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Removal of Toxic Heavy Metals from Contaminated Industrial Wastewater by Adsorption Techniques

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Abstract- In the environment and the world of heavy metals discharge into water bodies is still a serious environmental and public health issue, especially in areas of heavy industrial activity. Electroplating, metal finishing, mining, tannery, battery, textile and pigment industry wastewater has toxic levels of lead, cadmium, chromium, nickel, copper, zinc, arsenic, and mercury. These metals are not biodegradable and are commonly deposited in sediments, biota and food chains, and hence pose a greater environmental risk as well as human risk. Adoption of adsorption is one of the most effective ways to remove heavy metals, and the low concentrations, low cost and economic feasibility of adsorption make it the current best treatment method. The heavy metals are present in industrial effluents, and adsorption can be considered as a treatment strategy with lower cost and renewable adsorbents. The performance of activated carbon, natural minerals, agricultural by-products, biosorbents and new nanostructured materials is evaluated in terms of adsorption capacity, removal mechanism, regeneration and real-world applications. pH, contact time, adsorbent dose, competing ions and surface chemistry are also addressed. There is solid evidence that many of the low-cost adsorbents are capable of metal uptake in laboratory settings, but still, a huge amount of work remains on scaling, regeneration efficiency, stability in complex effluents, and disposal of spent sorbents. A great deal of progress in the future will be to compare results, to have realistic wastewater testing, and to integrate adsorption into circular and resource recovery-based treatment processes.

Keywords- Heavy metals, industrial wastewater, adsorption, low-cost adsorbents, biosorption, water treatment, remediation.

I. INTRODUCTION

Industrial wastewater contamination with heavy metal is still one of the most serious environmental problems in the world. It has become more apparent as the industrial sector expands, the city expands and the demand for manufactured products grows. Many industries produce wastewater with dissolved metal ions, and in many cases this wastewater is discharged without the full treatment. This is particularly serious in developing regions where treatment facilities are limited, outdated or not always operational. Metal-laden effluents are still entering rivers, lakes, ponds and groundwater systems and present long-term threats to ecosystems and humans. Heavy metal pollution is difficult to control, in part because heavy metals do not break down in exactly the same way as most organic pollutants.

Organic contaminants can be converted into less toxic products through various processes. Chemical or biological processes may break down organic contaminants into less toxic items. But heavy metals are not easily destroyed. Heavy metals cannot be destroyed; they remain in the environment and can change with the environment depending on pH, redox conditions and the presence of other compounds. They may be able to change depending on the redox conditions, pH, and other chemical conditions. These changes can affect their mobility, toxicity and bioavailability. Over time, metals may accumulate in sediments, plants, microorganisms, fish and other living organisms. They can then move through the food chain and reach higher trophic levels such as humans (Fu & Wang, 2011; Bhateria & Jain, 2016).

Because of this persistence and movement through environmental systems, heavy metal contamination is often much more difficult to control after it has already occurred. Industrial wastewater may contain many different heavy metals and the exact nature of the effluent depends on the source of heavy metals. Electroplating and metal finishing industries often discharge chromium, nickel, copper and zinc. Mining, smelting and metallurgical activities often release arsenic, cadmium, mercury and lead. Tanneries are well known for producing chromium-rich wastewater because chromium salts are used in leather production. Battery manufacturing, pigment production, and electronics industries can also contribute significant levels of lead, cadmium, nickel, and cobalt to wastewater streams (Barakat, 2011). Not only are these metals toxic, they can have different chemical behaviors depending on the environment.

There are some situations in which they will be dissolved and moving in water and others in which they can settle down and be released again. They are thus complex and difficult to predict in their long-term behavior. Heavy metals are toxic and have been shown in the toxicological literature to damage human health. Lead exposure is clearly associated with neurological disorders in children, and learning, memory and development are also affected. Cadmium damages kidneys and bones long term. Hexavalent chromium is dangerous because it is mutagenic and carcinogenic. Mercury is toxic to the nervous system and may also damage fetal development. Nickel can cause skin and respiratory damage; copper and zinc are in very small quantities and are dangerous when there is too much (Tchounwou et al., 2012).

