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REVIEW

Low-cost Adsorbents: Review on Current Trends and Developments

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ABSTRACT

Pollution from human activities causes water contamination that impacts aquatic ecosystems and threatens public health while endangering environmental sustainability. This highlights the need for water restoration and biodiversity protection using indigenous, low-cost, and sustainable technologies. Adsorbents currently used in wastewater remediation are evolving from traditional materials to more cost-effective options. This study is focused on tracking advancements and the evolution of adsorbents while maintaining ecological sustainability, and to identify gaps requiring further research. The review consolidated the ongoing work on adsorbents collected from Google Scholar and dated 2020-2025 to evaluate emerging trends and developments in low-cost adsorbents. The evolution of these materials demonstrates remarkable adaptability and multi-functionality, enabling low-cost adsorbents to address a wide range of water quality issues efficiently; however, there is a need to maintain minimal environmental impact. Multifunctional adsorbents derived from biomaterials, nanotechnology, and stimuli-responsive materials show promising potential for simultaneous removal of multiple pollutants. These adsorbents also facilitate tailored recycling and secondary applications of exhausted materials, thereby reducing secondary pollution. The integration of biomaterials, nanotechnology, and stimuli-responsiveness marks a significant advancement in creating more versatile and effective wastewater treatment technologies capable of tackling diverse challenges. Their notable features—such as high surface area for adsorption, responsiveness to environmental stimuli, and photocatalytic abilities—enable low-cost adsorbents to effectively eliminate pathogens, as well as organic and inorganic contaminants from wastewater. The study highlights

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current challenges related to real-world pilot studies, secondary pollution, and scaling up. It concludes that integrating low-cost adsorbents with enabling technologies can be the key to their successful deployment in practical pilot settings that are easy to scale up, ultimately supporting ecosystem health and enhancing ecological resilience.

Keywords: Low-cost Adsorbents; Environmental Remediation; Wastewater Remediation; Ecosystem Restoration; Water Quality Maintenance; Aquatic Systems Protection; Ecological Sustainability

1. Introduction

Pollution due to anthropogenic sources leads to water contamination that affects aquatic ecosystems and threatens public health while compromising environmental sustainability. This calls for water restoration and biodiversity protection through indigenous technologies that are low-cost and sustainable. Adsorbents that are currently applied in the field of adsorption for wastewater remediation are evolving from conventional to cost-effective adsorbents. Tracing these developments is important to avoid reinventing the wheel and to ensure that gaps for further research can be identified. This study will focus on evaluating articles on low-cost adsorbents for wastewater treatment plants. It will only include studies published between 2020 and 2025, retrieved from Google Scholar using keywords: low-cost adsorbents in removal of pollutants, low-cost adsorbents in remediation studies, low-cost adsorbents in environmental remediation, low-cost studies for removal of pollutants, low-cost adsorbents review paper, and challenges in low-cost adsorbents. Only articles on the removal of pollutants from water and wastewater will be considered, unless an article had some information relevant to the study. Cross-references were checked from the available articles as well. The study will identify trends in low-cost adsorbents as well as new developments in matters related to low-cost adsorbents' applications in wastewater treatment plants. The study will critically highlight areas of ecological concern as trends and developments evolve in low-cost adsorbents. The study will end by identifying areas for further research to make low-cost adsorbents applicable in real settings.

2. Water Quality Maintenance and Sustainable Development Goals

Aquatic ecosystems are significant in fostering different forms of life [1]. However, the pollution of freshwater ecosystems is rising due to anthropogenic activities, thereby leading to disastrous decreases in freshwater biodiversity and threatening public health. Wetlands are also threatened by these human activities, and freshwater species are now faced with extinction. The main causes of deteriorating freshwater biodiversity include loss of habitats, inconsistent water quality due to pollution and climate change, among others [1]. Inadequate management of liquid waste affects water quality greatly. To achieve the Sustainable Development Goals (SDG) 6.3, 3 and 12 on access to safe water for good health and wellbeing, indigenous technologies that are low-cost, produced and consumed responsibly must be invented to reduce the proportion of untreated wastewater discharged into the environment, thereby compromising biodiversity, public health, and environmental sustainability [2–5].

Toxic substances have diverse sources of origin and are mostly carried into wastewater treatment plants for removal before the effluent is discharged back into the environment. Examples of such toxic substances are microorganisms, organic, inorganic, and emerging pollutants. If this wastewater is released untreated into the environment the hazardous constituents can affect both the ecological sustainability and the public health [5].

Diverse types of wastewater contain different types of pollutants, each with associated problems. Municipal wastewater is a type of wastewater mainly from toilets, showers and bathrooms, kitchen sinks, and washing machines in residential areas and commercial organizations that contains pathogenic organisms, organic matter, suspended organic matter, nutrients (predominantly nitrogen and phosphorus), and many other household chemicals. Dyes from textile, paint, cosmetics, plastics, paper, leather, and food industries are produced in tons worldwide and form the constituents of wastewater. If waste from these industries is not properly treated, it may be discharged into the environment, posing adverse effects on both humans and animals, causing toxicity, carcinogenicity, and mutagenicity [6,7]. There are increased levels of both trace and toxic metals due to storm runoff, leachate, and industrial wastewaters, with a tendency to cause diseases that harm the kidneys, heart, memory, liver, skin, eyes, gastrointestinal tract, and the central nervous system [7,8]. The emerging pollutants like hormones, pharmaceuticals, pesticide residues, fertilizers, and personal care products are also found in wastewaters, most of which are potentially hazardous enough to disrupt aquatic life and cause non-communicable diseases, as shown in **Figure 1** [9–11].

Pollutants originate from point and non-point sources. Point source pollutants come from one source, whereas non-point source pollutants are derived from diverse sources. Examples of different sources of wastewater are presented in **Figure 2** [9].

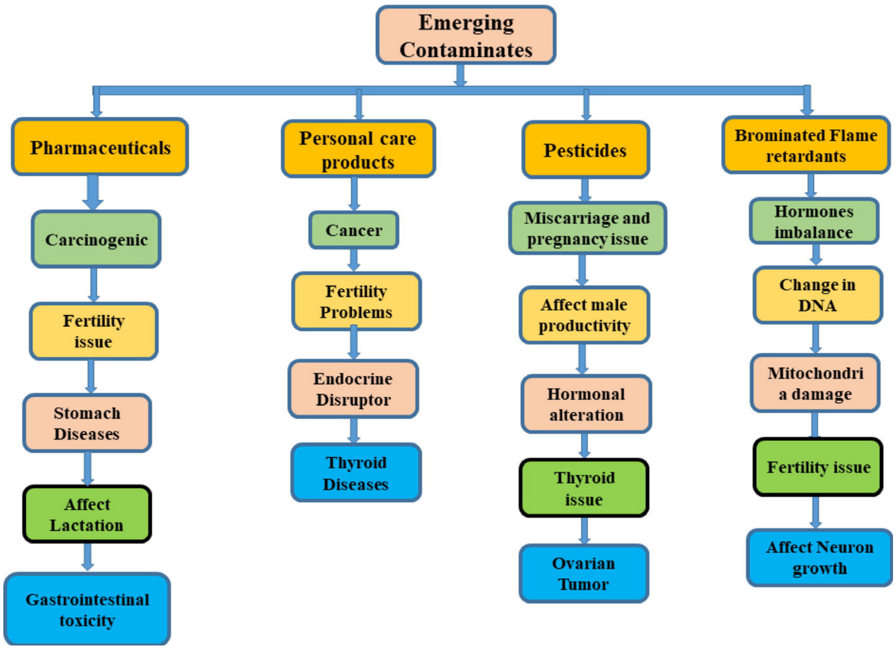

Figure 1. A variety of diseases due to emerging contaminants [11].

