; Langmuir fits; regen with acid	Lister & Line 2001
Tannin gel		Cr(VI)	274	5.3	Tests at pH 3; Langmuir fit	Nakajima & Baba 2004
Tannins fr. bark		Cu(II), Pb(II)	9, 31	.14,.15	Pseudo 2 nd order rate; Langmuir fit; ion exchange/complexation	Oo & el. 2009
Aquatic humic		Cd(II), Ni(II), Cu(II), Mn(II), Pb(II)	No eval	No eval	Slow first-order rate alter initial quick uptake; Cu > Pb > Mn > Ni > Cd	Rocha et al. 1997
Tannic acid, C	Immobil.	Cu(II), Zn(II), Cd(II)	2.2,1.2, 1.5	.03,.02, 0.01		Ucer et al. 2006
Compost		Cu(II), Cd(II)	17, 18	0.26, 0.16	Langmuir fits; better performance than activated carbon, cellulose pulp, etc.	Ulmanu et al. 2003
Peat, peat moss						
Sphagnum peat	NaCl	Cr(III)	19	0.37	Ion exchange; 2 nd order rate; Langmuir fit; regenerated with HCl	Balan et al. 2009
Peat		Pb(II), Cd(II), Zn(II)	—	—	Competition, binary & ternary; ion exchange/complexation	Balasubramanian et al. 2009
Milled peat		Cr(III), Cr(VI)	14, 31	.26,.60	Best pHs 4, 2, resp.	Dean & Tobin 1999
Humin	Immobil.	Cu(II), Pb(II). Cd(II), Cr(III)	18, 31, 1.3, 8	.28,.15, .01,.15	Cr(III) > Pb(II) > Cu(II) > Cd(II) > Ni(II)	De la Rosa et al. 2003

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Peat, humic acids		Cu(II)	16-28	.25-.44	Best pH 4; regen. with HCl	Gardea-Torresdey et al. 1996a
<i>Pleurozium schr.</i>		Cu(II)	11	.17	Pseudo 2 nd order rate; Langmuir fit; regenerated with HCl	Grimm et al. 2008
Moss peat		Ni(II)	9	.15	Best pH 4-7; Langmuir fit;	Ho et al. 1995
Moss peat		Cu(II), Ni(II)	—	—	Pseudo 2 nd order rate; pore diffusion control; competition	Ho et al. 1996
Moss peat		Cu(II), Ni(II), Pb(II)	12, 8, 12	.19, .14, 0.06	Pseudo 2 nd order rate	Ho & McKay 2000
Moss peat			—	—	Pseudo 2 nd order rate; model derived	Ho et al. 2000a
Moss peat, pith		Cu(II)	13	0.20	Pseudo 2 nd order rate; model	Ho & McKay 2003
Peat		Cr(III), Cu(II), Cd(II)	22-25	.42-.48	Extended Langmuir fit	Ma & Tobin 2004
Peat moss		Cd(II), Cr(III)	32, 42	.28, .81	Pseudo 2 nd order rate; Langmuir fit	Sari et al. 2008
Peat moss		Pd(II)	37	0.18	2 nd order rate; Langmuir fit; ion exchange; exothermic	Sari et al. 2008
<i>Drepanocladus r</i>		Hg(II)	94	0.47	Best pH 5.5; pseudo 2 nd order rate; Langmuir fit; ion exchange; regen. with HCl	Sari et al. 2009c
Moss peat		Cr(VI)	119	2.3	Best pH 1.3 to 3; regen with NaOH (50%)	Sharma & Forster 1993
Moss peat		Cr(VI)	66	1.3	Best pH 2; reduction favored by flow	Sharma & Forster 1995a
Moss peat		Cr(VI)	36-44	.69-1.1	Tested at pH 2-2.5	Sharma & Forster 1995b
Sludge						
Activated sludge	Dried	Cr(VI)	577	11.1	Tests at pH 1, Langmuir fit	Aksu & Akpınar 2001
Activated sludge	Immob.	Cr(VI)	19	0.36	Best pH 1; Langmuir fit	Aksu et al. 2002a
Activated sludge		Cr(VI)	294	5.7	Best pH 1; Langmuir fit	Aksu et al. 2002b
Anaerobic sludge		Pb(II), Cd(II), Cu(II), Ni(II)	255, 60, 55, 26	1.2, .53, .87, .44	Langmuir fit	Hawari & Mulligan 2006
Biogas residuals		Cr(VI)	6	0.11	Best pH 1.5; First order rate; Langmuir fit	Namasivayam & Yamuna 1995a
Biogas residuals		Pb(II)	28	0.14	Langmuir fit	Namasivayam & Yamuna 1995b
Biogas residuals		Cr(III)	5.2	0.10	Langmuir fit; endothermic	Namasivayam & Yamuna 1999
Distillery sludge		Cr(VI)	6	0.11	Langmuir fit	Selvaraj et al. 2003

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
CHEM. MODIFIED BASE TREATED						
Sugar bagasse	5N NaOH, EDTA	Cu(II), Cd(II), Pb(II)	39-93, 88-149, 192- 333	.61-1.5, .78-1.3, .92-1.6	Mercerization greatly increased adsorption capacities.	Karnitz et al. 20009
Sugar bagasse	NaOH, EDTA dianhydr	Ca(II), Mg(II)	16-54, 14-43	.40-1.4, .58-1.8	Modified sugarcane bagasse showed higher adsorption than modified pure cellulose.	Karnitz et al. 2010
OXIDIZED						
Oxycellulose		Cd(II), Zn(II), Ni(II)	31, 17, 10	.28,.26, .17	Cd ²⁺ , Zn ²⁺ > Ni ²⁺ >> Ca ²⁺ > Mg ²⁺ >> Na ⁺ , behaved like ion exchange resin	Foglarova et al. 2009
Periodate oxidn		Ag(I), Mg(II), Ca(II), Sr(II), Ba(II), Mn(II), Co(II), Ni(II), Cu(II), Zn(II), Fe(III), Cr(III)	390, 87, 144, 270, 343, 198, 206, 188, 240, 216, 229, 135	3.6, 3.6, 3.6, 3.1, 2.5, 3.6, 3.5, 3.2, 3.8, 3.3, 4.1, 2.6	2,3-dicarboxycellulose up to 70% DS remained insoluble in water; gave viscous complexes with the metals that solidified in air	Maekawa & Koshijima 1984
Bagasse	Various COO Rx	Cu(II), Ni(II), Cr(III), Fe(III)	99-381, 80-470, 440, 84-469	1.6-6.0, 1.4-8.0, 8.5, 1.5-8.4	Carboxymethylated bagasse > periodate oxidized > succinylated .	Nada & Hassan 2006

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Cotton linters	TEMPO, CMC fib.	Mg(II), Al(III), Ca(II), Mn(II), Co(II), Ni(II), Cu(II), Sr(II), Ag(I), Cd(II), Ba(II), La(III), Pb(II)	3.9-5.6, 4.0-5.1, 13-18, 14-19, 16-24, 16-25, 17-23, 18-32, 35-53, 24-37, 27-44, 49-53, 99-108	.16-.23, .15-.19, .32-.45, .25-.34, .28-.41, .27-.42, .27-.37, .20-.36, .32-.49, .21-.33, .21-.32, .35-.38, .48-.52	Higher pHs favored to 4; $Pb^{2+} > La^{3+} > Al^{3+} > Cu^{2+} > Ba^{2+} > Ni^{2+} > Co^{2+} > Cd^{2+}, Sr^{2+}, Mn^{2+}, Ca^{2+} > Mg^{2+}$; approx 1:1 molar uptake of Pb(II), Ca(II), Ag(I)	Saito & Isogai 2005
ADSORBED ...						
POLYMER ADS.						
Porous cellulose	PEI cross linked	Hg(II)	288	1.43	PEI crosslinking restricts ligand mobility	Navarro et al. 1996
Chitosan, cellulose	Blend coagula.	Pb(II), Cd(II), Cu(II)	68, 36, 19	.33,.32, .30	Best pHs 4-5; competition: $Pb^{2+} > Cd^{2+} > Cu^{2+}$; regen. with HCl; complexation	Zhou et al. 2004
Dye adsorption						
Oil palm fibers	Dye use	Cu(II), Pb(II), Cr, Ni(II)	1.9,.08, .06,.50	.03,.00, .00,.01	Tests at pH 2.9 (electroplating); dye greatly increased uptake.	Low et al. 1993
Coconut husk	Dye mod	Cu(II)			Treatment enhanced uptake; Langmuir fit	Low et al. 1995b
Yeast	Cationic surfact.	Cr(VI)	94	1.80	Tests at pH 4.5-5.5; Langmuir fit	Bingol et al. 2004
DERIVATIZATION						
Succinylation						
Cellulose	Succin.	Cd(II)	180	1.60	Best at intermediate pH; regeneration with NaCl	Belhalfaoui et al. 2009
Cellulose	Mercer- ized first	Cu(II), Cd(II), Pb(II)	30, 86, 206	.47,.77, 0.99	Langmuir fits	Gurgel et al. 2008