And those health problems can get worse because heavy metals can accumulate over time, sometimes not immediately visible. Ecological effects are of course just as important as they may be. Heavy metal contamination can spoil water quality, disturb microbial communities, damage fish and aquatic invertebrates, and even hinder plants' growth. It can also result in sediment contamination that's a long-term source of toxic metals. And once metals get into sediments and even into the food chain, even if they're removed from the source of wastewater, they are still toxic. Heavy metal pollution is not just a toxicity problem (as the source of wastewater) but also an ecosystem imbalance and biodiversity loss problem. A number of methods have been developed for removing heavy metals from wastewater including chemical precipitation, ion exchange, coagulation-flocculation, membrane filtration, electrochemical treatment and biological approaches.

All methods have their advantages, but many have their limitations. Some methods are expensive to apply. Some require high energy inputs, produce large volumes of sludge, or are less effective when metal concentrations are low (Babel & Kurniawan, 2003; Fu & Wang, 2011). These problems make treatment more difficult and expensive in industrial settings. Because of these disadvantages, adsorption has received a great deal of attention as a treatment alternative or complementary approach. Adsorption is frequently viewed as an attractive option as it is quite simple, adaptable and effective in a wide range of conditions. It can be applied for several metals and is also effective even when metal concentrations are low. Another advantage of adsorption is that it can be made with conventional adsorbents and cheap materials from natural sources, agricultural waste or industrial by-products.

It is very attractive in both technical and economic terms (especially in those areas that need to be treated inexpensively) for the treatment of heavy metals. The aim of this review is to remove heavy metals in industrial wastewater with adsorption. Adsorption techniques are particularly targeted at low-cost adsorbents, adsorption mechanisms of materials and most important processes which affect metal uptake. Adsorption should not be a laboratory procedure but also be seen in practice, current obstacles and future applications for sustainable wastewater management as well.

II. HEAVY METALS IN INDUSTRIAL WASTEWATER AND THEIR SIGNIFICANCE

Heavy metals enter wastewater streams through many industrial routes and their presence is closely related to the type of industrial activity taking place. Electroplating, metal finishing, mining, smelting, battery manufacturing, leather tanning, textile dyeing, fertilizer production, paint formulation and electronics processing are all important sources of metal-bearing effluents. The amount and type of metal released can differ greatly from one industry to another. Even within the same industry, wastewater composition may change depending on the raw materials used, the chemicals added during processing, the amount of water consumed, and how much water is recycled in the plant. Pollution control systems are also a major factor.

Hence facilities with good treatment facilities may discharge far lower concentrations than others, and poorly maintained or old systems might discharge highly polluted wastewater. Heavy metals are seldom presented as a single product in real industrial effluents. They are often present as well as other substances such as suspended solids, dissolved salts, acids, alkalis, dyes, surfactants, oils, grease and natural or synthetic organic matter. Such a mixed mixture makes treatment much harder. In adsorption processes, in particular, the presence of multiple components can have a strong effect on metal removal. Other ions can compete with the target metals for binding sites on the adsorbent surface. Organic compounds can block pores or cover active sites. pH and ionic strength may also change metal speciation and reduce adsorption efficiency.

Therefore, the performance of an adsorbent in a simple laboratory solution may not always reflect its behaviour in actual industrial wastewater (Fu & Wang, 2011). The term "heavy metals" is commonly used in environmental studies although this term refers to a group of elements with different physical and chemical properties. Lead, cadmium, chromium, mercury, nickel, copper, and zinc are among the most commonly discussed metals as they are common to industrial effluents and pose serious health and ecological hazards. However, they do not respond in the same way when they enter water. Their reactivity, mobility and toxicity would depend not only on the element but also on the chemical structure of the element. This is so because the same metal can behave very differently under different conditions. For example, chromium is mainly composed of chromium(III) and chromium(VI) and the toxicity and mobility of these two types are very different. Chromium(III) is generally less mobile and less toxic, whereas chromium(VI) is much more toxic, highly mobile and carcinogenic. In the same way, copper and zinc are highly dependent on pH, complex formation with ligands, redox conditions and ionic strength. Some metals may be dissolved in water and others will either adsorb on sediments or may precipitate.

This means that metal speciation is an important part of the treatment strategy and environmental risk prediction. Human exposure to heavy metals can take place in a number of ways. One way of getting that drinking water is contaminated in a country where industrial discharge is being sent into the surface or groundwater system. The exposure in the food chain might also be due to metal accumulation in fish, crops or livestock. Industrial workers who work in industries with metals in the water may also be exposed to these factors in the workplace. The metals, after disposal of wastewater or sludge, can also be spread through soil, dust and air. How much of it will have an adverse impact on health depends on the metals involved, concentration, route of entry and the duration of exposure.