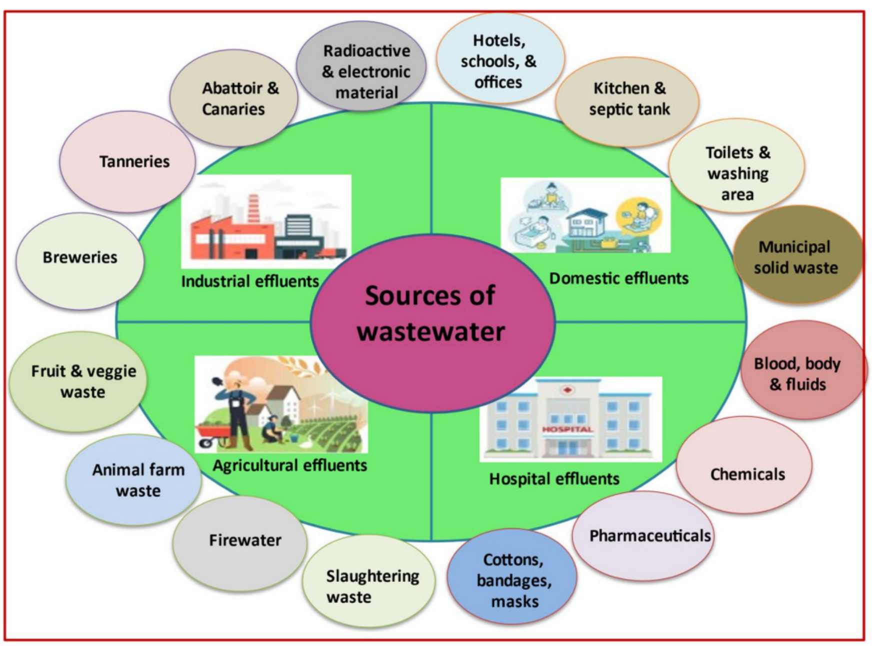

Figure 2. Schematic presentation of wastewater [9].

2.1. Wastewater Treatment Plants and Remedial Technologies

Wastewater is collected through sewer systems into wastewater treatment plants for removal of impurities through pre-treatment, primary, secondary, and tertiary stages. In wastewater treatment plants, pollutants are removed using different techniques. The conventional and advanced techniques include physico-chemical and biological methods, and examples according to Rashid et al. (2021) are illustrated in **Figure 3**; these are coagulation/flocculation, membrane filtration, adsorption, advanced oxidation, ozonation, enzymes, and microbes [12].

Homaeigohar (2020), in his study on "The Nanosized Dye Adsorbents for Water Treatment," summarizes what is shown in **Figure 3**. He states that amongst the main techniques employed in wastewater treatment, namely coagulation, flocculation, biodegradation, adsorption, ion-exchange, and advanced oxidation, adsorption is the most favorable since it can remove diverse kinds of pollutants, thereby making adsorption both energy and cost-effective [6,12]. Other authors argue that adsorption supports the circular economy, enabling repair, reuse, and recycling of the adsorbent [13].

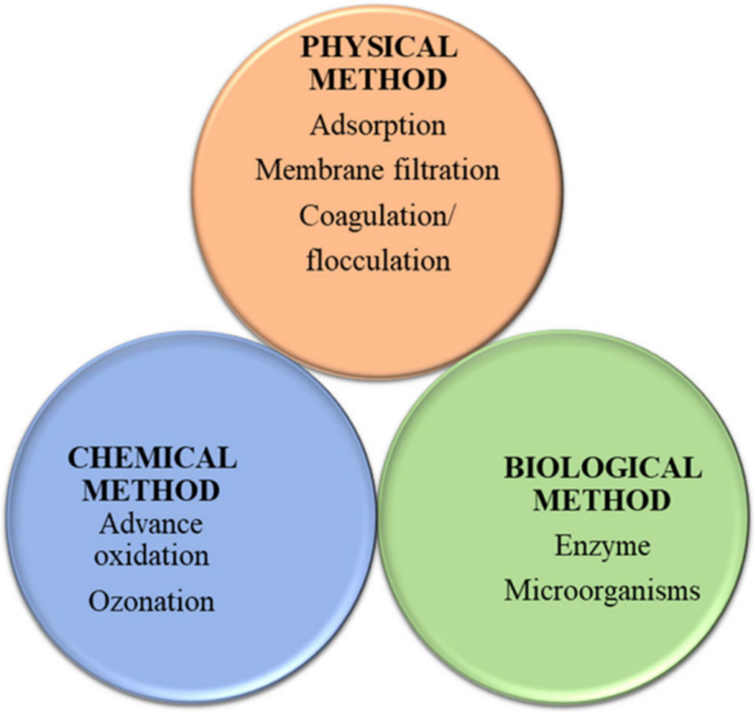

Figure 3. Conventional and advanced techniques used for wastewater treatment [12].

2.1.1. Types of Adsorbents

From the literature, there are diverse ways in which adsorbents are made and from what they are made, resulting in several types of adsorbents. Examples of such types are activated carbon, natural adsorbents, synthetic adsorbents, industrial by-products and solid waste, nano(ad)sorbents, emerging adsorbents, and hybrid systems.

a. Activated Carbon is the Conventional Adsorbent

The use of carbon for water treatment is historical, with ancient Indians and Egyptians; nevertheless, the commercial activated carbons were patented by Raphael von Ostrejko, filed in 1900 and 1901. Commercial activated carbons, also known as charcoal, although effective, are relatively expensive. Activated carbon has since been the mainstream adsorbent dominating the market. However, low-income countries find it expensive. Low-cost adsorbents, which are made from carbon precursors obtained from locally available materials, are alternatives to this activated carbon that is widely used to remove contaminants from polluted bodies of water [14]. Other authors note that non-conventional adsorption techniques for wastewater treatment are better in performance, and higher efficiencies compared to other conventional methods [15,16].

The surface integrity of activated carbon has stood the test of time minimizing secondary contamination of ecological systems and habitats. Exhausted activated carbon is generally disposed of landfills as the mainstream form of disposal. However, leaching might still occur contaminating underground water.

b. Natural Adsorbents

These are sustainable and cost-effective adsorbents made from materials of natural origin. They can be of plant, mineral, or microbial (biomass) origin. Examples are agricultural, wood, leaves, manure, and tree roots wastes, natural polymers, cellulose, biochar, sawdust, zeolites, soils, rocks, clays, iron oxide, microalgae, bacteria, and animal waste [17–19]. Biomass is sometimes used to describe organic material or microbial biomass, or fungi [20]. These adsorbents of natural origin are prepared and modified to remove pollutants from wastewater. Bilal et al. (2022) reported that some can be used untreated. However, pore clogging is the main challenge facing unmodified natural adsorbents. They can remove organic and inorganic contaminants such as biopharmaceuticals, heavy metals, pesticides, and pentachlorophenol from effluent waters [7].

The natural adsorbents obtained from biological origins are called biosorbents. Biosorbents are considered ecologically sustainable as they are renewable. Renewable adsorbents are those that can be replaced as quickly as they are consumed. Biosorbent materials can be divided according to sources of origin, like wood-based, herbaceous-based, crop-based, biomass-based, and animal waste-based biosorbents [21]. **Figure 4** summarizes these categories. However, one noted disadvantage of biosorbents is that they are susceptible to biodegradation, which raises concerns about their surface stability and is likely to cause secondary pollution in ecological systems.