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Alhagi	Tartaric & heat	Zn(II)	—	—	2 nd order rate; Langmuir fit; exothermic	Hashem et al. 2008
Sugar bagasse	Succin.	Cu(II), Cd(II), Pb(II)			Polylamines anchored by the derivatized material adsorbed metal	Karnitz et al. 2007
Sugar beet, corn cob, oat hull	Succin., maleate, phthalate	Ca(II)	22-139	.55-3.5	Sugar beet pulp was easiest to derivatize;	Lehrfeld 1996
Coconut husk, moss	Nitrilotri- acetic ac.	Cr(III)	14-39	0.28- 0.75	Enhanced uptake by 50%	Low et al. 1997
Cellulose	Hydrox- amic	Fe(III), Cu(II), Ag(I), Mn(II), Zn(II), Ni(II), Cr(III)	212, 165, 226, 5.5, 20, 2.3, 5	3.8, 2.6, 2.1, 0.1,0.3, .04,.09	Periodate oxidation; metal complexes were characterized	Maekawa & Koshijima 1990
Wood meal	Succinic anhydr	Cd(II)	200	1.8	Below theoretical due to di-ester formation	Marchetti et al. 2000a
Bagasse	Various COO Rx	Cu(II), Ni(II), Cr(III), Fe(III)	99-381, 80-470, 440, 84-469	1.6-6.0, 1.4-8.0, 8.5, 1.5-8.4	Carboxymethylated bagasse > periodate oxidized > succinylated .	Nada & Hassan 2006
Coir pith	Succinic anhydrid	Co(II)	24-33	.41,.56	Modification highly beneficial; pseudo 2 nd order rate; Langmuir fit; regen. with HCl	Parab et al. 2008
<i>Eichhornia c</i>	Xantho- genate	Cu(II)	100- 260	1.6-4.1	Xanthogenate of water hyacinth achieved the highest uptake; first order rate	Tan et al. 2008
Citric acid ester						
Sawdust	Esterif.	Zn(II)	0-270	0-4.1	Freundlich fit better	Hashem et al. 2006b
Wood	Citric ac.	Cu(II), Pb(II)	24, 83	.38,.40	Treatment increased adsorption by about 10X; 2 nd order rate	Low et al. 2004
Corn fiber	Citric ac	Cu(II)	127	2.0		Wing 1996
Corn fiber	Citric ac	Cu(II)	83	1.31		Wing 1997
Rice husk	Tartaric	Cu(II), Pb(II)	32,120	.50,.58	Langmuir fit; regen. with HCl	Wong et al. 2003

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Carboxylated						
Beads	CMC	Ni(II), Co(II), Cu(II), Cd(II), Pb(II), Fe(III), Al(III)	19,14, 20,35, 71,26, 5	.32,.23, .32,.31, .34,.47, .21	Tested at pH 6; metal adsorption decreased water retention value, especially in the case of Al(III) adsorption	Heinz et al. 1993
Cyanoethylation		Cu(II), Ni(II), Co(II)	25,14, 15	0.4,.23, 0.26	Photografted amidozime groups increased metal adsorption; higher pH favored	Kubota & Shigehisa 1995
Spherical cotton cellulose	Acrylo- nitrile Carbox- ylated	Cr(III)	73-90	1.4-1.7	Tests at pH 5; carboxylated; Langmuir fit; endothermic; regeneration with either NaOH or HCl	Liu et al. 2001
Spherical cellulose	Carboxyl- ated	Cu(II)	64	1.00	Carboxylated; ion exchange/complexation; Langmuir fit; endothermic; regen. with NaOH	Liu et al. 2002
	CMC, phosphat oxycell	Cu(II) perchlorate	34, 81	0.53, 1.3	Carboxymethylation greatly improved uptake	Padilha et al. 1995
Wood pulp	CMC	Na(I), K(I), Ca(II), Mg(II)	—	—	Donnan ion exchange	Sundman & Ohman 2006
Wood pulp	CMC	Ca(II), Cu(II)	No eval	No eval	Donnan ion exchange & complexation, two carboxylate groups per ion	Sundman et al. 2008
Aminated, etc.						
Wood quat.	Quatern.	Cr(VI)	26-27	.50-.52	Suppressed by sulfate; Langmuir fit	Low et al. 2001
Beech sawdust	Quatern., cross-link		—	—	Nitrogen level correlated with capacity	Simkovic 1999
Cotton	Aminated	Hg(II)	28-29	.14-.15	Amination was more effective than PEI adsorption	Roberts & Rowland 1973
Other						
<i>Undaria pinnat.</i>	Oxime	Cu(II)	900	9.5	Uptake of Cu(II) increased 4.5X by oxime; highly selective vs. Ca(II), Cd(II), Pb(II)	Kim et al. 1996

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
<i>Undaria pinnat.</i>	Xanth- ated	Pb(II), Cu(II), Cd(II)	1200	9.8	Xanthation increased adsorption capacity 3X; selective adsorption possible (compared to Ni(II), Zn(II), and Co(II))	Kim et al. 1999
30 strains	H ₃ PO ₄	Cd(II), Pb(II), Ni(II), Zn(II)	269, 600, 153, 163	2.4, 2.9, 2.6, 2.5	Langmuir fits; different selectivities, different optimum pHs; phosphorylation beneficial in some cases	Klimmek et al. 2001
Bagasse peroxy- acid, kraft pulping	phosphor ylation	Cr(), Cu(II), Mn(II), Ni(II), Pb(II)	4.7,4.4, 3.8,2.9, 6.2	.09,.07, .07,.05, .03	Peroxyacid pulping lignin yielded higher level of phosphate groups, higher sorption capacity	Nada et al. 2008
Cellulose powder	Amidoxyl ated	Cu(II), Cr(III)	240, 203	3.8, 3.9	Stoichiometric complexes formed; desorption by EDTA	Saliba et al. 2000
Cellulose	Amidoxyl ated	Cd(II), Ni(II)	402, 106	3.6, 1.8	Stoichiometric complexes; desorption by EDTA	Saliba et al. 2001
Cellulose powder	Amidoxyl ated	Cu(II), Cr(III), Cd(II), Ni(II)	102,83, 180,47	1.6,1.6, 1.6,0.8	Simultaneous or sequential adsorption; stoichiometric; reversal by EDTA	Saliba et al. 2002a
Wood flour & sawdust	Amidoxyl ated	Cu(II), Cr(III), Cd(II), Ni(II)	—	—	Increased adsorption capacity; 1:1 or 2:1 complexes	Saliba et al. 2005
Chlorodeoxy- cellulose	Ethdiam, thiourea,	Hg(II)	1.5	0.007	Best results after reacting CDC with thiurea, then oxidizing the substrate	Tashiro and Shirmura 1982
Corn stalk	Acrylo- nitrile	Cd(II)	13	0.12	Four-fold increase due to derivatization; best pH 7; pseudo 2 nd order rate; Freundlich fit	Zheng et al. 2010
Grafting						
Bead cellulose	Graft amidox PAM	Ag(I), Cu(II), Pb(II), Zn(II), Cd(II)	—	—	NaOH treatment increased uptake by the grafted cellulose beads; sulfuric acid regeneration (>90%)	Aoki et al. 1999b
Cellulose	PAM	Hg(II)	712	3.6	Other ions don't interfere; regeneration with hot acetic acid	Bicak et al. 1999
Pine needle cellulose	Glycidyl methacr.	Fe(II), Cu(II), Cr(VI)	2.1, 0.9, 1.0	0.038, 0.014, 0.019	Structures of the graft copolymers	Chauhan et al. 2005a

