Chapter 1
Introduction

Adrián Bonilla-Petriciolet, Didilia Ileana Mendoza-Castillo, and Hilda Elizabeth Reynel-Ávila

Abstract This chapter covers fundamental aspects of adsorption process engineering. In particular, the importance of adsorption processes for water treatment is discussed and analyzed. Environmental impact of some key aquatic pollutants is also reviewed. Opportunity areas for adsorption process intensification are also highlighted in this chapter including a brief overview of the content of this book.

Keywords Adsorption • Water sanitation • Process intensification • Aquatic pollutants

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A. Bonilla-Petriciolet (✉)
Instituto Tecnológico de Aguascalientes, Av. Lopez Mateos 1801, C.P. 20256, Aguascalientes, Mexico
e-mail: petriciolet@hotmail.com

D.I. Mendoza-Castillo • H.E. Reynel-Ávila
Instituto Tecnológico de Aguascalientes, Aguascalientes, Mexico
e-mail: didi_men@hotmail.com; helizabeth_00@hotmail.com

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1.1 Adsorption: A Cost-Effective Technology for Water Treatment

Water pollution control is a major environmental concern worldwide. For example, it has been estimated that one third of world population can be affected by the lack of safe drinking water (Schwarzenbach et al. 2010). Pollution of water resources is caused by synthetic and natural chemicals that are released from a variety of anthropogenic and natural sources including the geological composition of aquifers. Different technologies for water treatment and purification have been extensively discussed in the literature where the design and operation of affordable methods can be still considered as a challenge. Herein, it is convenient to highlight that all treatment methods have their own technical and economic boundaries for real-life applications.

In particular, the adsorption process has been recognized as a viable technology for water sanitation. Adsorption processes are widely used for the treatment of wastewaters, groundwater, and industrial effluents including the production of drinking water. This treatment method may offer several advantages for water purification because it can be operated at different scenarios besides its easy use, flexibility, versatile design, low-energy requirements, and cost-effectiveness tradeoff. Overall, the economic and technical feasibility of adsorption processes depends on several factors including the adsorbent type, fluid properties and pollutants to be removed, operating conditions, process configuration, regeneration, and waste disposal.

Batch and continuous adsorption systems can be employed for water treatment, and they offer different capabilities. Batch reactors are useful to determine adsorption rates, maximum adsorption capacities, and thermodynamic parameters including the analysis of the adsorbate(s)-adsorbent interactions. On the other hand, packed-bed columns are suitable for water purification in large-scale applications where the treatment of significant volumes of fluids can be performed in short operating times. Adsorption tests in packed columns are required to calculate relevant parameters for scale-up such as the breakthrough and saturation times, the bed adsorption capacity, and mass transfer parameters. This process configuration also allows to determine the maximum performance of the adsorbent and to identify the best dynamic operating scenario. Note that the operational conditions of dynamic adsorption systems imply residence times lower than the equilibrium time, and, consequently, the mass transfer resistances play a major role in the removal of pollutants. Therefore, the removal effectiveness of continuous adsorption systems is usually lower than that obtained for batch processes.

Activated carbon is the universal adsorbent for liquid phase and still prevails as the main commercial product for water pollution control (Rivera-Utrilla et al. 2011; Bhatnagar et al. 2013). However, a variety of alternative adsorbents has been synthesized and proposed for the adsorption of aquatic pollutants. For illustration, Table 1.1 shows a survey of different materials that can be employed in the removal of anthropogenic and geogenic pollutants in the context of environmental water

Table 1.1 Survey of materials used as adsorbents for water treatment and purification

Adsorbent	Heavy metals	Metalloids	Halogens	Dyes	Pharmaceuticals	Toxins	Radioisotopes	Organic pollutants
Alumina	√	√	√	√	√	√		
Activated carbon	√	√	√	√	√	√	√	√
Biological materials	√	√	√	√				√
Bone char	√	√	√	√	√	√	√	√
Clays	√	√	√	√	√	√		√
Composites	√	√	√	√	√		√	√
Graphene-based adsorbents	√	√	√	√	√	√	√	√
Low cost adsorbents[a]	√	√	√	√	√		√	√
Nano adsorbents	√	√	√	√	√	√	√	√
Polymeric materials	√	√	√	√	√	√	√	√