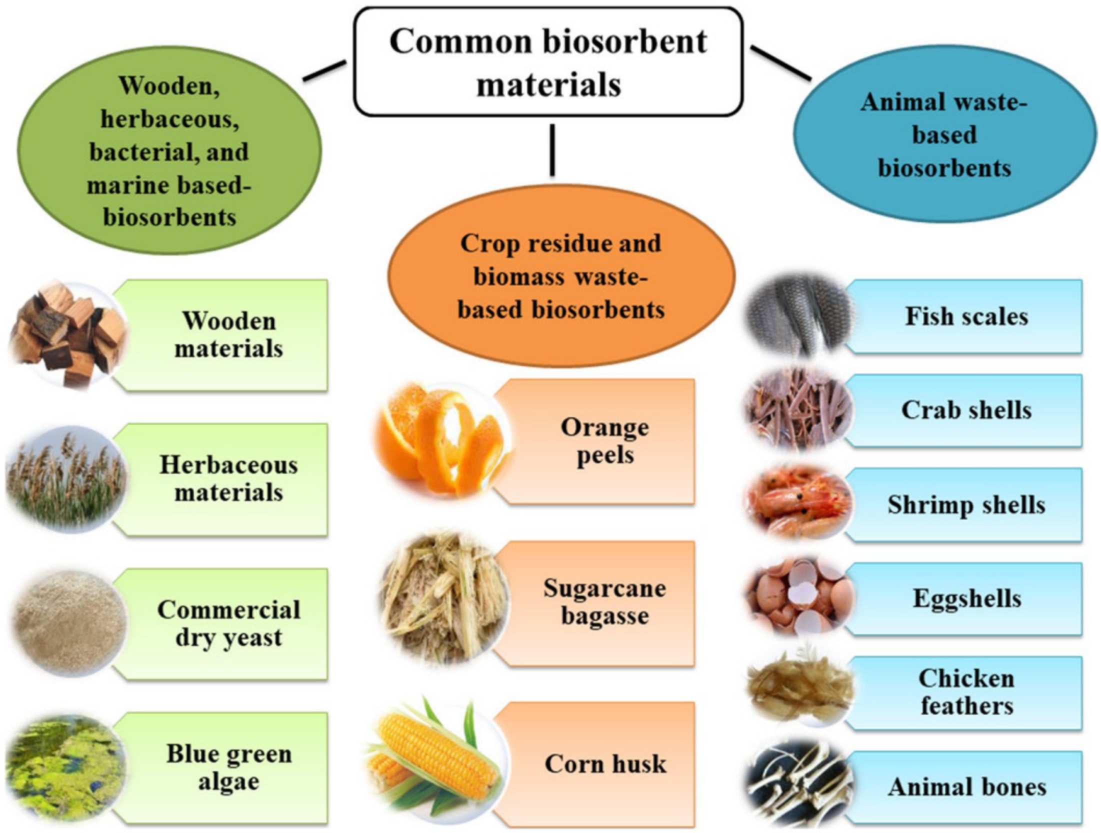

Figure 4. Categorization of common biosorbent materials [21].

c. Synthetic Adsorbents

These are adsorbents derived from man-made materials. Examples are silica gel, metal oxides, and polymers [14]. Pollution from byproducts, side reactions, and unreacted reagents used during the synthesis of these adsorbents is of ecological concern.

d. Industrial By-products and Solid Waste

Industrial by-products are wastes from the industries that can be used to make low-cost adsorbents for decontaminating wastewater. Industrial wastes are helpful in that they are low-cost and readily available, and are a form of waste management for ecological sustainability, but still need more research to understand their application. Examples of such industrial wastes are blast furnace slag (BFS) and red mud [22]. They remove pollutants such as pharmaceutical pollutants, Cu (II), and U (VI) [23–25].

e. Nano(ad)sorbents

Nanomaterials are adsorbents made from substances less than 100 nm in diameter. They can be made from both natural and synthetic sources. There are two ways of synthesizing them: "bottom up" and "top down". Bottom-up methods involve assembling atoms, and "top-up" involves breaking down solids into finer particles to an atom's level [25]. The synthesis of nanomaterials can also be conventional (traditional) or non-conventional. Conventional methods use physical or chemical means of production. In these methods, hazardous chemicals and extremely high temperatures are employed; thus, they are of ecological concern. In non-conventional methods, green nanotechnology that involves low-cost, safe, and environmentally friendly processes is employed. In green methods of producing nanoparticles and their derivatives, plant extracts or components serve as reducing, capping, and stabilizing agents [25]. However, surface stability, leaching of unreacted nanoparticles and disposal of used-up nanosorbents remains an environmental, ecological and public health threat.

Nanomaterials that play a significant role in wastewater treatment by adsorption of pollutants are termed nanosorbents. They provide opportunities for higher efficiency in removing pollutants in a low-cost, simple, and environmentally acceptable way. Examples of biosynthesized nanomaterials that are used in water pollution control are biopolymer-coated metal nanoparticles, zinc oxide nanoparticles, and silver nanoparticles [25].

Homaeigohar (2020), a strong advocate for nanosorbents, argues that the agricultural waste-derived adsorbents are inexpensive and that they have earned research interest in a significant way [6]. However, he notes that despite their promising applicability in environmental remediation, they are used as microparticles [6]. This surface area at the micro-level seems to give a slower adsorption process than the nano-level size, he argues. He further shows that application of biosorbents poses significant challenges for industrial applications and therefore recommends nano-sized adsorbents whose production is both fast and low-cost at a large scale [6].

From the literature, there is evidence of hybrid adsorbents in which biosorbents are functionalized with metal oxides and/or reduced to a nano size to enhance adsorption. The use of plant extracts with polyphenols that "serve as reducing, capping, and stabilizing agents" can increase the environmental friendliness of the nanosorbents [25]. In their study on a review of the synergic effect of plant extracts on nanomaterials for the removal of metals in industrial effluents, whereby titanium dioxide nanoparticles were synthesized by different plant extracts for wastewater treatment, Vishnu and Dhandapani (2021) found that metal oxide nanoparticles portray increased stability, magnetic inertness, and optical and electrical properties. They also noted that some nanomaterials that were applicable in medical applications are also applicable in adsorption. The duo concluded their study by narrating that integrating plant extract with metal/metal oxide nanoparticles seems to be efficient in specific reactivity for the elimination of organic and inorganic pollutants from the industrial wastewater [26].

Combination of biomaterials and nanomaterials with anti-microbial activity is likely to overcome the problem of biodegradation in biosorbents. Nanomaterials made from polyphenolic compounds and flavonoids can enhance their effectiveness in the removal of pollutants from the environment with added antimicrobial properties and reduced surface degradation, thereby safeguarding the natural ecosystems.

f. Emerging Adsorbents

Other adsorbents have been developed but are only starting to be relevant recently. Examples include stimuli-responsive materials like metal–organic frameworks, polymers, polysaccharide/stimuli-responsive polymer composites, and composite materials, and magnetic sorbents for water treatment. Stimuli-responsive materials are adsorbents that respond to stimuli like light, pH, and moisture [21,27]. They are unique in their ways of recovery and regeneration that include "magnetic separation, pH and gas responsiveness, thermal and light activation" [27]. However, much remains to be established about these emerging adsorbents before their real-setting application can be rolled out. Their methods of syntheses are rather complex involving many reagents with stability that is not established. Therefore, further research is required to finally apply these emerging adsorbents in real-setting, and during the course of their investigation it is important to take precautions to protect the ecosystems, environment, and public health.

g. Hybrid Systems

Another recommended type of adsorbents is hybrid systems. Hybrid systems are materials in which adsorbents are combined with other materials, such as metal oxides, polymers, and nanoparticles, to diversify their functionality [27]. Multifunctional adsorbents are adsorbents that are afforded the ability to perform distinct functions in water treatment issues. They however are characterized by complex synthesis made of composites of various kinds. They are evolving with extraordinary capacity to remove diverse types of pollutants from wastewater even at minute concentrations, yet with extraordinary ecological, environmental, and public health risks [28].

2.1.2. Arguments and Debates on Low-cost Adsorbents in the Last Decade

There is notable progress in the last decade of adsorption research in areas such as nanotechnology, biosorbents, and functionalised adsorbents for multiple pollutants. However, there are concerns as well.

a) Nanotechnology and Adsorption

One notable progress is a breakthrough in the fabrication and application of nano-adsorbents in the field of nanotechnology. This breakthrough comes with merits such as higher surface area and the ability to be functionalized to increase specificity and affinity for target pollutants. Examples include metal oxides, zeolites, magnetic nanoparticles, and metal-organic frameworks [14]. These innovations have improved specificity, reusability, and precise removal of pollutants such as heavy metals, organic compounds, pharmaceutical pollutants, and hormone disruptors [12].