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Cellulose	Hydroxyp ropyl, etc	Fe(II), Cu(II), Cr(VI)	—	—	Functionalization greatly increased uptake.	Chauhan et al. 2005b
Cellulose	Acrylami de-based	Fe(II), Cu(II), Cr(VI)	—	—	NaOH treatment yielded Fe(II), Cu(II) uptake with complete rejection of Cr(VI)	Chauhan et al. 2006
Bacterial cellulose	PAM graft		No eval	No eval	Cation exchange material	Choi et al. 2004
Sawdust	PAA	Cu(II), Ni(II), Cd(II)	47-104, 40-97, 76-168	.74-1.6, .68-1.7, .68-1.5	15-40X higher binding due to grafting; regeneration with HCl	Geay et al. 2000
Cellulose	PAA,AM, sulfonic	Pb(II), Cu(II), Cd(II)	4-60, 1-18, 2-33	0.02- 0.29 (each)	Pb>>Cu≈Cd; great increase vs. raw cellulose	Guclu et al. 2003
Sunflower stalks	Acrylo- nitrile	Cu(II)	33	0.52	Amidoxylated (grafted), Langmuir fit	Hashem 2006
Sunflower stalks	Acryl- amide	Hg(II)	625	3.1	Langmuir fit	Hashem et al. 2006a
Cyanoethyl cellulose	Acrylo- nitrile	Cu(II)	No eval	No eval	Cotton linter	Kamel et al. 2006
Carboxylate, phosphate	Textiles	Cu(II), Cd(II)	13-248, 22-427	0.2-3.9, 0.2-3.8	Best results with Na salt of the carboxylate product; regeneration	Lacour et al. 2001
Wood meal	Acrylic acid	Cu(II), Ni(II), Cd(II)	46-104, 40-97, 76-168	.74-1.6, .68-1.7, .68-1.5	Grafting increased capacity 40X; regeneration with HCl	Marchetti et al. 2000b
Acrylamide		Cr(II), Pb(II), Mn(II), Ni(II)	189, 180, 185, 165	3.6, 0.87, 3.4, 2.8	Hydrolysis increases affinity for water and for metal ions	Nada et al. 2007a
	Glycidyl methacr, PEI	Co(II), Cu(II), Zn(II)	2-16, 38-57, 12-24	.03-.27, .60-.90, .18-.37	Graft polymerization increased sorption	Navarro et al. 1999
	Glycidyl methacr, PEI	Co(II), Cu(II)	No eval	No eval	Anion interactions with substrate can be used to understand ion exchange interactions	Navarro et al. 2001

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Cellulose	Glycidyl methacr, imidazole	Cu(II)	70	1.10	Pseudo 2 nd order rate; Langmuir fit; exothermic	O'Connell et al. 2006a
Cellulose	Glycidyl methacr, imidazole	Ni(II)	48	0.81	Pseudo 2 nd order rate; Langmuir fit; endothermic	O'Connell et al. 2006b
Cellulose	Glycidyl methacr, imidazole	Pb(II)	72	0.35	Pseudo 2 nd order rate; Langmuir fit; exothermic	O'Connell et al. 2006c
Cellulose	Glycidyl methacr, imidazole	Cu(II)	66-71	1.04-1.11	Copper sulfate hydroxide (antlerite) was present at the surface	O'Connell et al. 2010
Coconut coir pith		Cr(III)	12	.23	Langmuir fit	Parab et al. 2006b
Sawdust	PAM graft	Cr(VI)	6-12	.11-.23	Exothermic; not adversely affected by other ions; Freundlich fit; regen. with NaOH or NaCl	Raji & Anirudhan 1998
Pine needle	HEMA & copolym.	Fe(II), Cu(II), Cr(VI)	—	—	Enhanced uptake	Sharma & Chauhan 2009
Banana stalk	PAM	Hg(II)	138	0.69	Best pH 6-9; pseudo 2nd order rate; Langmuir fit; regen. with HCl	Shibi & Anirudhan 2002
Banana stalk	PAM	Co(II)	13-55	.22-.93	Best pH 6.5-9; Langmuir fit; higher uptake than commercial resin; regen. with HCl	Shibi & Anirudhan 2005
Banana stalk	PAM	Pb(II), Cd(II)	185, 66	0.89, 0.59	Best pH 5.5-8; repressed by salt; pseudo 2 nd order rate; Langmuir fit; regen. by acid	Shibi & Anirudhan 2006
Fabric wastes	Glycidyl methacr	Co(II), Cr(VI)	14-18, 3.2	.24-.31, 0.06	Conversion of epoxy groups into various functional groups for binding; best chromate adsorption at pH 9	Sokker et al. 2009
Cellulose	Calix[4] arene	Co(II), Ni(II), Cu(II), Cd(II), Hg(II), Pb(II), Cr(VI)	4.7, 7.6, 6.3, 10, 16, 17, 13-36	.08, .13, .10, .09, .08, .08, .25-.69	For Cr(VI) best pH 1.5; grafted cellulose was effective for uptake	Tabakci et al. 2007

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Rubberwood dust		Cr(VI)	144-172	2.8-3.3	Tests at pH 3; higher temperature favored; Langmuir fits	Unnithan et al. 2001
Coconut coir pith	Graft amino-	Cr(VI)	12-127	.23-2.4	Tests at pH 3; 2 nd order rate; Langmuir fit; alkali regeneration	Unnithan et al. 2004
Baker's yeast	Polyamic acid	Cd(II), Pb(II)	95, 210	0.84, 1.01	Grafting of carboxylic and amide groups greatly increased uptake; pseudo 2 nd order rate; Langmuir fit; complexation	Yu et al. 2007
Cellulose	Acrylic ac acrylamid	Cu(II)	50	0.79	Freundlich fit; regen. with ammonia	Zhao et al. 2006
Solution-phase						
Solution	Mercap.	Ag(I), Cu(II), Pb(II), Cd(II)	No eval	No eval	6-Deoxy-6-mercaptocellulose and its S-substituted derivatives; uptake in the range of 0.1 to 1.5 moles per mole	Aoki et al. 1999a
ACTIVATED CARBON						
Granular		C(VI)	147	2.8	Best pH 1; Langmuir fit	Aksu et al. 2002
Tamarind wood	ZnCl ₂	Pb(II)	44	0.21	Langmuir fit; pseudo 2 nd order rate	Acharya et al. 2009
Carbon cloth	NaOH	Bi(III), Cd(II), Co(II), Ag(I), Cu(II), Ni(II), Fe(III), Sb(III), Sn(IV), Sr(II), Pb(II), Zn(II), Ti(I)	19, 19, 12, 140, 8, 19, 30, 113, 77, 26, 8, 26	.09, .17, .22, 1.3, .13, .32, .54, .93, .65, .30, .04, .39, .30	NaOH treatment increased adsorption; uptake 0.1-2 mmole/g; Langmuir fits	Afkhami et al. 2007
Various	Oxidation	Cr(III), Cr(VI)	10-30, 10-70	.19-.58, .19-1.4	Oxidation with nitric acid, persulfate, H ₂ O ₂ , or O ₂ increased Cr(III) uptake but decreased that of Cr(VI); degassing had opposite effects; Langmuir fits.	Aggarwal et al. 1999
Coconut shell		Cr(VI)	2-16	.04-.31	Uptake depends on conc.; Freundlich fits ; low pH adsorption attributed to reduction	Alaerts et al. 1989