[a]Biomasses, agricultural, and industrial wastes and by-products

protection. They include aluminas (Kasprzyk-Hordern 2004), zeolites (Koshy and Singh 2016), clays (Vinati et al. 2015), and novel adsorbents such as nanomaterials (Santhosh et al. 2016), graphene-based adsorbents (Peng et al. 2017), magnetic materials (Mehta et al. 2015), metal-organic frameworks (Kumar et al. 2017), and others. Additionally, some studies have suggested the application of low-cost adsorbents that comprise agricultural and industrial wastes and by-products (Bhatnagar and Sillanpaa 2010; Adegoke and Bello 2015; De Gisi et al. 2016; Ahmed and Ahmaruzzaman 2016) and biomasses (Bhatnagar et al. 2015).

To date, the vast amount of studies performed on the adsorption of aquatic pollutants has mainly focused on the analysis and understanding of single solutions (i.e., one adsorbate in solution). However, the multicomponent adsorption is relevant for the design, optimization, and operation of real-life systems for purification of wastewaters, industrial effluents, and groundwater. The simultaneous adsorption of several adsorbates may imply synergic, antagonistic, or non-interaction effects depending on the adsorbent, the number and type of adsorbates (i.e., pollutants), and their concentrations, besides the fluid properties such as temperature and pH. The presence of several pollutants in the same solution may significantly affect the adsorbent performance. For instance, the adsorption of heavy metal ions in multimetallic systems is affected by the properties and concentrations of the co-ions (Choy and McKay 2005), while some dyes may favor the adsorption of metallic species in mixtures metal + dye (Hernandez-Eudave et al. 2016). The complex physicochemical nature of real-life multicomponent systems imposes new challenges for water treatment technologies including adsorption processes.

Although adsorption is a consolidated technology, it is clear that there are opportunity areas to improve its performance for facing current pollution problems of groundwater and wastewater including the treatment of industrial effluents. With this in mind, this book covers scientific advances related to the intensification of adsorption processes for water treatment and purification. Chapters contained in this book focus on the discussion and analysis of current topics from adsorption research and gaps for further study that can contribute to the consolidation of this separation process as a robust, economically feasible and environmentally friendly method for water sanitation.

1.2 Priority Pollutants in Water Purification

There is a great variety of water pollutants with a wide range of physicochemical properties and toxicological profiles. They include anthropogenic chemicals, geogenic pollutants, and persistent compounds that imply different challenges for adsorption processes. The most relevant aquatic pollutants include heavy metal ions, metalloids, pesticides, biocides, pharmaceuticals, and other emerging inorganic and organic compounds (Schwarzenbach et al. 2010). These pollutants can be toxic for human beings and biota at the nanogram to milligram per liter level. In some cases, they are considered priority in the context of water pollution control due to their persistence in the environment, bioaccumulation, and toxicological profile. With illustrative purposes, key aquatic pollutants are discussed in the next subsections.

1.2.1 Heavy Metals

Metallic species represent a significant proportion of the pollutants contained in the effluents generated by a wide variety of industries. Heavy metal ions imply an environmental risk due to their cumulative, toxic, and non-biodegradability characteristics (Mouni et al. 2009). At certain concentration threshold, heavy metals are toxic for human beings causing damages in the gastrointestinal, cardio-vascular, renal, and peripheral central nervous systems (Ibrahim et al. 2006). The toxicity of heavy metals is due to their ability to form compounds with cellular components that contain sulfur, oxygen, or nitrogen producing the inhibition of enzymes or the modification of protein structures leading to cellular dysfunctions in the organism (Ibrahim et al. 2006). Mercury, cadmium, copper, zinc, nickel, lead, chromium, aluminum, and cobalt are considered as priority aquatic pollutants due to their toxicity (Dias et al. 2007; Fu and Wang 2011). According to literature, several studies have focused on the adsorption of heavy metal ions (e.g., Rao et al. 2010; Barakat 2011; Gupta and Bhattacharyya 2012; Malik et al. 2016; Shah et al. 2016; Yu et al. 2016; Uddin 2017).