Hence, even acute exposure can cause serious symptoms, but chronic exposure is more dangerous because metals accumulate slowly in tissues. The cumulative toxicity of many heavy metal toxicities is one of the main reasons they are so dangerous. Long-term exposure can cause oxidative stress, interfere with enzymes and proteins, damage organs and disrupt normal cell function. Some heavy metals are associated with neurological diseases, kidney damage, liver injury, developmental problems, immune system dysfunction and cancer. Low-level exposures over long periods can have severe biological consequences, particularly in children, pregnant women and vulnerable populations (Tchounwou et al., 2012). This makes heavy metal contamination much more than just water quality problems. Removal of metals from industrial wastewater is more than just about discharge standards.

This is a public health problem as well as an environmental protection matter. Well-treated wastewater reduces direct human exposure and environmental damage, and we can avoid long-term contamination of soil and water resources. Heavy metals will not be easily removed and are very hard to get out of the system and there is no easy solution for that problem; they are so toxic that we need to control them at the wastewater stage so it is a top priority to avoid pollution in the industry.

III. ADSORPTION AS A PREFERRED STRATEGY FOR HEAVY METAL REMOVAL

Adsorption is still one of the most widely used and applied methods for removing heavy metals from contaminated wastewater. Its popularity is primarily because it is a balance between removing heavy metals efficiently, operational simplicity, and economical feasibility. Dissolved metal ions are transferred from the liquid to the surface of a solid material called an adsorbent. Since adsorption is largely a surface process, it can be quite effective even in low metal concentrations in wastewater. The same is true for other chemical precipitation methods, which are less effective in low metal concentrations or require polishing to meet discharge standards (Babel & Kurniawan, 2003).

Adsorption is also very flexible, and this is why it is so attractive in other ways. The process can be performed in simple batch systems for lab work or small-scale treatment, or in concentrated batch and continuous flow or fixed-bed column systems for larger-scale industrial applications. This makes adsorption practical for wastewater applications in general and is also suitable for numerous wastewater volumes and compositions. Moreover, adsorption does not always require super-complex equipment and hence is more practical because it is feasible in low-resource situations and in the absence of high-level industrial settings where resources and infrastructure are limited.

Adsorption is a good alternative to other treatment methods. Chemical precipitation is common for metal removal but usually results in massive amounts of sludge which must be treated and disposed of in a clean manner. It is expensive and causes secondary waste problems. Membrane-based processes can produce very high removal yields at very high effective levels, but they require expensive equipment with high energy requirements and continuous membrane maintenance. Ion exchange is also a good option, but resins are expensive and sensitive to wastewater composition. Adsorption, on the other hand, is simpler, cheaper and more flexible. It can use a wide range of adsorbent materials, such as low-cost and locally available.

That is why natural materials, agricultural by-products and biomass-based adsorbents have been studied so extensively during the past 20 years (Bailey et al., 1999; Babel & Kurniawan, 2003; Bhateria & Jain, 2016). The strength of adsorption is the variety of adsorbents which can be used. Many researchers have also focused on clays, zeolites, chitosan, crop residues, fruit peels, sawdust, biochar, algae, and industrial by-products as possible adsorbents for heavy metals. This variety allows adsorption systems to be designed based on local availability, cost and target pollutants. Waste adsorbents can be used to add value to low-cost materials that can be discarded. Adsorption is of great value but the properties of adsorbent and wastewater are crucial.

The adsorbent properties are surface area, pore structure, particle size, surface charge, mineral content and active functional groups of the adsorbent such as hydroxyl, carboxyl, amino and sulfhydryl groups. These factors determine the strength and choice of adsorbent for the binding of metal ions. At the same time, the wastewater conditions are very critical. pH, temperature, initial metal concentration, contact time, mixing conditions and competing ions can all affect adsorption efficiency. In industrial wastewater, when many dissolved substances are present together, those can be even more important. It is therefore not an exact technology but a broad treatment platform that is the result of the nature of the wastewater and the metal contamination. If adsorption is to work, the right adsorbent needs to be selected for the right situation, and the process is optimized for it. This balance of material flexibility and process adaptability is why adsorption is still the preferred resource in place to remove heavy metals from industrial wastewater.

IV. ADSORBENT CLASSES AND THEIR PRACTICAL RELEVANCE

Commercial activated carbon is considered as one of the most common adsorbents for wastewater treatment. As a reference material for adsorption research it has a very high surface area and pore structure and can remove various contaminants. Activated carbon is highly effective in heavy metals due to the presence of sites that could interact with dissolved metal ions. This adsorption is further enhanced by chemical or physical surface modification to allow more functional groups or to change the surface charge to favor metal binding. These properties of activated carbon are studied in research and applied in water treatment. But commercial activated carbon is expensive, and so it is difficult to substitute it.