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Coconut shell	Chitosan; phos- phoric ac	Zn(II)	45-60	.69-.92	Coating of activated carbon with chitosan increased uptake ; Langmuir fit ; regen. with NaOH	Amuda et al. 2007
Coir pith	H ₃ PO ₄ , NaOH	—	—	—	Phosphoric acid activation was effective	Ash et al. 2006
Coconut shell	Chitosan, oxidizing	Cr(VI)	2-15	.04-.29	Nitric acid was more effective than sulfuric; Langmuir fits	Babel & Kurniawan 2004
Olive waste	H ₃ PO ₄ , KMnO ₄	Cu(II)	12-35	.19-.55	Permanganate treatment enhanced adsorption by 3X	Baccar et al. 2009
Pecan shell	H ₃ PO ₄ , Steam, CO ₂	Cu(II), Pb(II), Zn(II)	No eval	No eval	Competition; acid-modification helped Pb & Zn uptake; steam activation helped Cu	Bansode et al. 2003
Activated carb.		Cr(VI)	—	—	Best pH 3.6 ; endothermic Langmuir fit	Barkat et al. 2009
<i>Arundo donax</i>	H ₃ PO ₄ ,	Cd(II), Ni(II)	55, 29	.49,.49	Pseudo 2 nd order rate; Langmuir fit	Basso et al. 2002b
Peach stone, eucalyptus	CO ₂ , steam	Cr(VI), Hg(II)	35-93, .37-.42	.67-1.8, .02- .002	Pore structure important, diffusion; CO ₂ acti. Favored Hg(II) uptake , steam favored Cr(VI)	Bello et al. 1999
Coconut shell	KOH, ZnCl ₂ , CO ₂ atm.	Cr(III), Cr(VI)	534- 721	10.3- 13.9	Activation was effective ; phenol and carbonyl groups important, electrostatic mechanism	Bendezu et al. 2005
Granular	Electro- chem		No eval	No eval	Both anodic and cathodic treatments increased surface oxygen; cathodic treatment increased pores in presence of oxygen	Berenquer et al. 2009
Rice husk		Cr(VI)	No eval	No eval	Best pH 2; not Langmuir fit	Bishnoi et al. 2004
Birch biomass	H ₃ PO ₄ + steam	Hg(II)	160	0.80	Phosphoric acid followed by steam pyrolysis yielded 1360 m ² /g surface area, adsorption.	Budinova et al. 2006
Activated carbon	H ₃ PO ₄ + steam	Pb(II)	69	0.33	Endothermic	Bueno & Carvalho 2007
Various biomass		Cr(VI)	300	5.8	Lower pH favored; physical activation effective ; reduction dominant below pH 1	Candela et al. 1995
Bean husk	HNO ₃ post	Cd(II)	180	1.6	Oxygen content governs uptake	Chavez-Guerrero et al. 2008

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Carbon	Citric ac.	Cu(II)	15	0.24	Citric acid mod increased Cu(II) uptake	Chen & Wu 2003
Carbon	HCl, HNO ₃ , NaOH	Cu(II)	5-15	.08-.24	NaOH increases OH groups; HCl increases C-O bonds; HNO ₃ oxidation incr. Cu uptake	Chen & Wu 2004a
Carbon	Humic acid	Cu(II)	3-8	.05-.13	Low amounts of humic acid competed with Cu(II) adsorption; higher amounts helped.	Chen & Wu 2004b
Carbon fibers	Steam, ZnCl ₂ , H ₃ PO ₄	Ag(I)	—	—	Reduction of Ag(I) on adsorption; graphitization helped reduction	Chen et al. 2002
Carbon fibers	Steam, ZnCl ₂ , H ₃ PO ₄	Pt(IV)	200	1.0	Reductive adsorption; capacity increased with sp. surf. Area and lower electrode potential; some converted to Pt(II)	Chen et al. 2007
Sisal-based	ZnCl ₂ , H ₃ PO ₄	Ag(I)	700	6.5	Reductive adsorption of Ag(I) and Au were enhanced by ZnCl ₂ and H ₃ PO ₄ activation, also by methylene blue; oxidants did the opposite.	Chen & Zeng 2003
Rayon-based	NaCl + H ₃ PO ₄		No eval	No eval	Activation enhanced pores; fractals, BET	Chen et al. 2008
Charcoal		Ni(II), Al(III)	—	—	Rate law	Choksi & Joshi 2007
Hydrous act. C		Cu(II), Pb(II), Ni(II), Zn(II)	No eval	No eval	Surface complexation model; participation of free ions and their hydroxo species	Corapcioglu & Huang 1987
Varous carbons		Cr(III)	0.4-32		Tests at pH 3; Langmuir fits	Cordero et al. 2002
Flax shive	Hot sulfuric	Au(III), Pd(II), Ag(I), Pt(II)	—	—	Au(III) > Pd(II) > Ag(I) > Pt(II) ≈ Pt(IV); ion exchange; regeneration possible	Cox et al. 2005
Cow dung	Sulfuric post	Cr(VI)	11	0.21	Low pH favored ; first order rate ; Langmuir fit	Das et al. 2004
Pecan shell	Air, H ₃ PO ₄	Cu(II)	41	1-2	Bound phosphorus important at high levels (complexation); ion exchange of protons	Dastgheib & Rockstraw 2001
Pecan shell	Air, H ₃ PO ₄	Hg(II), Cr(III), Cu(II), Ni(II), Cd(II), Ca(II), Sr(II), Zn(II), Co(II), Mn(II), Mg(II), K(I)	360,78, 201,59, 112,32, 53, 33, 35, 33, 10, 12	1.8,1.5, 1.6,1.0, 1.0,0.8, 0.6,0.5, 0.6,0.6, 0.4,0.3	Ion exchange; Slips and Freundlich fits	Dastgheib & Rockstraw 2002a

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Pecan shell	Air, H ₃ PO ₄	Cu(II), Mn(II)	51-102, 33	.8-1.6, 0.6	Site competition; charge buildup, speciation; models with more parameters fit better.	Dastgheib & Rockstraw 2002b
Carbon	HNO ₃ oxidation		—	—	Oxidation increased acid groups with pKa<4, favoring uptake	De Mesquita et al. 2006
Olive bagasse		Cr(VI)	88-110	1.7-2.1	Best pH 2; Pseudo 2 nd order rate; Langmuir fit	Demiral et al. 2008
Hazelnut shells		Ni(II)	6-12	.10-.20	Langmuir fit; exothermic	Demirbas et al. 2002
Apricot stone, almond shell		Cr(VI)	—	—	Best pH 1; pseudo 2 nd order	Demirbas et al. 2004
Almond shells		Cr(VI)	190	3.6	Langmuir fit; endothermic	Demirbas et al. 2008
Hazelnut shells		Cu(II)	58	0.9	Best pH 6; pseudo 2 nd order rate; Langmuir fit; endothermic; regeneration (74+%)	Demirbas et al. 2009
Pine cone	ZnCl ₂ , H ₃ PO ₄	Cr(VI)	60-80	1.2-1.5	Best pH 2; activating agents decreased porosity; highest adsorption with phosphoric acid activation	Duman et al. 2009
Pomegran. peel		Pb(II), Cu(II)	—	—	2 nd order rates; Langmuir fits	El-Ashtoukhy et al. 2008
Corn cob	H ₃ PO ₄	Pb(II)	37-120	.18-.58	Activation increased area and sorption.	El-Hendawy et al. 2001
Corn cob	HNO ₃	Pb(II)	130- 440	.63-2.1	Nitric acid widened pores and decreased surface area; removal of phenol increased O functionalities; lead uptake greatly enhanced	El-Hendawy 2003
Date pits	HNO ₃	Pb(II), Cd(II)	100- 160, 110- 160	.48-.77, .98-1.4	Higher pH favored; Langmuir fits; oxidation led to high affinity sorption; importance of oxygen sites	El-Hendawy 2009
Date palm seed	H ₂ SO ₄	Cr(VI)	120	2.3	Best pH 1; pseudo 2 nd order rate; Langmuir fit (equilibrium data)	El Nemr et al. 2008
Rice husk	H ₂ SO ₄	Cr(VI)	—	—	First order rate; reduction by the sorbent	El-Shafey & Canepa 2003
Rice husk	H ₂ SO ₄	Zn(II), Hg(II)	11-12, 100- 120	.17-.18, .50-.60	Pseudo 2 nd order rates; Hg(II) reduced to Hg(I), as adsorbed;	El-Shafey 2010
<i>Ulva lactuca</i>		Cr(VI)	112	2.2	Best pH 1; not sensitive to salt; pseudo 2 nd order rate; Langmuir fit	El-Sikaly et al. 2007