However, there are still challenges in real-world practical application, reusability, adsorbent stability, and safe disposal of exhausted nanosorbents. Although carbon-based adsorbent nanocomposites are applicable for use in wastewater treatment of contaminants, and although their nano-size may increase surface area, it is claimed that their tiny size "enhances toxicity as well" and bioaccumulation in host and predator is highly likely [29,30]. It is also highlighted that synthesis of nano-adsorbents can be both complex and costly, with uncertainties regarding their stability and potential impact on the environment [14].

b) Biosorbents

Biosorbents are currently receiving much attention in research. In their study on wastewater treatment techniques Rashid et al. (2021) point out that agricultural waste is considered to be one of the best alternatives because of its low-cost and high adsorption efficiency, noting that these materials are inexpensive, environmentally friendly, and viable for use to remove dyes and heavy metals from the aqueous systems due to their unique chemical composition, abundant availability, and renewable nature [7,8,12]. Other authors argue that biosorption is now the dominant process even in methods of pathogen removal in bioreactors using adsorbents like biochar [9,31]. The biological materials are abundantly available, exhibit notable structural differences, and contain various ligands in their structure. These make biosorbents potential removers of a diverse range of pollutants, thereby making them strong alternatives to conventional adsorbents [21].

c) Functionalised Adsorbents for Multiple Pollutant Removal

In recent studies, it has been found that carbon precursors can be functionalized to obtain multiple properties. Chua et al. (2021), in their study on the emergence of multifunctional adsorbents, claim that multifunctional adsorbents remove multiple pollutants simultaneously, as shown in **Figure 5**. This route is promising since it overcomes a challenge of wastewater composition in which pollutants exist in combinations, and a challenge of combined desorption [28]. An example of such functionalized adsorbents is a magnetized adsorbent that is expected to desorb the magnetic adsorbates by applying a magnetic field of a higher strength [21].

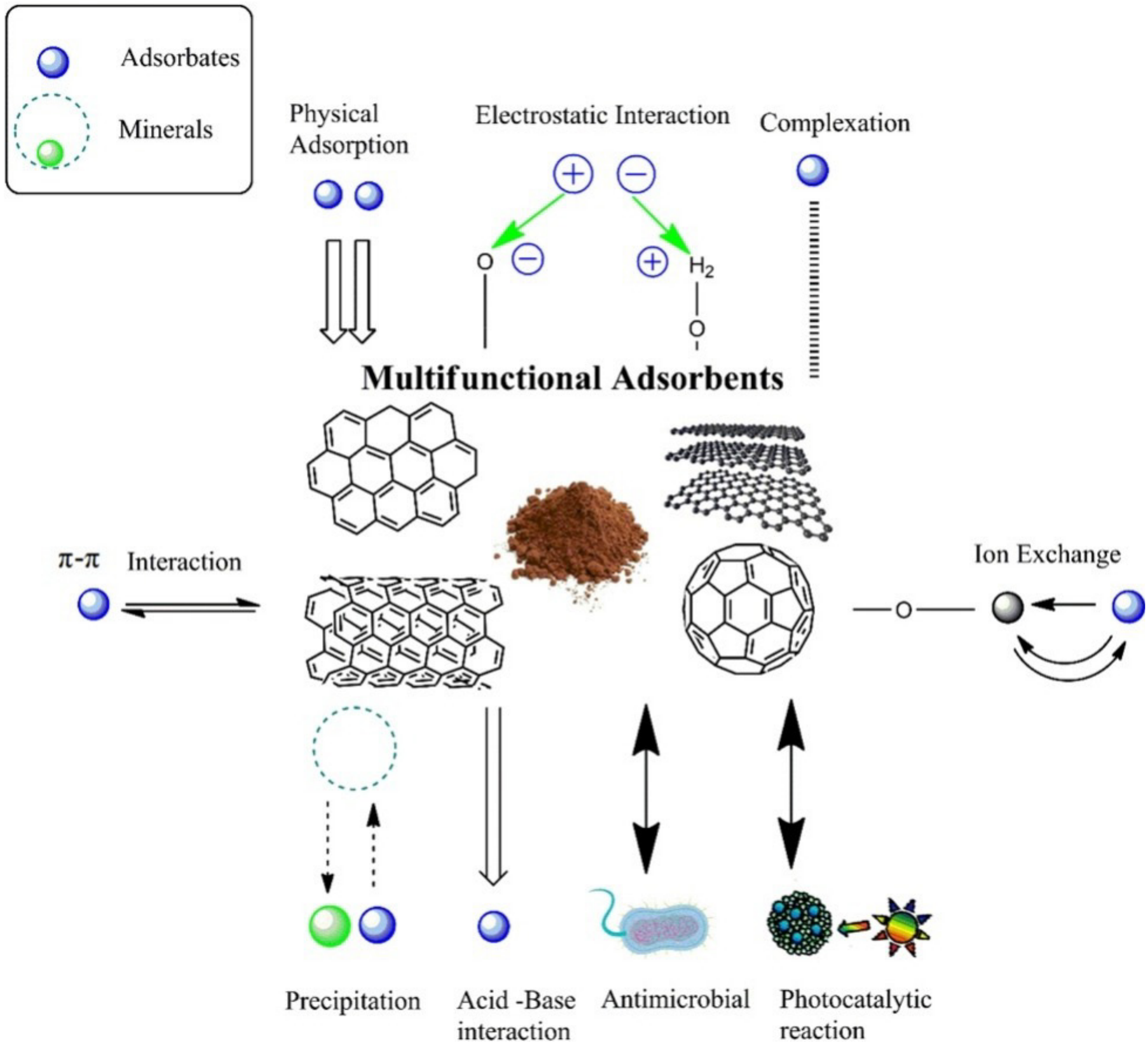

Figure 5. Multifunctional adsorbents [28].

3. The Principle of Adsorption

In the adsorption process, target substances adhere to a modified solid surface. The surface onto which the substance sticks is called the adsorbent, while the adhered substance is called the adsorbate. The adsorbed species are bound to the adsorbent through physicochemical interactions, as shown in **Figure 6** [12,32,33].

Carbon precursors, which are substances with high carbon content forming their structural backbone, are considered reliable sources of low-cost adsorbents. Examples of such carbon precursors are wood, coal, cellulose, agricultural waste/biomass, coconut shells, and lignite [34]. These low-cost adsorbents can be modified by different methods of activation to increase the potential of functional groups such as chlorine, oxygen, nitrogen, sulfur, and hydrogen, thereby increasing the adsorption capacity of adsorbents, resulting in high affinity for the organic or inorganic pollutants. Activation also increases the surface area for sorption through pores, as shown in **Figure 7** [12,34,35].

Activation alters the physicochemical properties of the resulting low-cost adsorbent, as shown in **Figure 8**, thereby increasing its affinity and ability to sorb pollutants. The choice of activating agents will leave the surface of the adsorbent positively charged to sorb anions or negatively charged to sorb cations.

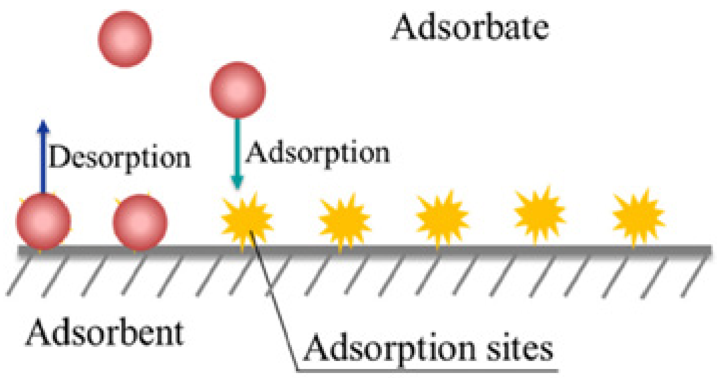

Figure 6. The adsorption process by adsorbent and adsorbate [32].