1.2.2 Dyes

Pigments and dyes are pollutants generated by food, rubber, paper, cosmetic, pharmaceutical, automotive, and textile industries (Gong et al. 2008; Wong et al. 2009; Ghodbane and Hamdaoui 2010). It has been estimated that ~7×10^5 tons of dyes per year are generated worldwide due to inefficient dyeing techniques (Wong et al. 2009). Therefore, residual industrial effluents often contain a diversity of dyes. These compounds can be classed in acid, basic, disperse, reactive, and direct dyes (Ghodbane and Hamdaoui 2010). They have high molecular weights, complex structures, and, consequently, a persistent and recalcitrant nature (Qui and Zheng 2009; Hernández-Montoya et al. 2013). Dyes and their metabolites can be toxic, mutagenic, and carcinogenic to a wide variety of living organisms (Al-Ghouti et al. 2003). Adsorption process has proved to be an effective option to treat dye polluted fluids. Several studies have been performed to evaluate the dye uptakes of a vast number of adsorbents (e.g., Allen and Koumanova 2005; Demirbas 2009; Chincholi et al. 2014; Yagub et al. 2014; Adeyemo et al. 2015; Seow and Lim 2016; Vital et al. 2016).

1.2.3 Pharmaceuticals

Pharmaceuticals are considered as one of the emerging hazardous water pollutants (Sarici-Ozdemir and Önal 2010; Bagheri et al. 2014). These pollutants have been reported in trace levels (typically in ng/L and μg/L) in surface waters, wastewaters, groundwaters and even drinking water (World Health Organization 2011). Pharmaceuticals are generally better chemically characterized than other environmental pollutants (World Health Organization 2011). The most common pharmaceuticals are antibiotics, analgesics, anti-inflammatories, painkillers, and hormones. They can be absorbed by the tissues of animals and humans (especially liver and kidney) obstructing the metabolic processes and inhibiting the hormone receptors (World Health Organization 2011). They can enter into the environment via the human or animal excreta, and, consequently, these pharmaceuticals can reach the wastewater treatment plants (Baccar et al. 2012; Bagheri et al. 2014). Recent literature has reported that the conventional sewage treatment plants are not effective to remove/degrade these species because they were not specifically designed for handling trace pollutants (Baccar et al. 2012; Bagheri et al. 2014). Therefore, the pharmaceuticals can be continually introduced into water resources representing an environmental risk for both ecosystems and human beings (Önal et al. 2007; Yu et al. 2008; Sarici-Ozdemir and Önal 2010; Baccar et al. 2012). Adsorption has been proposed to remove these pollutants with satisfactory results. Adsorbents used for pharmaceutical removal include activated carbons, silica, and zeolites (Fukahori et al. 2011; Baccar et al. 2012; Martucci et al. 2012; Kim et al. 2014; Kyzas and Deliyanni 2015). On the other hand, the most studied pharmaceuticals in adsorption tests are naproxen, ibuprofen, diclofenac, erythromycin, atenolol, and carbamazepine (Kim et al. 2014).