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Apricot waste	K ₂ CO ₃	Ni(II)	17-101	.29-1.7	Best pH 5; Langmuir fit	Erdogan et al. 2005
Sugar waste		Cr(III)	27	0.52	Best pH 5; Langmuir fit	Fahim et al. 2006
Granular carbon	Quat poly	Cr(VI)	54	1.0	Best pH low; reversible 2 nd order kinetics; much less reduction to Cr(III) if treated; ion exchange; reduction if pH<4	Fang et al. 2006
Act. C cloths		Cu(II), Ni(II), Pb(II)	11, 7, 33	0.18, 0.12, 0.16	Cu ²⁺ > Ni ²⁺ > Pb ²⁺ ; results attributed to electronegativity, ionic radius ; adsorption occurred below precipitation pH	Faur-Brasquet et al. 2002
Granular carbon		Cd(II), Cu(II)	3.3,2.5	.03,.04	Higher pH favored	Gabaldón et al. 2000
Coconut shell		Cd(II)	No eval	No eval	Higher pH favored to 6; Freundlich fit	Gaikwad 2004
Act. carbon	Diphenyl carbazid	Cr(VI)	1.7-2.6	-	Removal as complex is favored by oxidized state, not Cr(III); data as carbazide	Gajhate et al. 1992
Olive, apricot, peach stones	H ₂ SO ₄ , persulf.	Zn(II)	2-32	.03-.49	Surface complexes; both basic and acidic carbons were effective	Galiatsatou et al. 2002
Rosewood	H ₂ SO ₄	Cr(VI)	15-25	.29-.48	Best pH 3; first-order rate	Garg et al. 2004
Peach stone	Atmosph, H ₃ PO ₄	Pb(II)	65-204	.31-.98	External gases reduced porosity, except air and steam increased mesoporosity; acidic carbons removed Pb well (air addition)	Girgis et al. 2007
Cotton stalks	H ₃ PO ₄	Pb(II)			No purging gases; effective uptake	Girgis et al. 2009
Act. carbon	Heated, sulfurized	Hg, Cd, Pb	360, 34, 83	1.3-1.8, 0.2-0.3, 0.2-0.4	Best for Hg, especially when sulfurized; pH effects	Gomez-Serrano et al. 1998
Evergreen oak	H ₃ PO ₄ levels	Zn(II)	0.9-1.6	0.013-0.024	Phosphoric treatment reduced microporosity ; surface area was key	Gomez-Tamayo et al. 2008
Kraft black liquor	H ₃ PO ₄ pyrolysis	Cr(VI)	80-93	1.5-1.8	Tests at pH 3; higher temperature widened the pores; favorable results	Gonzalez-Serrano et al. 2004
Rice husk	KOH, NaOH	Cr(VI)	38	0.73	Low pH favored; pore sizes important	Guo et al. 2003
Sawdust Waste tires Commercial		Cr(VI)	1.9-2.3, 48-58, 44-53	.03-.05, 0.9-1.1, .84-1.0	Sawdust carbon not nearly as effective as carbon from tires; best pH 2; first-order reversible; Langmuir fit; endothermic	Hamadi et al. 2001

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Granular		Cr(VI)	20-60	0.4-1.2	Tested at pH 4; dissolved oxygen inhibited uptake; treatment with reductants did not help; regeneration with K ₂ PO ₄ ; reduction of Cr to Cr(III) acidic	Han et al. 2000
Act. C. cloth	Electroch reduction	Cr(VI)	198	3.8	Electroreduction of the carbon greatly increased Cr(VI) uptake; ion exchange	Harry et al. 2008
Almond husks	H ₂ SO ₄	Zn(II)	5	.076	Best pH 5.5; Langmuir fit	Hasar et al. 2003
Several carbons		Cr(VI)	40-101	.96-1.9	Tests at pH 3; Langmuir & Freundlich fits in different cases	Hu et al. 2003
Filtrisorb 400		Cr(VI)	26	0.50	Best pH 5-6; Adsorption & reduction; Cr(III) is less adsorbable than Cr(VI), which is adsorbed in the 6-valent state	Huang & Wu 1977
Hazelnut husks	ZnCl ₂	Cu(II), Pb(II)	—	—	Langmuir fit	Imamoglu & Tekir 2008
<i>Terminalia cata.</i>	H ₂ SO ₄	Hg(II)	94	0.47	Best pH 5-6; Langmuir fit	Inbaraj et al. 2006
Jackfruit peel	H ₂ SO ₄	Cd(II)	52	0.46	Second order rate; Sips fit; regenerated with HCl	Inbaraj & Sulochana 2004
Indian almond	H ₂ SO ₄	Hg(II)	94	0.47	Best pH 5-6; Langmuir fit; KI could displace	Inbaraj & Sulochana 2006
Cherry stone	Air, CO ₂ , steam, O ₃ , H ₂ O ₂ , HNO ₃ ,	Cu(II)	4-28	.06-.44	Oxidation greatly enhanced uptake; Langmuir fit; ion exchange/complexation	Jaramillo et al. 2009
Coconut shell	HNO ₃	Au(III), Ag(I) cyanides	24-55, 14-30	.12-.28, .13-.28	Nitric acid treatment hurt Au-cyanide complex adsorption; free CN ion suppressed Ag uptake	Jia et al. 1998
Coconut shell	HNO ₃	Cd(II)	2-38	.02-.34	Oxidation greatly enhanced Cd(II) uptake; ion exchange; binding to carboxylate was irreversible	Jia & Thomas 2000
Coconut shell	HNO ₃ , NH ₃	Cd(II), Ni(II), Cu(II), Ca(II)	2-16, 1-5, 2-14, 0.4	.02-.14, .02-.08, .04-.22, .01	High-N carbons had higher adsorption; complexation	Jia et al. 2002

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Soft vs. hard lignocellulosics	CO ₂ , steam	Pb(II), Cu(II), Ni(II), Cd(II), Zn(II)	14-50, 13-51, 0-0.6 1-4, 0-5	.07-.24, 0.2-0.8, .00-.01, .01-.04, .00-.03	Oxidation helped metal adsorption for carbons from soybean hull, sugarcane bagasse, peanut shell, and rice straw	Johns et al. 1998
Granular		Cd(II), Pb(II)	—	—	Column breakthrough equation fits	Jusoh et al. 2007
2 activated Cs		Cu(II), Ni(II), Pb(II)	8-32, 2-45, 5-211	.13-.50, .03-.77, .02-1.0	Higher pH favored to two units below precipitation ; ion exchange	Kadirvelu et al. 2000
Act. carbon cloth		Cu(II), Ni(II), Pb(II)	No eval	No eval	Higher pH favored to 6 ; max adsorption pH zones 2 units; ion exchange; carboxylate involvement	Kadirvelu et al. 2001
<i>Parthenium</i>		Ni(II)	54	0.92	Higher pH favored; Langmuir fit; regen. with HCl	Kadirvelu et al. 2002
Rubberwood	H ₃ PO ₄	Cu(II)	4.8-5.7	.08-.09	Best pH 6; pseudo 2 nd order rate; Langmuir fit best; film & particle diffusion control	Kalavathy et al. 2005
Paper mill sludge	KOH	Cu(II), Cd(II), Cr(III)	12, 10, 5	0.19, 0.09, 0.10	Tests at pH 6 ; char; monolayer metal adsorption	Kang et al. 2006
Straw, sawdust, date pit		Cd(II)	3.6-4.3	.03-.04	Smaller particle size better; salt interference; straw carbon was best	Kannan & Rengasamy 2005a
Straw, sawdust, date pit		Ni(II)	—	—	Higher pH favored to 6; Smaller particle size better; salt interferences; first order rate; Langmuir fit;	Kannan & Rengasamy 2005b
Rubberwood		Cr(VI)	44-66	.85- 1.26	Best pH 2; pseudo 2 nd order rate; diffusion control; Langmuir fit best; endothermic	Karthikeyan et al. 2005
Wood	KOH, H ₃ PO ₄	Cr(VI)	33-316	.63-6.1	KOH activation best; lower pH best; diffusion control; Langmuir fit	Khezami & Capart 2005
Oxidized act. C	ZnO	Pb(II), Cu(II), Cd(II)	8-46, 4-15, 2-14	.04-.22, .06-.23, .02-.12	ZnO loading and oxidation both favored adsorption; carboxyl groups important	Kikuchi et al. 2006
Peach stone	H ₃ PO ₄	Cd(II)	No eval	No eval	Phosphoric acid activation was effective.	Kim 2004
Hazelnut shells		Ni(II)	—	—	Pseudo 2 nd order rate	Koby et al. 2002