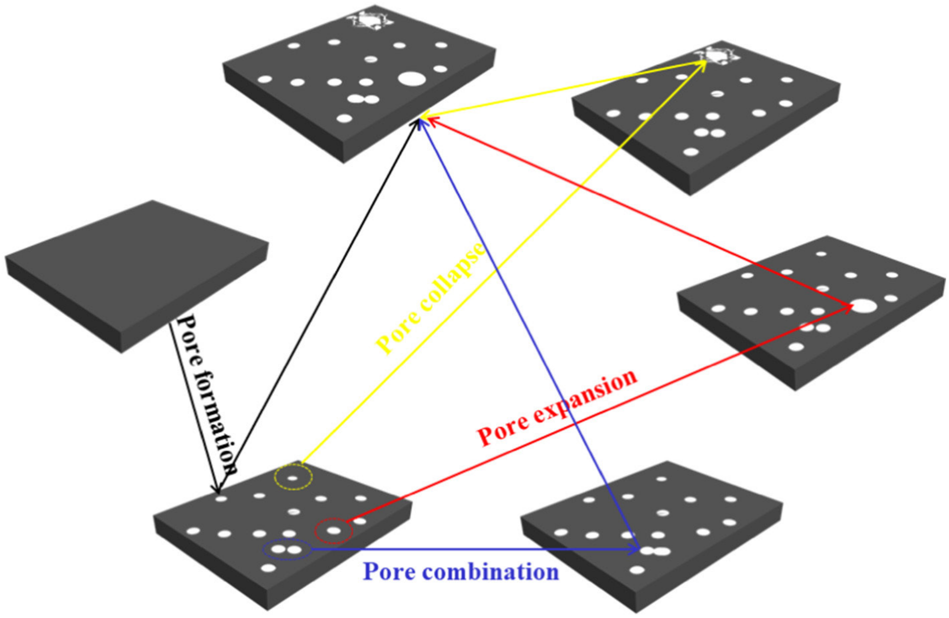

Figure 7. Formation of porous adsorbent through chemical activation [35].

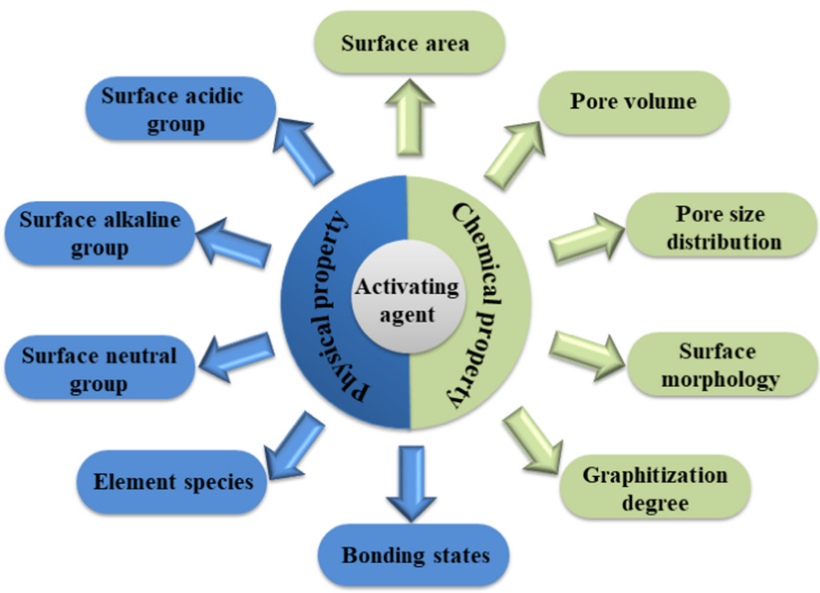

Figure 8. Effect of activating agent on physicochemical property of resultant carbons [35].

3.1. Steps in Carbon Precursor Surface Activation

3.1.1. Pretreatment

The preparation of the activated carbon precursors involves pre-treatment steps which are then followed by activation. Examples of such pre-treatment steps are additional washing to remove impurities, drying at ≈100 °C for a defined period to remove free moisture in the material, which could affect the carbonization step [34]. Milling and sieving of the carbon precursors to obtain a defined standardized starting material is another preparation step [34].

3.1.2. Surface Activation

Examples of methods of activation to modify the surface chemistry and surface area of carbon precursors are listed in **Table 1**.

Rehman et al. (2019) report what happens during carbonization (activation of carbon precursors), moisture and volatile compounds escape, leaving behind char. Physical or chemical activation methods can further be applied to generate highly porous activated carbons. They confirm that these low-cost adsorbents have been widely studied as effective adsorbents due to their porous structure, and enriched surface chemistry with the highly reactive surface sites [36].

Devi et al. (2021), in their study on “Modification techniques to improve the capacitive performance of biocarbon materials”, define activation as the introduction of high surface area as well as well-organized pore structure and functional groups into a carbon skeleton using activation agents [37]. They highlight that the properties of the carbon materials, such as surface area and functional properties, can also be improved by controlling the different processing parameters, such as activation temperature, duration, environment, and biomass/biocarbon to reagent ratio [37]. They therefore classify activation processes into physical, chemical, physicochemical, and microwave-assisted activation based on these conditions.

The most common activation methods are physical/thermal and chemical, as shown in **Figure 9** and described below.

Table 1. Examples of methods of activation for carbon precursors.

Physical Methods	Thermal Methods	Chemical Methods	Composite Formation
Microwave, ultrasonic, mechanical	Pyrolysis, carbonization, steam activation	Acid, alkali, oxidation, green nanotechnology	Combining low-cost adsorbents with other materials

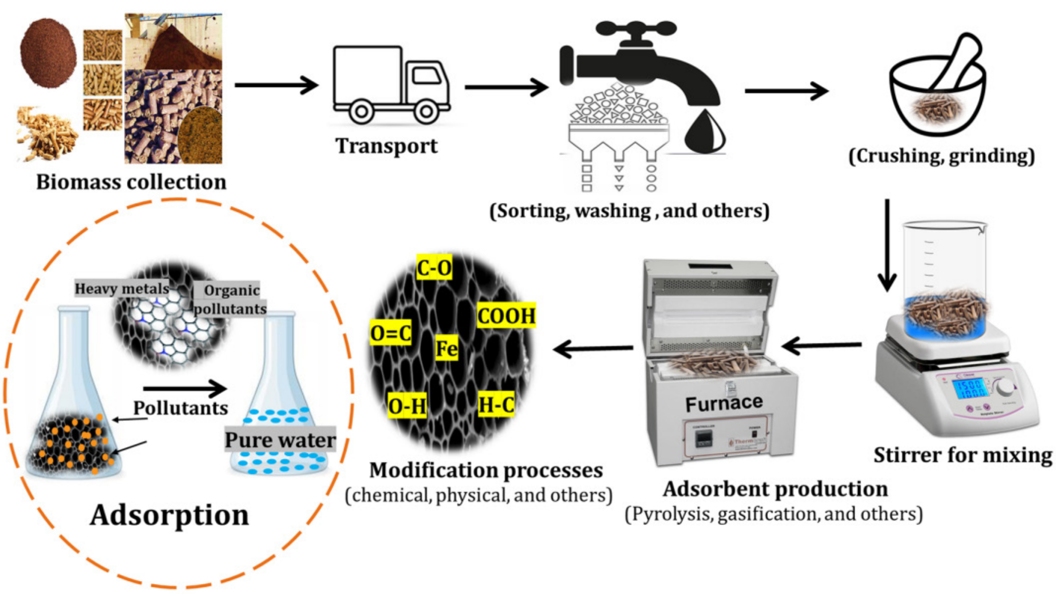

Figure 9. Biosorbents from synthesis to application [21].

3.1.3. Examples of Surface Ctivation Methods

i) Physical/Thermal Activation

Devi et al. (2021) describe physical and thermal activation as being synonymous. They argue that it is a simple, yet economical and environmentally friendly approach to modify surface functional groups, hydrophobicity, and polarity of carbon precursors, and this includes low-cost adsorbents. Physical activation is a two-step process involving carbonisation and activation. Carbonization is achieved under an inert atmosphere (N_2 and Ar), while activation is achieved through oxidising gases such as steam, carbon dioxide (CO_2), and at temperatures between 700 °C and 1100 °C [37]. Gao et al. (2020) concur and summarise physical activation as a two-stage process using an inert gas (N_2 or Ar) followed by the activation (O_2, CO_2, H_2O steam) at temperatures ranging between 800–1200 °C [35].