1.2.4 Fluoride

Fluoride is recognized by the World Health Organization as a toxic geogenic pollutant that is present in groundwater (Jadhav et al. 2016). Fluoride pollution of water resources is considered as a relevant environmental issue that is associated to public health problems in several developing countries. It has been estimated that over 260 million people worldwide consume fluoride-polluted groundwater (Sani et al. 2016). Water consumption with fluoride concentrations higher than 1.5 mg/L is associated to dental and skeletal fluorosis in human beings. Other health effects of a chronic fluoride ingestion may include endocrine gland injury, thyroid disorder, renal dysfunction, gastrointestinal disorders, gastric irritation, arthritis, cancer, infertility, Alzheimer's syndrome, and osteoporosis (Das et al. 2005; Gupta et al. 2007; Ozvath 2009; Tomar and Kumar 2013; Jadhav et al. 2016). Fluoride may interfere with proteins, carbohydrates, vitamins, and enzymes that mediate coagulation, glycolysis, oxidative phosphorylation, and neurotransmission causing serious disruptions to these important biochemical processes (Tomar and Kumar 2013; Kut et al. 2016). Water defluoridation can be performed via adsorption (e.g., Mohapatra et al. 2009; Bhatnagar et al. 2011; Miretzky and Cirelli 2011; Jagtap et al. 2012; Loganathan et al. 2013; Velazquez-Jimenez et al. 2015; Vinati et al. 2015). However, activated carbons and other conventional adsorbents may show a poor performance for fluoride removal.

1.2.5 Arsenic

Arsenic is also a geogenic pollutant that is widely distributed in the earth crust (Mandal and Suzuki 2002). A chronic exposure to arsenic via mainly drinking water may cause melanosis, keratosis, cancer (in skin, bladder, kidney, and lung), arterial hypertension, and reproductive disorders (Shankar et al. 2014). The international concentration and threshold of arsenic for drinking water is 10 μg/L. As stated by Schwarzenbach et al. (2010), this pollutant exemplifies the dilemma between public health concerns and economic feasibility of water sanitation technologies to reach concentration levels of arsenic lower than the safety concentration threshold. The arsenic adsorption from water implies both economic and technical challenges. Several authors have analyzed the advantages and limitations of adsorption processes for the treatment of water polluted by arsenic (Verma et al. 2014; Baig et al. 2015) and various adsorbents have been reported for the arsenic removal from water (e.g., Mohan and Pittman 2007; Gallegos-Garcia et al. 2011; Verma et al. 2014; Baig et al. 2015; Habuda-Stanić and Nujić 2015; Jadhav et al. 2015).

1.2.6 Emerging Pollutants

In recent years, the advances in analytical instrumentation and techniques have facilitated to detect very low concentrations (i.e., ng/L to μg/L) of several chemicals present in groundwater and wastewaters (Nghiem and Fujioka 2016). This is 2the case for the emerging chemicals, which have been recently recognized as relevant aquatic pollutants despite they had occurred in the environment for a long time (Jeirani et al. 2016; Nghiem and Fujioka 2016). These emerging pollutants are generally defined as any synthetic or naturally occurring chemicals that are not routinely monitored but come mainly from wastewaters of municipal, agricultural, and industrial sources (Nghiem and Fujioka 2016). They can be classified depending on their origin, use, or properties (Nghiem and Fujioka 2016). These compounds include steroid hormones, phytoestrogens, personal care products, pesticides, hydrocarbons, and disinfection by-products (Nghiem and Fujioka 2016). They have the potential to cause adverse effects to biota and long-term human health effects such as cancer. Note that several of these pollutants can be classified as endocrine disrupting chemicals (Shi et al. 2012; Nghiem and Fujioka 2016). Conventional treatment processes are not effective to control the water pollution problem caused by these micro-pollutants. Adsorption has been explored for this purpose where activated carbon (Zhang and Hofmann 2013; Jeirani et al. 2016), zeolites (Lule and Atalay 2014), clays (Bojemueller et al. 2001), and some polymers have been employed as adsorbents of these emerging aquatic pollutants.

1.3 Adsorption Process Intensification

Process intensification is an engineering strategy to improve the performance, metrics, and attributes of a system under investigation and, overall, it implies the development of smaller, cleaner, and more energy-efficient technologies (Stankiewicz and Moulijn 2000). In particular, adsorption process involves several technical aspects that can be analyzed from a process intensification perspective; see Fig. 1.1. It is clear that research efforts have been directed toward to improve the different stages of adsorption process engineering for facing water pollution control. This section provides an overview of the opportunity areas for adsorption process intensification in water treatment and purification.