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Hazelnut shells		Cr(VI)	170	3.3	Best pH 1; pseudo 1 st order rate; Langmuir	Kobyas 2004a
Hazelnut shells		Cr(VI)	170	3.3	Best pH 1; Langmuir fit	Kobyas 2004b
Hazelnut shells	H ₂ SO ₄	Cr(VI)			Particle size important; Freundlich isotherm	Kobyas et al. 2004
Apricot stone	H ₂ SO ₄	Ni(II), Co(II), Cd(II), Cu(II), Pb(II), Cr(III), Cr(VI)	27,30, 34,24, 23,29, 35	.46,.51, .30,.38, .11,.56, .67	Cr(VI) > Cd(II) > Co(II) > Cr(III) > Ni(II) > Cu(II) > Pb(II); best pHs 3-6, except 1-2 for Cr(VI)	Kobyas et al. 2005
Eucalyptus bark	H ₃ PO ₄	Cu(II), Pb(II)	29, 110	.46,.53	Binary mixtures, competition; best pH 5; carboxylic, amine, & amide groups important	Kongsuwan et al. 2009
Deposit lignin	H ₃ PO ₄	Cu(II)			Good uptake observed.	Kriaa et al. 2010
Bagasse pith	Steam, sulfur	Hg(II)	67-94	.33-.47	Best pH 4-9; lower ionic strength better; pseudo 2 nd order rate; Langmuir fit; regenerable with HCl	Krishnan & Anirudhan 2002a
Bagasse pith	Sulfur	Pb(II), Hg(II), Cd(II), Co(II)	200,189 154,129	.97,.94, 1.4,2.2	Pb(II) > Hg(II) > Cd(II) > Co(II); higher pH favored; pseudo 2 nd order rate; Langmuir fit; regeneration by HCl	Krishnan & Anirudhan 2002b
Bagasse pith	Steam, sulfur	Cd(II)	150	1.3	Sulfurization helped; best pH 5-9; low ionic strength best; Langmuir fit	Krishnan & Anirudhan 2003
Bagasse pith	Steam, sulfur	Co(II)	150- 180	2.5-3.1	Best pH 4.5-8.5; Langmuir fit	Krishnan & Anirudhan 2008a
Olive stone	ZnCl ₂	Cd(II)	0.75	0.007	Higher pH favored to 6; pseudo 2 nd order rate; Langmuir fit	Kula et al. 2008
Olive stone	ZnCl ₂	U(), Th()	40, 20	.17,.09	Pseudo 2 nd order rate	Kutahyali & Eral 2010
Activated carbon	Graphite electrode	Cr(VI); Pb(II), Zn(II), Cr(III)	No eval	No eval	Graphite electrode method; only the specialized carbon removed the anion; commercial C removed Pb, Zn, Cr(II)	Lalvani et al. 1998
Activated carbon		Cr(VI), Cr(III)	—	—	A commercial activated carbon was not able to adsorb the Cr(VI), just Cr(III)	Lalvani et al. 2000
Activated carbon		Cr(VI)	16+	0.3+	Best pH 6; Freundlich fit; reduction	Leyva-Ramos et al. 1994
Activated carbon		Cr(III)	6-7	.12-.13	Best pH 5; hydroxide ppt above pH 6.4; Langmuir fit	Leyva-Ramos et al. 1995

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Activated carbon		Cd(II)	8.0	0.071	Higher pH favored, except hydroxide precipitates at pH>9; lower temperature favored; Langmuir fit best;	Leyva-Ramos et al. 1997
Activated carbon		Cd(II), Zn(II)	16, 18	0.14, 0.27	Langmuir fits including bi-solute isotherms; partial competition	Leyva-Ramos et al. 2001
Carbon cloth	HNO ₃	Cd(II)	5-13	.04-.12	Oxidation increased uptake; best pH 8; regen. by decreasing pH	Leyva-Ramos et al. 2005
<i>Spartina altern.</i>		Pb(II)	99	0.48	Best pH 4.8-5.6; pseudo 2 nd order; Freundlich fit	Li & Wang 2009
Rice husk	H ₃ PO ₄ , ZnCl ₂		No eval	No eval	Base-leaching & acid washing enhanced uptake capacity, surface area	Liou & Wu 2009
Raw act. carbon	HNO ₃ & NaOH	Cr(VI)	4-11	.08-.21	The treatment increased Cr(VI) uptake; effect attributed to acidic sites	Liu et al. 2007
Activated carbon		Hg(II)	24-40	.12-.20	Higher pH favored; reduction to Hg(I) was a key mechanism	Lloyd-Jones et al. 2004
Mixed wastes, Oxidized carbon		Cr(III)	26-57; 46-53	.50-1.1, .89-1.0	Langmuir fits	Lyubchik et al. 2004
Granular act. C		Pb(II)	14	.066 (.047 & .075)	A two-site model was proposed to account for fast & slow rates for both adsorption & desorption; 2-site Langmuir fit	Machida et al. 2004
Lab carbon	SO ₂ at temps.	Cd(II)	34-48	.30-.43	Heating increased the carbon's capacity; the SO ₂ treatment was unimportant	Macias-Garcia et al. 2003
Lab carbon	SO ₂ at temps.	Pb(II)	33-81	.16-.39	Sulfur treatment slowed down the rate but increased the capacity for Pb(II) sorption	Macias-Garcia et al. 2004
Activated carbon	H ₃ PO ₄	Pb(II), Cu(II)	116, 32	.15-.56, .26-.51	Continuous proton affinity distribution explains dissociation and uptake behavior	Malik et al. 2002
Coconut husk	Cu(II) impregn	As(III)	160	2.1	Best pH 12; Langmuir fit; regenerable with H ₂ O ₂ and HNO ₃	Manju et al. 1998
Flax shive	H ₃ PO ₄ , H ₂ SO ₄	Cd(II), Cu(II), Ni(II), Zn(II)	664,97, 48, 53	5.9,1.5, .82,.81	Phosphoric treatment more effective than sulfuric acid	Marshall et al. 2007
<i>Militia f.</i> leaves		Pb(II)	3	0.015	First order rate; Freundlich fit	Mengistie et al. 2008
Haxelnut shells	Steam, ultrasound	Cu(II)	239	4.5	Ultrasound helped; diffusion control; Langmuir fit	Milenkovic et al. 2009