During physical activation, inaccessible and new pores are developed resulting from burning away the trapped reactive products and from selective oxidation. There is also the widening of the intrinsic pores of the carbon skeleton [37]. Gases such as CO, CO_2, H_2, or CH_4 are burnt off and evolved, and this controlled burn-off is important in porosity development. On the other hand, porosity development is greatly dependent on the nature of the precursor, activation gas used, flow rate, activation temperature, and duration of activation [37]. Devi et al. (2021) divide types of physical activation processes into three:

1. CO_2 activation, in which CO is burnt off and evolved [37].
2. Steam activation (normally combined with pyrolysis). It is a common activation approach since it is easily available, low-cost, and can produce high oxygen-containing surface functional groups. The reactions are as follows [37].
   $C + H_2O \rightarrow CO + H_2$
   $CO + H_2O \rightarrow CO_2 + H_2$

It is noted that steam is more reactive than CO_2, and therefore requires a lower activation temperature, resulting in a large volume of meso/macro pore formation.

3. Air (or oxygen) has also been used at a lower activation temperature (< 500°C). It has very high reactivity with carbon. This also requires low activation energy and cost. It is, however, difficult to control the reaction, and excessive burn-off is possible [37].

Although physical activation of carbon precursor materials results in relatively cheaper adsorbents with good physical strength and reduced surface degradability, their economic value can only be significant if the waste material such as industrial waste or agricultural waste are used as carbon precursors since this will significantly promote circular economy. If natural resources are used without being replaced, then the evolution is environmentally costly. Another issue of concern is the high consumption of energy (high activation temperatures) for a considerable amount of time with a low yield that is associated with the use of physical activation, making it economically unviable. Possible emission of greenhouse gases and toxic fumes also poses ecological concern. However, the fact that physical activation is applicable on a commercial scale makes physical activation viable for large scale synthesis of low-cost adsorbents [37].

ii) Chemical Activation

In their study titled "Insight into activated carbon from different kinds of chemical activating agents: A review", Gao et al. (2020) say chemical activation is also known as wet oxidation. While in other studies, chemical activation is called chemical modification [20,35]. It is a one-step process in which carbonization and activation take place simultaneously at temperatures around 450–850°C [35]. It involves the application of chemical reagents to modify the surface chemistry of a carbon precursor by porosity development. Chemical activation includes treatments like impregnation, grafting, and coating of chemicals on the surface of the adsorbent [14]. Chemical modification may induce degradation, dehydration, and complexation reactions on the surface of a low-cost adsorbent [14,37]. Chemical activation is advantageous in that it requires a low heating temperature, short processing time to give a high carbon yield, well-controlled porosity, high specific surface area charge, and hydrophobicity [35]. However, chemical activation causes corrosivity and necessitates extensive washing. Devi et al. also emphasize the importance of post-activation washing to remove intercalated chemicals [37].

Physical treatment is limited for remediation of dyes, but chemical treatment, which uses chemicals such as acids, bases, organic solvents, surfactants, chelating agents, and other compounds, not only increases the surface area of biosorbents, but also activates the available pore sites while introducing new surface functional groups [38,39]. The added functional groups increase the affinity of the adsorbent for the adsorbates and help in binding the dye molecules, resulting in enhanced adsorption potential.

Examples of activating agents include bases "such as potassium hydroxide (KOH), sodium hydroxide (NaOH) and potassium carbonate (K_2CO_3); acids such as phosphoric acid (H_3PO_4), nitric acid (HNO_3) and sulphuric acid (H_2SO_4); and transition metal salts like zinc chloride ($ZnCl_2$) and calcium chloride ($CaCl_2$)" [37]. Examples of surface functional groups that can be added on the low-cost adsorbent are carboxyl, hydroxyl, sulphonic acid, primary and secondary amine and amides, olefinic, methylene groups, and C-O bonds [7].

Unless chemical activation agents used in synthesis of adsorbents are of low toxicity with lower concentrations and reduced volumes, the environmental and economic impact of such activation processes remains questionable. It is also in the interest of eco-friendliness that activating chemicals are recovered or neutralized to minimize ecosystem contamination.

iii) Thermochemical Activation

This modification is a simultaneous heat and chemical treatment to enhance the adsorbents with much lower adsorption potential. An adsorbent derived from *Sapindus mukorossi* (reetha) bio-waste (RBW), involved treatment with 0.1 M H_2SO_4 at room temperature (rtp) for 4 h in a mass ratio of 1:1, resulting in a chemically modified biomass [7].

3.2. Surface Activation, Selectivity and Non-specificity

For low-cost adsorbents to be sustainable, researchers should target activation that yields selectivity and prohibits non-specificity [14]. This is mostly desirable if the pollutant is to be recovered for reuse. Selectivity depends on several factors, such as adsorbent physicochemical properties, like functional groups on the surface, pore size and distribution, molecular shape and size of adsorbent, polarity, and charge. Also, selectivity is very much dependent on adsorption operating factors like pH, temperature, and ionic strength (initial concentration) [14].

3.2.1. Selectivity through Optimization

Selectivity that maximizes adsorption and minimizes competition on the binding sites between organic molecules and water (polar) molecules is called selectivity by optimization. Selectivity also minimizes the competitive adsorption effect resulting from a variety of adsorbate species competing for limited binding sites on the adsorbent, especially when the initial concentration of the adsorbates in solution increases [14]. In this case, selectivity can be achieved through optimization—finding optimum conditions for maximum adsorption of individual adsorbates on the adsorbent within the shortest possible time.

3.2.2. Selectivity through Surface Functionalization

Through the years, activation involving a combination of methods has evolved. This is called multifunctional activation. Multifunctional activation results in adsorbents that can remove various categories of contaminants in wastewater due to multiple functionalities [27]. They can remove different types of pollutants (organic, heavy metals, inorganic, or emerging pollutants) or ions of different charges of pollutants of the same molecular species (anion or cation) by a single treatment. Multifunctionalization affords adsorbents with different surface functional groups. Magnetization, for example, involves magnet-responsive composites. The resulting adsorbent is highly efficient, with better adsorption, desorption capacity, and selectivity [28]. When optimizing spent adsorbents, specificity can be achieved through targeted research during design. This can be achieved through specific targeting [27].

Multifunctionalized adsorbents are adsorbents made from materials such as metal oxides, polymers, and nanoparticles to produce adsorbents with multiple functions to adsorb diverse pollutants [27]. This gives the resulting hybrid adsorbents with selectivity towards pollutants. They may have antibacterial properties, photocatalytic functions, and oil/water separation properties. Examples of multi-functional adsorbents, some of which are listed in **Table 2**, are magnetic microspheres, graphene, polymer-based aerogel, and hydrogel, and they are very suitable for wastewater with a complex mixture of adsorbents. They can be carbon-based, carbon nanomaterial-based, polymer-based, and inorganic-based [28].

Table 2. Types of carbon-based multifunctional adsorbents with adsorbate, adsorption mechanism, and additional functions [28].