1.3.1 Synthesis of Tailored Adsorbents

The synthesis of novel adsorbents with outstanding properties for the adsorption of aquatic pollutants is a permanent research area. Several studies have shown that the effectiveness of adsorbents for the removal of organic pollutants is usually higher

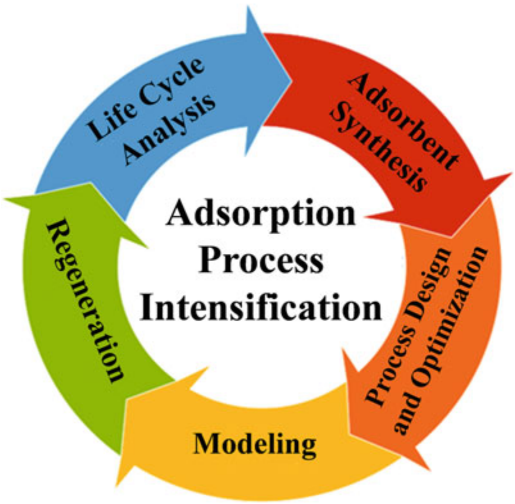

Fig. 1.1 Engineering aspects involved in the adsorption process intensification for water sanitation

than that obtained for inorganic compounds including geogenic chemicals. It is important to remark that textural properties and surface chemistry are fundamental to establish the performance of adsorbents in wastewater treatment and water purification. Physicochemical properties of adsorbents can be tailored for a specific application using proper synthesis protocols. The synthesis route and feedstock (i.e., precursor) determine both the surface chemistry and textural parameters of the adsorbent. The surface chemistry of adsorbents can be modified using thermal and chemical treatments with acids, bases, ozone, reactive gases, and surfactants. Also, impregnation procedures with organic and inorganic species (e.g., rare earth elements), biological modification, plasma, and microwave treatments can be used to modify the adsorbent surface properties (Bhatnagar et al. 2013). Novel synthesis technologies based on microwave and ultrasound offer several possibilities for obtaining new adsorbents for water pollution control (Jamshidi et al. 2016). The selection of a proper surface modification protocol is paramount to impact the cost-efficacy trade-off of adsorption processes. It is convenient to remark that a significant number of variables can be involved in the synthesis of an adsorbent, which should be manipulated using proper experimental designs to identify their effect on adsorbent properties and the best conditions for the adsorbent preparation. This type of studies also allows to understand the solid-liquid interfaces involved in the adsorption of water pollutants.

During the last years, several studies have given an emphasis of tailoring the adsorption properties of activated carbons and other adsorbents for the removal of water inorganic and organic pollutants. However, the synthesis of effective adsorbents for the simultaneous removal of several pollutants in the same solution is still a challenge. It is expected that the synthesis conditions that improve the adsorbent performance for one pollutant could be contradictory with those conditions required to maximize the adsorption of other pollutant. Therefore, there is a lack of studies related to the multiobjective optimization of adsorbent synthesis for an effective simultaneous removal of different aquatic pollutants. Green and energy-saving technologies are also required for the industrial production of outstanding adsorbents for water treatment.

1.3.2 Optimization and Design of Adsorption Systems

Adsorbent performance in water treatment is a nonlinear function of several operating parameters including fluid properties (e.g., pH, temperature), pollutant characteristics and concentration, and the presence of other adsorbates. It is well known that both adsorbent and adsorbate characteristics determine the adsorption mechanism, which may include ion exchange, electrostatic interactions, surface precipitation, chemical reactions, or a combination of them. The operating conditions of adsorption processes can be optimized via experimental designs and statistical analysis to maximize the adsorbent performance for the removal of a specific compound or set of pollutants. For instance, the adsorption effectiveness in packed-bed columns is a function of both the operating conditions and bed geometry where adsorbent size and distribution, fluid flow rate, adsorbate concentration, pH, temperature, and adsorbent mass are the main design parameters. These design variables can be manipulated to identify those conditions that provide the maximum bed adsorption capacity.