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Bagasse		Cr(VI)			Best pH 2; Langmuir fit	Mise & Shantha 1993
Bagasse		Cd(II), Zn(II)	30, 29	.27,.44	Film diffusion; Freundlich fits	Mohan & Singh 2002
Act. C cloth		Cr(VI)	1-117	.02-2.2	Tests at pH 2; pseudo 2 nd order rate; Langmuir fits	Mohan et al. 2005
Act. C cloth, coconut shell		Cr(III)	40, 12	0.63, 0.23	Pseudo 2 nd order rate; Langmuir fit	Mohan et al. 2006
Woody biomass; Pine, oak: Barks, wood	Char fr. bio-oil	Pb(II), As(III), Cd(II),	2-14, 1-12, 1-4	.01-.07, .01-.16, .01-.04	Best pHs 3-5; Langmuir fit	Mohan et al. 2007
<i>Terminalia arj.</i>	ZnCl ₂	Cr(VI)	28	0.04	Chemical ratio, temperature, & time of preparation; best uptake pH 1; first-order rate; Langmuir fit	Mohanty et al. 2005
Activated carbon		Cr(VI)	1.0	0.02	Best pH 2; Langmuir fit	Mor et al. 2007
Dates stone	H ₂ SO ₄	Pb(II), Zn(II)	20, 10	0.10, 0.15	Best pH 6; pseudo 2 nd order rate; Langmuir fit	Mouni et al. 2010
Activated carbon	Na acetate	Cu(II)	20-33	0.31-0.52	Acetate treatment increased uptake by 2.2X ; regeneration with NaOH	Mugisidi et al. 2007
Spent grain lignin	H ₃ PO ₄	Ni(II), Fe, Cr, Si	No eval	No eval	Performance comparable to commercial activated carbon	Mussatto et al. 2010
Agricultural wastes		Cr(VI)	9	.17	Oxidizing agents increased the surface area; in-situ reduction	Muthukumaran et al. 1995
Husk and pod	CTAB, H ₃ PO ₄ , H ₂ SO ₄ , HCl	Pb(II)	25-30	.13-.15	Pseudo-2 nd order rate; Langmuir fit	Nadeem et al. 2006
Coir pith		Hg(II)	154	0.77	Higher pH favored to 5; Langmuir fit; regeneration with HCl or KI	Namasivayam & Kadirvelu 1997
Coir pith		Hg(II),	154	0.77	Higher pH favored to 4; First order rate; Langmuir fit	Namasivayam & Kadirvelu 1999
Peanut hull	NaHCO ₃	Hg(II)	2-20	.01-.10	The bicarbonate-treated carbon was 6X more effective than the control; Langmuir fit	Namasivayam & Periasamy 1993
Activated carbon		Pb(II), Cu(II), Co(II)	No eval	No eval	Best pH just below formation of hydroxide for each metal; competition very important	Netzer & Hughes 1984

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Oil palm shell	Chitosan	Cr(VI), Cr(III)	0.45	0.009	Best pH 4-5; ionic interactions & complexation; adsorptive reduction; regeneration with NaOH	Nomanbhay & Palanisamy 2005
Activated carbon	Ag metal, acid treat	Na(I)	—	—	Sodium carbonate, bicarbonate, NaOH uptake	Oh 2005
Sugar beet pulp	H ₃ PO ₄	Cd(II)	68-73	.60-.65	96% uptake; 2 nd order rate; Langmuir fit	Ozer & Tumen 2003
Pitch-based C		Cr(VI)	24-25	.46-.48	Langmuir fits	Park et al. 2003
Activated carbon		Cr(VI)	No eval	No eval	Reduced to Cr(III) on contact/adsorption	Park et al. 2006a
Activated carbon	Anodic treatment	Cr(VI), Cu(II), Ni(II)	18-26, 7-17, 4-10	.35-.50, .11-.27, .07-.17	Oxidized carbons had higher adsorption	Park & Kim 2004
Peanut hulls		Cd(II)	2-20	.02-.17	Good pHs 3.5-9.3; Freundlich fit	Periasamy & Namasivayamm 1994
Peanut hulls		Ni(II)	0.7-20	.01-.34	Good pHs 4-10; Langmuir fit	Periasamy & Namasivayamm 1995a
Peanut hulls		Pb(II)	14-20	.07-.10	Good pHs 3-10; Langmuir fit	Periasamy & Namasivayamm 1995a
Peanut hulls		Cu(II)	3-32	.05-.50	Good pHs 4-10; Langmuir fit	Periasamy & Namasivayamm 1995a
Jute, coconut fibers	CO ₂ , H ₃ PO ₄	Cu(II)	10-137	0.15-2.15	Acidic surface sites active in adsorption	Phan et al. 2006
<i>Hymenaea</i> shell	ZnCl ₂ , H ₃ PO ₄ , H ₂ SO ₄ , HNO ₃ , HCl	Cd(II)	—	—	Freundlich fit	Poleo et al. 2010
Activated carbon	H ₃ PO ₄	Cu(II)	No eval	No eval	Key role of P-containing groups	Puziy et al. 2002
Activated carbon		Cd(II)	10	0.19	Vs. carbon nanotubes, magnetic particles ; higher pH favored; pseudo 2 nd order; Langmuir fits	Pyrzynska 2010
Activated carbon		Th	No eval	No eval	Higher pH favored to 3; Langmuir fit; regen with HNO ₃	Qadeer et al. 1992
Activated carbon		Sr	—	—	Diffusion into micropores controls rate	Qadeer et al. 1995a

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Activated carbon		Sr(II), Sm(III), Gd(III), Th(IV) UO ₂ ²⁺	—	—	Fast & slow processes; diffusion into fine pores controls rate	Qadeer et al. 1995b
Activated carbon		Dy(III), Gd(III), Eu(III), Sm(III)	—	—	Adsorption correlated with Z/r; Dy ³⁺ > Gd ³⁺ > Eu ³⁺ > Sm ³⁺	Qadeer et al. 1996
<i>Parthenium w</i>	H ₂ SO ₄ , NH ₄ per- sulfate	Cr(VI), Hg(II), Fe(II)	> 1, > 1, > 1	> 0.02, > .005, > 0.02	Found to be effective	Rajeshwarisivaraj & Subburam 2002
Sawdust		Cr(VI)	50	0.10	Pore diffusion control; reduction at lower pH; Langmuir fit; regen. with NaOH	Raji & Anirudhan 1997
Sawdust	NaHCO ₃	Pb(II), Hg(II), Cd(II)	—	—	Best pHs 4-9; Langmuir fit; regen. with HCl	Raji et al. 1997
Activated carbon		Cr(VI)	15-35	.29-.67	Tests at pH 3; Langmuir fit	Ranganathan 2000
Act. carbon cloth	HNO ₃ , O ₃ , elec. oxidation	Cd(II)	6-147	.05-1.3	Oxidation of activated carbon increased the ion exchange capacity by a factor of 3.5; higher pH favored	Rangel-Mendez and Streat 2002
Act. carbon fiber	AlCl ₃ , ZnCl ₂	Zn(II), Cd(II)	—	—	Treatments affected pore sizes	Rincon et al. 2007
Activated carbon	Ozonized	Cr(III)	7-19	.13-.37	Tests at pH 6; Langmuir fits	Rivera-Utrilla et al. 2003a
Activated carbon	<i>E.coli</i> adsorp.	Pb(II), Cd(II), Cr(VI)	21-26, 5-8, 3-4	.10-.13, .04-.07, .06-.08	Bacteria in the solution enhanced adsorption of cations, but not Cr(VI)	Rivera-Utrilla et al. 2003b
Activated carbon		Ce(III), Sm(III) Eu(III), Gd(III)	18, 19, 15, 18	.13, .13, .10, .11	Adsorption controlled by effect of pH on dissoved metal species; best pH 8-9.5	Saleem et al. 1994
Activated carbon	Control Air ox'd “ Nitric acid ox'd	Cu(II) Cu(II), Zn(II), Ni(II), Cd(II); Cu(II), Zn(II), Ni(II), Cd(II)	0.25; 3.2, 8.5, 3.5, 26; 27, 10, 12, 24	0.004; .05, .13, .06, .23; .42, .16, .20, .21	Oxidation by nitric acid increased Cu uptake by 100X; regeneration with 0.1 M HCl worked best for Cu	Saha et al. 2003
Coir pith	KOH	Cd(II), Cu(II), Zn(II)	No eval	No eval	Higher pH favored; 1st order rate; Freundlich fit; regen. by HCl	Santhy & Selvapathy 2004
Biomass mixture		Mn	3.0-3.4	.05-.06	Surface oxides play key role; ion exchange	Savova et al. 2003
Hazelnut	KOH, ultrason.	Cu(II)	40	0.63	Open pore structure	Sayan 2006