Adsorbent	Adsorbate	Adsorption Mechanism	Additional Functions
Iron oxide modified-clay-Ac beads	Pb^{2+} Cd^{2+} AsO_4^{3-}	-Electrostatic attraction, ion exchange -Electrostatic attraction, inner sphere complexes -Electrostatic attraction	-
ACC	Cd^{2+} Phenol	-Electrostatic attraction -π-π interaction	-
IONPACs	BPA NOM	-Hydrogen bonding, surface coordination, (phenolic group) -Surface coordination (carboxyl group)	-
SnO_2-NPs-AC-MnO_2-NPs	Pb^{2+}, Cd^{2+}, Cu^{2+} $Pb^{2+,}$ Cr^{4+}	-Electrostatic attraction -Electrostatic attraction	-
Halloysite nano-tube@carbon	MB	-Chemical interaction (Cr (III) and carboxyl group -Electrostatic interaction, π-π interaction	-
MMIC-Fe (III)	TC Cd^{2+} MB	-Electrostatic attraction, chelation, complexation reaction -Electrostatic attraction, formation of ternary complexation -Ion-dipole interaction, hydrogen bonding, electrostatic attraction	-
ZnONPs-PWAC	MB	-Ion-dipole interaction, hydrogen bonding, electrostatic attraction	-
TNTs@ACF	Cr^{4+} Cd^{2+}	-Ion-dipole interaction hydrogen bonding, electrostatic attraction -Electrostatic attraction	Photocatalysis
KOH-CSs	Cd^{2+} CR	-Electrostatic attraction	Photocatalysis
C-TiO2	RhB, MO	-Physical electrostatic attraction	Photocatalysis
Delonix regia AC	RR-120	-Hydrophobic effect, π-π interaction and electrostatic interaction	Antibacterial
AC-HKUST-1-MOF	CV, Disulfine blue (DSB), Quinoline Yellow	-Electrostatic attraction, hydrogen bonding, ion exchange, soft-soft and dipole ion interaction	Antibacterial
MOP-AC	Bromocresol Purple (BCP)	-Hydrogen bonding, complexes, antibacterial hydrophobic interaction	Antibacterial
$ZnCl_2$AC and AC/AgNP	Indigo carmine	-Electrostatic attraction, redox reaction	Antibacterial

However, it is evident that multi-functionalization of adsorbents involves a lot of reactants. Any excess reagents may remain in solution after activation and some may form unwanted or unknown byproducts. Leaching of these residues from the surface of the adsorbents, or during disposal may find their way into the aquatic and terrestrial ecosystems thereby endangering life. This is another form of unwanted secondary pollution.

It is essential to characterize the adsorbent's surface structure, porosity, and functionality after each regeneration cycle to fully understand the regeneration process [21]. In a study by Osman et al. (2023), the most generally applied methods for synthesizing magnetic sorbents, for example, sol-gel, thermal decomposition, co-precipitation, hydrothermal, poly-ol, microwave, and micro-emulsion [21].

Multifunctionalized adsorbents seem to come with high costs, especially when incorporating photocatalysts, although Chua et al. (2021) explain that photocatalytic degradation is a low-cost pollutant degradation process [28]. Another challenge is that although it minimizes the spent adsorbent disposal problem, intermediate byproducts formed during degradation need to be addressed. To incorporate or integrate multiple functions in low-cost adsorbents, cost issues must then be resolved. Other challenges to consider are the scalability, long-term stability, and probable environmental risk to maximise their large-scale applicability [28,40].

However, Neeti et al. (2023) in their study on the role of green nanomaterials as effective adsorbents in wastewater treatment, state that green nanomaterials can be made from biological materials like microbes, trees, organic polymers such as lipids, carbohydrates and proteins, and that due to their small size, these nanomaterials play a critical role in wastewater treatment with higher efficiency in removing pollutants. Examples of such polymers include silver nanoparticles in Aloe-Vera plant extract, magnetic nanoparticles, and silver-impregnated cyclodextrin nanocomposites, which are biosynthesized nanoadsorbents used in water quality management. They argue that green nanoparticles offer a wastewater treatment method that is cost-effective and environmentally friendly, with phyto-capping to prevent secondary pollution during landfilling [20,41]. However, their surface stability is still in question as surface degradation will contaminate the water and soil with nanoparticles thereby threatening aquatic and terrestrial life.

3.3. Surface Degradation and Stability

This concept has been mentioned under types of adsorbents in previous sections. The surface degradation and stability of an adsorbent refer to the ability of an adsorbent to maintain its structure, performance, and function during the surface activation and adsorption process [14]. The morphology of the adsorbent, its chemical composition, and crystallinity are especially important for low-cost wastewater adsorbents to withstand the harsh environmental conditions of the wastewater. The degradation and stability of the adsorbent material depend on factors such as the adsorbent's chemical composition, crystallinity, morphology, the adsorbate's acidity, redox potential, biodegradability, and the operating conditions, such as temperature, pH, and contact time, as highlighted in **Table 3** [14]. For a low-cost adsorbent to be sustainable, it needs to have a relatively high stability compared to the harsh and complex conditions of wastewater. The adsorbent's stability and degradability must not decrease as contact time or repeated use increase [14].

Table 3. Challenges and Recent Breakthroughs in Improving Stability of Adsorbent Materials [14].

Adsorbent	Challenges	Advancements
Activated carbon	Surface oxidation, functional group loss, pore collapse	Surface medication, templating synthesis
MOFs	Structural collapse, linker degradation, thermal stability	Designer linkers, post synthetic modifications, dual passive heat dissipation approach
Zeolites	Dealumination, lattice collapse	Hydrothermal stabilization, silylation
Polymer resins	Physical aging, swelling, chain scission	Crosslinking, imprinting
Biosorbents	Biodegradation, pore blockage	Chemical modification, immobilization
Silica gels	Dissolution in high pH environments	Surface modification, composite formation
Alumina	Loss of porosity and surface area	Sol-gel synthesis, doping
CNTs	Oxidation, loss of walls/layers	Functionalization, encapsulation
Graphene oxide	Loss of functional groups, restacking	Reduction methods, composite formation

3.4. Surface Recovery and Reusability

Regeneration (recovery or reusability) of adsorbents is defined as the process in which the adsorbent can be separated from the adsorbate. Several regeneration or desorption methods exist, as shown in **Figure 10**. Factors that affect regeneration, according to Satyam and Santra (2024), are the characteristics of the adsorbent, the adsorbate, and the regeneration operating conditions [12]. However, Alsawy et al. (2022) claim that the performance of any chemical regeneration depends on adsorption methods, functional groups on an adsorbent, adsorbent pore configuration, and changes in active adsorbent sites [20].

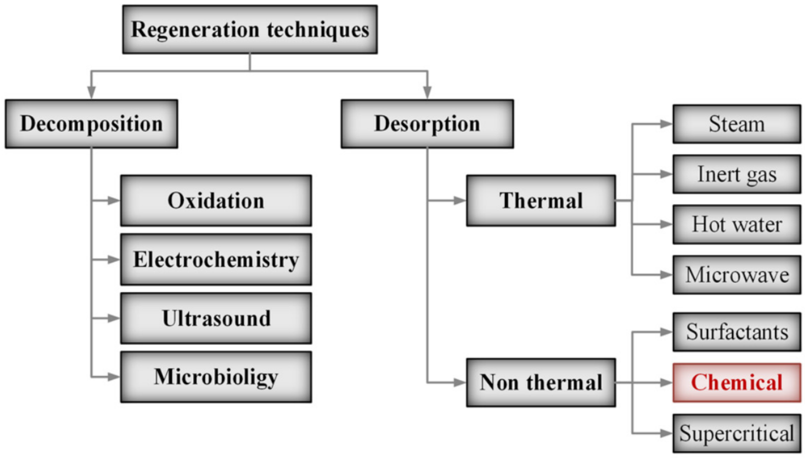

Figure 10. Different regeneration or desorption techniques proposed for adsorbents' reactivation [20].

3.4.1. Adsorption Mechanisms

Adsorption mechanisms are the processes by which adsorbates attach to adsorbents. They are important because they create bonds between the adsorbent and the adsorbates. The bond type and strength between these two entities depend on the type of adsorption and influence the number of adsorption/desorption cycles through which the adsorbent can go [21]. Just like the collisions between the adsorbent and the adsorbate depend on surface activation, desorption also depends on adsorption mechanisms, which are in turn dependent on the type of collisions between the adsorbent and the adsorbate. Adsorption mechanisms directly affect the method of regeneration.