In terms of adsorption design, the reduction of mass transfer resistances is paramount to improve the separation effectiveness and to reduce the operational costs especially for continuous adsorption systems. In this direction, some studies have evaluated the use of alternative bed geometries/configurations to enhance the removal performance of packed-bed columns. For example, the adsorption of water pollutants with tapered convergent and stratified beds (Pota and Mathews 2000; Sze and McKay 2012) and helical coil-packed columns (Moreno-Pérez et al. 2016) have been analyzed. Other authors have reported the application of external forces to improve the adsorption of aquatic pollutants. They include the application of ultrasound (Dashamiri et al. 2017), electrical, and magnetic fields (Lounici et al. 2004; González Vázquez et al. 2016) with promising results. These emerging technologies require further investigation to determine their capabilities and limitations for scale-up and industrial applications.

1.3.3 Modeling of Adsorption Processes

The modeling of adsorption processes is relevant for the design, operation, optimization, and control of water purification technologies for real-life applications. Adsorption models can be classed as theoretical, semiempirical, and empirical. They may involve simple analytical expressions or complex systems of algebraic and differential equations when mass transfer phenomena are considered. Adsorption data can be also modeled using computationally intelligent data processing algorithms such as artificial neural networks (Tovar-Gómez et al. 2013) or fuzzy logic (Asl et al. 2017).

Adsorption models are indeed nonlinear and multivariable especially when they are applied in the analysis of multicomponent systems (i.e., groundwater, industrial effluents, and wastewater). Therefore, the modeling of adsorption data is considered as a challenging mathematical problem that should imply a nonlinear data regression procedure for the determination of model parameters with a proper error function and a detailed statistical analysis for establishing the model performance (Dotto et al. 2013). Note that, depending on the model complexity, the application of other computational strategies is often necessary in adsorption data correlation, e.g., the use of numerical methods for solving partial differential equations when mass transfer models are applied. It is desirable that an adsorption model can provide a reliable estimation of the process performance without requiring the use of extensive experimental data and it should have a suitable mathematical complexity, a capability for providing an acceptable accuracy in the correlation and estimation of adsorption performance at different operating conditions, and the model should be useful for assessing the effect of operating variables on the adsorption effectiveness. In summary, the selected model should reflect a compromise between its mathematical complexity and the accuracy obtained for process description.

It is convenient to remark that the numerical performance of adsorption models cannot be determined a priori and they may show limitations for data analysis depending on the adsorption system under study and its operating conditions. In fact, there is no general model applicable to all adsorbate(s)/adsorbent systems, and different adsorption models should be tested for identifying the best option for the case of study at hand. To date, there is a lack of studies to identify and to compare the relative advantages and limitations of available models in the analysis of adsorption processes for the removal of priority water pollutants especially in multicomponent systems. As stated, multicomponent adsorption systems impose challenges for available models due to the simultaneous presence of antagonistic, synergic, and non-interaction effects. For example, the simultaneous removal of heavy metals and acid dyes is complex due to the synergistic adsorption promoted by the dye molecule and the competitive adsorption between metallic species (Tovar-Gómez et al. 2015). For this type of mixtures, traditional models may fail to reproduce and predict the adsorbent performance at different operating scenarios. It is clear that reliable adsorption models are required for the analysis of multicomponent systems containing different organic and inorganic pollutants, which should be representative of groundwater, wastewater, and industrial effluents.