The cost of activated carbon preparation, activation, regeneration and replacement will increase with the volume of wastewater and the process of wastewater. So the search for cheaper solutions has become a prominent research area for the removal of heavy metals (Mohan & Pittman 2007; Fu & Wang 2011). Natural mineral-based adsorbents such as clays and zeolites have attracted attention as they are inexpensive, readily available and available in many parts of the world. They are known to have some useful structural and chemical properties for metal adsorption. Clay minerals are mostly layered structures with high cation exchange capacity so that negatively charged surfaces can interact with positively charged metal ions.

Zeolites are ideally suited for these applications because they have a porous crystalline structure and exchangeable cations in their structure. They are also excellent at binding cationic metals such as lead, copper, nickel and zinc. In addition to their ion exchange roles, natural minerals have stable physical structures and less processing than some synthetic adsorbents. Their low cost and local availability are good for decentralized treatment systems where the treatment materials are not readily available. Among all low-cost adsorbents, agricultural waste-derived materials have received the most attention. Agricultural by-products and plant residues have been used to remove heavy metals from water.

These include rice husk, sawdust, coconut shell, peanut husk, wheat bran, sugarcane bagasse, orange peel, and banana peel. Indeed, their popularity is because they are cheap, renewable and are often seen as waste after agricultural processing. Agricultural adsorbents also provide value to materials that would be discarded or burnt. Their adsorption is related to their natural composition. Many of these plant-based materials contain cellulose, hemicellulose, lignin, pectin and other biopolymers with functional groups like hydroxyl, carboxyl, methoxy, and phenolic groups. These are able to interact with metal ions via ion exchange, electrostatic attraction, chelation, or surface complexation. In some cases, raw agricultural materials are already good at adsorption and in others, their adsorption is improved significantly after physical treatment or chemical modification.

This has made agricultural waste adsorbents one of the most active and practical research areas in adsorption science (Sud et al., 2008; Bhatnagar & Sillanpää, 2010). Algae, bacteria, fungi, and chitosan products are also very important metal-binding adsorbents. Many biological materials have active groups which can capture heavy metal ions from water. However, cell wall components in microorganisms such as algal and microbial biomass contain a lot of carboxyl, phosphate, sulfate, and amino groups that bind to metal ions. Among these biosorbents, chitosan has been most extensively studied. Chitosan is made up of chitin, and therefore has a lot of amino groups which bind to many heavy metal ions. It can be made into beads, membranes, hydrogels, and composite materials and is therefore versatile in treatment applications.

Biosorption is often characterized as a low-cost and environmentally friendly method, especially in the developing world where biological materials are readily available. Still, there are limitations; biosorbents can have weak mechanical strength, limited durability in acidic or highly saline environments, and variable performance when used in complex industrial wastewater. Regeneration and repeated use are also challenging in some systems (Wang & Chen, 2009). Recently, for instance, the interest has also increased in the development of more advanced adsorbent materials such as magnetic particles, metal oxide nanomaterials, carbon nanotubes, graphene-based structures, and nanocomposites. Such materials are commonly developed to have high adsorption capacity, rapid uptake, and better selectivity for metals.

Their very high surface area and flexibility of surface chemistry are particularly attractive for treatment applications. Magnetic adsorbents are particularly attractive because they can easily be separated from treated water when exposed to an external magnetic field, which makes it easier for recovery after adsorption. Graphene-based materials and carbon nanotubes have their promise as well as their unique structure and electronic properties. While these advanced materials have proved to be very promising in laboratory experiments, their practical application is still under examination. Production cost and regeneration requirements, environmental impact, long-term stability, and even the release of nanoparticles into the environment need to be considered when evaluating whether they can be used in an industrial environment (Hua et al., 2012).

These various types of adsorbents show that there is no one ideal material for all heavy metal removal problems. Adsorbents have their advantages and disadvantages of different types, too. Commercial activated carbon is good and reliable but it is also very expensive and may be too expensive for some applications. Natural minerals and agricultural wastes are cheap and readily available but their capacity and selectivity might be low or more variable. Biosorbents offer high biological ability with high biological function, while more expensive nanomaterials are more efficient and cheaper. So, the choice of adsorbent should be based not only on adsorption capacity but also on availability, regeneration potential, cost, stability and suitability for the wastewater to be treated.