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Coconut shell		Pb(II)	26	.12	Best pH 4.5; Langmuir fit; exothermic	Sekar et al. 2004
Coconut tree		Cr(VI)	3.5	0.067	Adsorption at pH 3; Langmuir fit	Selvi et al. 2001
Various act. Cs		Cr(VI)	1.9-4.9	0.036-0.09	H-type (from coconut shell or coat) vs. L-type (from wood) performed differently; for L the Best pH for Cr was 2; for H it was 3-4; the H type can reduce Cr(VI) to Cr(III).	Selomulya et al. 1999
Activated carbon		Cr(VI)	76	1.46	Very little reduction took place when using leaf mold; activated carbon caused reduction	Sharma & Forster 1996a
Activated carbon		Cr(VI)	145	2.8	Best pH 2.5 to 3; Langmuir fit	Sharma & Forster 1996b
Pitch	HNO ₃ , NaOH	Cu(II), Ni(II)	9, 2	.14, .03	Post treatments; HNO ₃ increased acid sites 3X, points of zero charge fell pH 6 to pH 4;	Shim et al. 2001
Lodgepole pine	Vacuum pyrolysis, steam, KOH	Cu(II), Cd(II), Mn(II), Ni(II), Pb(II), Zn(II)	50-400 (mixed)	0.5-10 approx.	The carbons outperformed commercial carbons for the metals mixture	Shin et al. 2008
Carbon slurry		Cr(VI)	24-26	.46-.50	Tests at pH 2.5; Langmuir fit; higher temperature favored	Singh & Tiwari 1997
Tamarind wood	H ₂ SO ₄	Pb(II)	134	0.65	Best pH 6.5; Langmuir fit	Singh et al. 2007
Various ag wastes	H ₃ PO ₄	Au	No eval	No eval	Heating temperature and time were critical	Soleimani & Kaghazchi 2007
Apricot stones		Au	—	—	Langmuir fit; regen. with base	Soleimani & Kaghazchi 2008
Sawdust		Pb(II)	41	0.20	Higher pH favored to 6; Citric acid lowered pH optimum; pseudo 1 st order rate; Langmuir fit	Sreejalekshmi et al. 2009
Coconut oilcake		Ni(II)	—	—	Pseudo 2 nd order rate; Langmuir fit	Srinivasan & Hema 2009
Coconut		Cd(II), Ni(II), Zn(II)	—	—	Best pH 6; pseudo 2 nd order rate	Srivastava et al. 2008b
Granular		Cr(VI)	—	—	Langmuir fit	Tandel & Oza 2005
Cashew nut		Cr(III)	14	0.27	Langmuir fit	Tanguank et al. 2009
Kraft lignin	H ₂ O ₂	Cr(VI)	76	1.46	Best pH 2; pseudo 2 nd order rate; Langmuir fit; endothermic	Tazrouti & Amrani 2009

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Almond, pecan	H ₃ PO ₄ , CO ₂ Air oxidn	Cu(II)	2-18	.03-.28	Oxidation increased uptake	Toles et al. 1997
Various nuts	H ₃ PO ₄ , Air oxidn	Cu(II)	17-18	.27-.29	Various oxidations increased uptake	Toles et al. 1998
Various nuts	H ₃ PO ₄ , Air oxidn	Cu(II)	6-60	0.1-0.9	Functional group abundance correlates with uptake: carbonyl, phenols, lactones, carboxyl	Toles et al. 1999
Sunflower husk	H ₃ PO ₄ in nitrogen	Cu(II), Cr(VI)	48, 19	.76,.36	Langmuir fit for Cu(II); Freundlich fit for Cr(VI); stoichiometric relationship to groups	Tupkanjana & Phalakornkule 2007
Activated carbon	Tannic acid	Fe(III)	—	—	Tannic acid enhanced metal uptake; Langmuir fit	Ucer et al. 2005
Olive stone	ZnCl ₂	Ni(II)	.28-.66	0.005- 0.01	Higher pH favored to 6; pseudo 2 nd order rate	Ugurlu et al. 2009
Bagasse	Hetero atoms	Cr(VI)	3.4- 10.1	.06-.20	Basicity of the carbon contributed to Cr(VI) uptake through heteroatoms	Valix et al. 2006
Bagasse		Cr(VI)	2-32	.04-.62	Reduction mechanism; uptake favored by miminal oxygen and hydrogen contents	Valix et al. 2008
Granular act C		Co(II), Zn(II)	No eval	No eval	Higher flow beneficial	Wang et al. 2003
Activated carbon		Pb(II)	50	0.24	Breakthrough prediciton	Xiu & Li 2000
Peanut shell	HNO ₃	Pb(II)	36	0.17	Langmuir fit; uptake enhanced by pore widening, oxygen groups, hydrophilicity	Xu & Liu 2008
Activated carbons	H ₂ SO ₄ , ZnCl ₂	Cd(II)	6-25	.05-.22	ZnCl ₂ gave a high surface area; 1 st order rate; ion exchange; competition; diffusion control	Youssef et al. 2004
Low cost	Low temp act.	Cr(VI)	8-40	.15-.77	High surface area, mesopores important	Yue et al. 2009
Activated carbons		Pb(II)	6.3-8.5	.03-.04	Adsorption accounted by surface area, pore size, and heteroatom concentrations	Zhang et al. 2005
Activated carbon	Zero- valent Fe	As(III), As(V)	18, 12	.24, .16	Arsenite and arsenate were taken up by the supported ZVI crystals; Langmuir fit; regen. with NaOH	Zhu et al. 2009b

Biomass type	Modifi- cation	Metals	Capac. (mg/g)	Capac. (mM/g)	Key findings	Citation
Ash						
Fly ash	Al, Fe	Cr(VI)	1.4-1.8	0.026-0.035	Tests at pH 2; Langmuir fit	Banarjee et al. 2004
Rice husk		Zn(II)	—	—	Langmuir fit	Chaves et al. 2009
Wood ash		Zn(II), Cd(II), Cu(II), Cr(III)	No eval	No eval	Pseudo 2nd order rate; Langmuir	Chojnacka & Michalak 2009
Oil palm waste		Zn(II)	11	0.17	Higher pH better; First order rate; Langmuir, other fits	Chu & Hashim 2002
Bagasse fly ash		Pb(II)	520	2.5	Best pH 3; Langmuir fit; treatment effective	Gupta et al. 1998
Bagasse fly ash		Cr(VI)	124-259	2.4-5.0	Tests at pH 1; Langmuir fits	Gupta et al. 1999
Bagasse fly ash		Cu(II), Zn(II)	—	—	Langmuir fit	Gupta & Ali 2000
Bagasse fly ash		Cd(II), Ni(II)	1.2, 1.0	.01, .02	Best pH 6-6.5; Langmuir fit	Gupta et al. 2003
Bagasse fly ash		Pb(II), Cr(III)	3.9, 1.9	0.02, 0.036	Langmuir fit; exothermic	Gupta & Ali 2004
Sugar beet fly ash		Cu(II), Zn(II)	7, 8	.11, .12	60-97% uptake; best pHs 4-5; Langmuir fit	Pehlivan et al. 2006
Bagasse fly ash	NaOH, acetic ac	Cr(VI), Ni(II)	52, 4.4	1.0, 0.075	Activated carbon was more effective than fly ash or the starting material	Rao et al. 2002
Bagasse fly ash		Cd(II), Ni(II)	2.3, 2.5	.02, .04	Higher pH favored to 6; Redlich-Peterson fit; competition; regen. with acid	Srivastava et al. 2006a
Bagasse fly ash		Cd(II), Zn(II)	6.2, 7.0	0.055, 0.11	Binary systems; best pH 6; Redlich-Peterson fit; competition	Srivastava et al. 2006b
Rice husk ash		Cd(II), Ni(II), Zn(II)	6.2, 4.2, 2.8	0.055, 0.072, 0.043	Higher pH favored to 6; pseudo 2 nd order rate;	Srivastava et al. 2006c
Rice husk ash; bagasse fly ash		Cd(II), Ni(II), Zn(II)	20-25, 22-25, 25-26	.18-.22, .38-.43, .38-.40	Thermodynamics; heterogeneous sites	Srivastava et al. 2007
Rice husk ash		Cd(II), Zn(II)	2.9, 6.2	0.026, 0.095	Binary; higher pH favored to 6; Redlich-Peterson fit; competition	Srivastava et al. 2008a
Rice husk ash		Cd(II), Ni(II), Zn(II)	2.3, 2.6, 3.1	.02, .04, .05	Ternary; Redlich-Peterson fit; competition	Srivastava et al. 2009a
Rice husk ash		Cd(II), Ni(II)	—	—	Competitive; Freundlich fit of binary	Srivastava et al. 2009b