1.3.4 Regeneration and Final Disposal of Exhausted Adsorbents

Regeneration of exhausted adsorbents is a fundamental stage to establish the economic feasibility of adsorption as a water purification technology. The adsorbent performance is gradually reduced due to the progressive accumulation of adsorbates on adsorbent surface causing its exhausting. The strength of the interactions adsorbate(s)-adsorbate and the adsorbate concentration loaded on the adsorbent play a major role in the regeneration process. Therefore, the regeneration is used to remove the adsorbates accumulated on the surface and to recover the adsorbent capacity. Note that there is a decrement of the adsorption capacity of the adsorbent in each regeneration cycle.

Regeneration strategies can be classified in thermal, chemical, microbiological, and vacuum regeneration (Salvador et al. 2015a, b). The mechanisms used in adsorbent regeneration may imply heating, pH variation, changes in the medium for adsorbate extraction, chemical reactions, and degradation (Salvador et al. 2015a, b). These regeneration methods can use different reagents such as solvents, organic and inorganic chemical compounds, electrical current, physical waves, and microorganisms (Salvador et al. 2015a, b). The recovery of adsorption capacity is determined by the regeneration agent, the physicochemical properties of adsorbent and loaded pollutants, and the operating conditions. Desorption and regeneration efficiencies of these methods may vary substantially, and the best option for the adsorbent and pollutants at hand should be identified. Regeneration conditions should be optimized to improve the adsorbent lifetime favoring its uses in several adsorption-desorption cycles and to reduce the damage in the adsorbent structure avoiding a significant loss of mass and active sites.

For the case of adsorbents used in water treatment, the chemical regeneration is the common approach to perform the adsorption-desorption cycles. Recently, novel regeneration methods have been proposed, and they include the use of microwaves or ultrasound (Salvador et al. 2015a, b). Electromagnetic and mechanical waves are applied in microwaves and ultrasound regeneration processes, which have been recognized as energy-saving methods. However, the industrial use of these technologies requires further research to solve their disadvantages. Some studies have also analyzed the potential of microbiological regeneration for adsorbents employed in water treatment (e.g., Aguayo-Villarreal et al. 2016). In conclusion, low-cost and eco-friendly regeneration technologies are required to enhance the cost-efficacy trade-off of adsorption processes for water treatment and purification.

Finally, the disposal of adsorbents at their end of operational life after several adsorption-desorption cycles is also a key aspect to reduce the environmental impact caused by solid waste generation. The traditional approach for the disposal of exhausted adsorbents includes their incineration and use in landfills. However, the improper disposal of exhausted adsorbents may increase the costs of water treatment. The use of spent adsorbents in other industrial applications is an attractive approach for waste minimization. For example, Rao et al. (2009) have analyzed the disposal of fluoride-loaded bone char as a fine aggregate of concrete. Further studies are required in this direction to determine alternatives for the reusing and disposing of spent adsorbents.

1.3.5 Life Cycle Analysis

Life cycle analysis is useful to assess and quantify all the environmental interactions over the stages of the life cycle of an adsorbent manufacturing chain, its use, and disposal in terms of inputs of energy and natural resources and of outputs of emissions to the different environmental compartments (Arena et al. 2016). This analysis should include the effects on natural resources, environment, and human health.

The capabilities and limitations of different adsorbents can be identified via the life cycle assessment providing a detailed sustainability analysis of the water purification process. For example, Alhashimi and Aktas (2017) have analyzed and compared the environmental and economic performance of biochar and activated carbon for the adsorption of heavy metals. Results showed that biochar is a better adsorbent with lower energy demand and global warming potential impact than those of activated carbon for heavy metal removal. Authors of this chapter consider that this type of comparisons should be extended for other adsorbents.

Although several promising adsorbents have been recently proposed for water treatment, the assessment of environmental impacts involved in the manufacturing chain of these materials is still lacking. Therefore, the industrial production and commercialization of these adsorbents can be a matter of debate. Further studies in this direction are required to identify and develop sustainable synthesis routes for the industrial production of adsorbents with outstanding properties for water sanitation. Therefore, it is mandatory to analyze the advantages and limitations, from environmental impact and economical perspectives, of novel adsorbents in comparison to activated carbon using the life cycle analysis.