V. ADSORPTION MECHANISMS AND CONTROLLING FACTORS

The Mechanics of Adsorption: How We Actually Capture Heavy Metals

If we talk about pulling heavy metals out of water with adsorption then it is natural to think that it is a simple “sticking” process. But in fact, it is a complex but multi-layered chemical dance. To really understand what’s happening at the interface of a biosorbent or mineral we need to know how these metals make permanent residence on a surface. Most often it starts with ion exchange. Think of this as a chemical swap: metal ions in water literally trade places with protons or other ions that are already here on the surface of the adsorbent. If the surface is studded with certain "functional groups" (oxygen, nitrogen, sulfur, etc.) we have surface complexation and the metal ions can actually form coordinate bonds with the surface, so they can actually lock themselves in that structure. Then there is simple electrostatic attraction: the negative charge of the adsorbent acts as a magnet for the positive metal ions. And if the pH is high enough we even have precipitation, where the metal forms a solid layer right on the surface of our material.

This is rarely one of these things; most of the time we see the same mechanisms working together (Wang & Chen, 2009; Volesky, 2007). Now if you are trying to optimize this process in the lab, you almost always have a control knob in mind, and that is most often pH. With pH at low, the solution is filled with hydrogen ions. These guys are small and aggressive; they crowd the surface of your adsorbent and beat the metal ions to the punch, effectively blocking them out. As pH increases the adsorbent surface begins to lose those hydrogen ions (it deprotonates). This opens the door for the metal to come in. But you can’t push the pH up to that level. If you do, the metals form hydroxides and precipitate out of the solution. It just becomes very hard for any researcher to tell if the material is doing the work or the metal is just settling out of the water on its own. We have to deal with the “timeline” of the process beyond pH as well. Adsorption is not a quick solution.

You will usually see a quick burst of activity early on when the metal ions reach the easy, open spots on the outside of the material. Then the rate drops quite a bit as the ions have to move to the deeper, less accessible pores. Last but not least, capacity or efficiency. You can increase the initial metal concentration to increase the amount of metal in a gram of adsorbent (the capacity) but you’ll see the total removal rate drop because active “seats” fill quickly due to it. And for those doing this for real-world applications, it is important to recognize that wastewater isn’t a clean, single-metal solution. It’s a competitive environment. Other ions in the mix will fight for the same binding sites and they’ll often damage the performance you saw for it in your perfect lab tests. And if they do, it will be the same. That’s why it’s so important to push for more realistic experimental designs—because the “clean” science of a beaker doesn’t always survive the messy reality of wastewater.

VI. LOW-COST ADSORBENTS: THE GAP BETWEEN LAB HYPE AND PRACTICAL REALITY

The academic literature is certainly enthusiastic about low-cost adsorbents. And if you get into the research, it is easy to see why: studies in the literature primarily on agricultural waste or byproduct materials show that we can pull toxic metals such as lead, copper and cadmium out of water with little more than plant matter or waste biomass (Babel & Kurniawan, 2003; Sud et al., 2008; Bhatnagar & Sillanpää, 2010). Environmental science is now a “green” field and a high-output field because it is a “dirty” problem. But when you dig a little deeper, you find that this “promising” data has some qualifiers that aren’t always spoken about. The first hurdle is the "apples-to-oranges" problem.

The research team is dealing with a lot of variables (pH, particle size, treatment methods, but also mathematical models to fit the data) so it is not easy to compare material A and material B. A material might look like a superstar in one study just because conditions were perfect to suit it and not because it is a better material than material B. Secondly, there is a "clean water" bias. Most of these studies are based on single metal synthetic solutions. Industrial wastewater is a cocktail of chemicals in reality. With multiple competing ions added, the low-cost adsorbents don't do so well, and the lab's "success stories" may be a myth about what these materials can actually do in a real, crowded wastewater stream. And the literature is also very inaccurate when it comes to "life after adsorption." Scientists are interested in how much metal the material could contain, but they gloss over the less glamorous, but more vital questions: • Mechanical Integrity: Will the material hold up in a continuous flow system, or will it go bad and turn to mush in the filter? • Regeneration: Do we ever really get to see the material again and use it again, or does it go bad and become an all-hazardous waste product? • Scalability: How much waste material can be made to be used and does it stay cheap once it goes from a beaker to an industrial plant? If we want to take these materials from the pages of a journal to actual wastewater treatment plants, we have to change the way we look at them. A high uptake capacity in a one-off batch test is a good start, but it's not the end. We need to start thinking about hydraulic behavior, long-term regeneration and how these materials handle the gritty, competitive chemistry of real-world waste. Only through such concrete operational metrics can we make the promise of low-cost adsorbents a reality.