1.4 Scope and Outline of Chapters

This book covers the state of the art of relevant topics of adsorption processes for water pollution control. Chapters contain the analysis and discussion of data modeling, synthesis of new adsorbents, and the application of adsorbents for the removal of aquatic pollutants.

In particular, Chap. 2 covers different fundaments related to adsorption equilibrium in liquid phase including its experimental determination, analysis, and modeling in batch reactors. Guidelines and experimental procedures to obtain adsorption isotherms are discussed. The Giles classification of adsorption isotherms in liquid phase is introduced and analyzed. Different models commonly used for data fitting of adsorption isotherms in liquid phase are discussed. In particular, this chapter introduces the basis of statistical physical models for representing and understanding the liquid-phase adsorption. Advantages and limitations of linear and nonlinear regression analysis are also discussed including statistical criteria for determining the model accuracy. Finally, the thermodynamics of adsorption process is described given a special emphasis in the calculation of equilibrium constant and its implication in the estimation of thermodynamic parameters.

Kinetics approaches used for adsorption modeling are covered and reviewed in Chap. 3. The description and fundaments of diffusional mass transfer and reaction models are provided. Additionally, the characteristics of the breakthrough curves obtained for dynamic adsorption systems (e.g., packed-bed columns) are analyzed including mass transfer and empirical models for their correlation and representation. This chapter also contains the design of fixed-bed columns, numerical methods used for solving mass transfer-based models, parameter estimation procedures, and statistical criterions for data analysis.

Hydrothermal carbonization is examined in detail in Chap. 4. Specifically, this chapter discusses the basis, synthesis variables, operating conditions, and advantages of using this thermochemical route for the preparation of adsorbents for water treatment. Authors have reviewed different raw materials and synthesis conditions for the preparation of hydrochars. Physicochemical properties of hydrochars are also compared with those adsorbents obtained with pyrolysis. A detailed review of the application of hydrochars in the adsorption of dyes, pesticides, drugs, endocrine disruptive chemicals, phosphorus, phenols, and heavy metals is reported. Some key points related to the reusability of hydrochars are also presented in this chapter.

The application of low-cost adsorbents for the removal of lead, cadmium, and zinc from aqueous solution is analyzed and discussed in Chap. 5. This discussion is focused on agricultural wastes, industrial by-products and wastes, marine materials, zeolites, and clays. The chapter provides the characteristics of these low-cost adsorbents, their sources, and metal adsorption capacities at different operating conditions. This analysis also includes the best kinetic and isotherm models used in adsorption data fitting of heavy metal ions.

The adsorption of tetracyclines and nitroimidazole drugs on different adsorbents is reported in Chap. 6. Commercial activated carbons, sludge-derived materials, and activated carbons obtained from petroleum coke with different chemical and textural natures have been studied. This chapter describes the results of adsorption studies in static and dynamic regime using ultrapure water, surface water, groundwater, and urban wastewater. Authors have highlighted the influence of solution chemical nature (pH and ionic strength) on the adsorption of these compounds analyzing the adsorbent-adsorbate interactions. Also, the impact of microorganisms on the performance of activated carbon for the removal of these pollutants has been analyzed.

In Chap. 7, authors have studied the biosorption of copper using *Saccharomyces cerevisiae*. This chapter illustrates the importance of developing a model capable of describing the effect of operating conditions on biosorption performance. Batch and packed-bed biosorption studies are reported given an especial emphasis on the modeling of experimental data.

Finally, Chap. 8 introduces the application of transition metal-substituted magnetite as a material with a dual function: adsorbent and heterogeneous catalyst for water sanitation. Authors have covered the synthesis of this type of adsorbents, their physicochemical properties, and its performance as both adsorbent and Fenton catalyst.

Editors and authors of this book consider that topics covered in these chapters are relevant to contribute for the development of adsorption processes for water treatment and sanitation.

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