Bridging the Gap: Moving Adsorption from the Lab to the Plant

If we want to make adsorption a real laboratory concept rather than an industrial tool, we need to stop thinking about it from a vacuum. Most of our research is done in the "batch test" stage, but for a facility manager a flask of water is not so much an industrial influent stream as it is a source of water. To fill that gap, we need to look at the operation in the field—fixed-bed column design, adsorbent regeneration, and most importantly integration. It's incredibly difficult for a single technology to deal with a complex wastewater stream by itself. For instance, precipitation or filtration is usually better before the water gets deposited in the adsorbent bed to pull out bulk solids and high-concentration debris. By taking the heavy lifting out of the adsorbent, we keep it from clogging or saturating too quickly. Depending on the pollutant profile, adsorption could work best as a "polishing" process at the end of a process, or it could be mixed in with membrane separation or well-designed biological treatment to catch whatever slips through the cracks. And we also have to rethink our endgame. For so long, the goal was to get rid of the metal and move on. Now we're in resource recovery mode. Some of the heavy metals we want to get rid of have real commercial value, and if we can desorb and return such metals then we are not just managing a waste stream but part of a circular economy. And it is a huge win for facilities that want to reduce operational costs even more and yet still minimize the environmental impact. And finally we need to be real about sustainability, with more "big picture" accounting. A lot of people think that because a material is "low-cost" or "waste-derived" it is just green. That isn't always true. If harvesting, drying, chemically modifying, and eventually regenerating that material requires vast amounts of energy or toxic chemicals, then the "sustainability" argument will never hold. We need to make the techno-economic and life-cycle assessments (LCA) more transparent as we go forward. We need to show that all this process from the cradle to the grave is actually lighter than the old-fashioned methods that we're trying to replace. If we hold ourselves to those higher standards of efficiency and environmental accountability, then adsorption will indeed be accepted into the mainstream of the industrial world.

VI. CONCLUSION AND FUTURE PERSPECTIVES

Adsorption remains one of the most promising techniques to remove toxic heavy metal from contaminated industrial wastewater. Many practical advantages of the method remain intact. It is easy to use, flexible in design and effective for a wide range of metal concentrations. It can be applied with many different adsorbent materials including natural minerals, agricultural by-products, biosorbents, activated carbons and newer engineered materials. Low-cost adsorbents are being rapidly developed over the last couple of decades since they are a cheaper and more readily available option to wastewater treatment in the areas where advanced treatment systems are not available. However, even with these benefits it is very clear that much work needs to be done before many adsorption systems can be successfully applied on a large industrial scale.

Most of the work in the literature is based on laboratory studies using synthetic metal solutions. It is helpful to understand adsorption behavior, but it does not necessarily reflect the complexity of real industrial wastewater. Actual effluents frequently contain multiple competing ions, organic matter, suspended solids and pH variations, which can all reduce adsorption efficiency. Adsorbent regeneration, long term stability, metal recovery, and safe disposal of adsorbents need to be addressed in a more precise manner in order to be more practical and sustainable in adsorption. The next step in this field will be a combination of material development with realistic process design.

More studies should be conducted to test adsorbents in real wastewater environments as opposed to just in ideal laboratory settings. There will also be a need to make better comparisons between adsorbents in a realistic environment with standardized experimental conditions. Such comparisons would make it easier to find the most effective and economically viable materials for regeneration. Regeneration processes that are efficient, cheap and ecologically friendly should also be given more attention. In the next few years, the most promising direction is to develop multifunctional and sustainable adsorbents.

These materials could include modified biochars, magnetic composite adsorbents, hybrid biosorbents, and materials made from industrial or agricultural waste. As such, adsorption could increase adsorption capacity and also improve waste reuse and circular economy. Meanwhile, adsorption should be studied as part of integrated treatment systems for better overall efficiency as it can be integrated with membrane processes, precipitation, electrochemical treatment and biological processes. Adsorption is in general a very strong technology in heavy metal wastewater treatment. It will no doubt be successful in the future only if it is able to show strong adsorption capacity, but it will also be dependent on its practical performance, cost effectiveness, environmental safety and scalability. With more realistic assessment and more process integration, adsorption can be a real solution for clean water and for better industrial operation and the environment.

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