Figueiredo et al. (2021) classify the strength of removal mechanisms into chemisorption (strong) and physicosorption (weak) [42]. It is also reported that chemisorption, precipitation, and complexation are characterized by high-impact mechanisms, while π- π-interactions and ion exchange are characterized by low-impact mechanisms [43]. From the literature, it appears that the biochar's chemisorption of pollutants results in lower regeneration performance than when adsorption occurs via physisorption [44,45]. This is because in chemisorption, pollutants bind to the active adsorbent sites to irreversibly form complexes or precipitates on the adsorbent surface [20]. As a result, the active sites on the adsorbent gradually decrease in number per cycle because the pores get blocked [46,47]. The biochar therefore loses its functionalities and degrades with the adsorption/desorption cycles [20]. In terms of secondary pollution and ecological sustainability, chemisorption is good in keeping pollutants bound to the active sites. It is also a guarantee that leaching out will not happen during land filling, although economically speaking the adsorbent will only be used once and twice before it gets saturated and disposed. Physisorption on the other hand allows easy escaping of pollutants from the active sites of the adsorbents, allowing for several regeneration cycles but risking secondary pollution.

3.4.2. Functional Groups

Reciprocated contact between functional groups and the pollutants also affects regeneration. One adsorbent with the same functional groups is likely to interact differently with different pollutants. It is reported that in biochar and heavy metals adsorption, the dominant adsorption mechanism is generally chemisorption. The removal mechanisms of heavy metals from biochar were therefore complexation with O–O functional groups, precipitation with OH– and C–O groups, and π-interactions, all of which influence the dominance of chemisorption over physisorption [20]. The biochar lost some of its active sites with each desorption cycle because of the strong chemical bonds in chemisorption, thereby affecting the regeneration process negatively. On the other hand, the same functional groups behaved differently during organic dye adsorption, which is rich in electrons.

3.4.3. Stimuli-responsive Adsorbents

Stimuli-responsive adsorbents are reversible adsorbents that respond to stimuli like light and changes in pH. They can go through well-ordered cycles of pollutant adsorption/desorption. For example, they can capture metals in acidic water and release them when the pH changes. Because of their reversibility, such adsorbents may go through sequential recycling and renewal, thereby lowering the cost [40, 48–50].

Studies in stimuli-responsive materials are trying to develop prompt desorption of pollutants in a multi-functionalized spent adsorbent. Future studies are still needed to fully confirm the concept [27].

4. Exhausted Adsorbent Management and Disposal

For the low-cost adsorbent to be sustainable, it must be able to go through several cycles before it is worn out. This is called adsorbent regeneration/recycling/reusability or surface recovery as covered in Section 2.4. After a certain time, a recycled adsorbent gets exhausted and needs to be disposed of sustainably to protect the environment.

4.1. Secondary Pollution

Secondary pollution is pollution associated with the disposal of contaminated adsorbents. To manage exhausted adsorbents, processes like reuse, landfill disposal, and/or incineration are carried out. However, these methods are not sustainable as they come with significant environmental and economic costs [27]. Landfilling is a common method for disposing of spent adsorbents after a hazard assessment of the adsorbent; pretreatment will be needed before landfilling. Other pre-treatment stabilization strategies of heavy metal-loaded adsorbent that could also be applied are microwave irradiation, phyto-capping, and phytoremediation [20].

Conventional desorption techniques for saturated adsorbents are divided into two groups: decomposition and desorption. Techniques like oxidation, electrochemistry, ultrasound, and microbiology fall under decomposition. Desorption techniques include thermal and non-thermal methods [20]. These conventional methods of desorption affect the quality of the adsorbent thereafter. During thermal treatment, the surface area of carbonaceous spent adsorbents is reduced. This lowers the regeneration cycles of the adsorbent. Chemical desorption methods use acids or alkalis, and these pose serious environmental risks [48]. On the other hand, discarding nano-enabled sorbents poses significant harm to ecological and environmental systems because of their inherent toxicity. Incineration is costly due to combined combustion, plant operations, and disposal fees. All these challenges call for sustainable and economical ways for recycling conventional spent adsorbents, turning them into secondary products for other industries—a process also referred to as repurposing, as depicted in **Figure 11** [21,27].

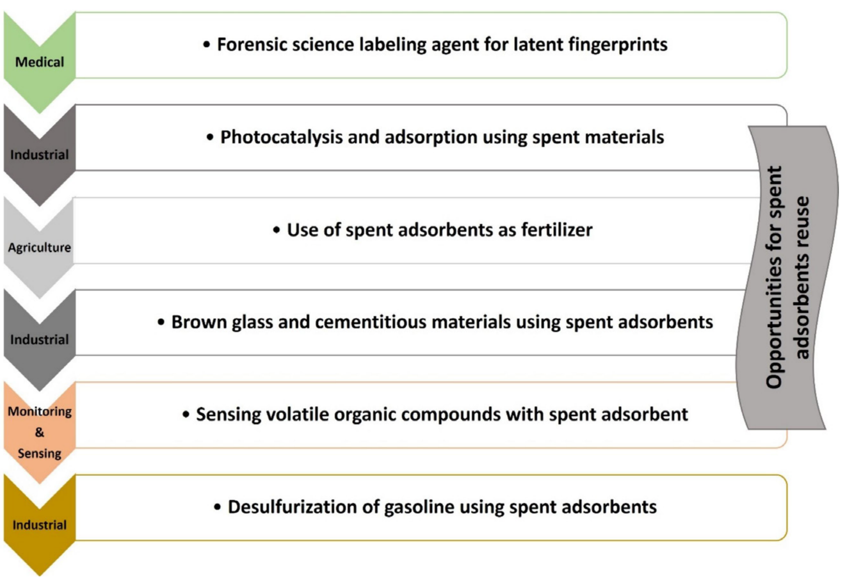

Figure 11. Sequential application of conventional spent adsorbents [27].

4.2. Tailored Recycling

In the study on regeneration of adsorbent and recovery of metals, Renu and Sithole (2024) propose that it is necessary to design the bioadsorbents with their secondary and final destination in mind [48]. Faheem et al. (2024) call it tailored recycling [27]. Tailored recycling is an approach that reuses exhausted adsorbents and turns them into valuable resources. This can be achieved through targeted research from design to functionalization to optimize specificity, faster response times, and enhanced reusability [21]. Numerous organic pollutants, like endocrine-disrupting substances and persistent organic pollutants, are efficiently removed with photocatalytic degradation [51]. Combining an adsorbent with these photocatalysts, like ZnO, will effectively degrade the pollutants. Tailored recycling is achieved by functionalization during adsorbent production, which allows a range of recovery and regeneration techniques such as separation by magnetic properties, response to pH change, gas responsiveness, and activation by heat and light energies [21,27]. After regeneration, the recovered adsorbents can be transformed into secondary products such as agents with antimicrobial activity, catalysis, fertilizers, and secondary adsorbents, thereby promoting eco-friendly regeneration methods [21]. During the design of the bioadsorbents, life cycle assessment metrics like energy costs, emission of greenhouse gases, resource use, and environmental implications should be considered to make their secondary and final destination environmentally friendly [27].

Studies show that the used-up adsorbents "can be recycled for soil fertilizers, energy transfer, storage devices, capacitors, and catalyst/catalyst support", also in construction, as fertilizers, anti-microbial agents, and secondary adsorbents [21,27]. Publications show that nutrient-enriched biochar can be turned into an organic fertilizer, thereby replacing synthetic fertilizers [21]. It is also reported that metal-impregnated green adsorbents could be used to replace carbon nanotubes or tar as supercapacitors [49]. The study of Blagojev et al. (2022) demonstrates one possibility to solve the post-adsorbent challenges of spent biosorbent. The used adsorbent was incinerated, the obtained ash was used as a filler in rubber production, preventing the premature start of vulcanization. Verifications showed no sign of secondary pollution through copper leakage from rubber. This green approach can therefore be used to turn saturated biosorbents into rubber fillers [52]. Exhausted biosorbents with hazardous oxyanion-forming elements and heavy metals would need lime or cement to stabilize them, with incurred costs. However, such spent adsorbents could be integrated into ceramic production materials, reducing both economic and environmental impacts [27]. Other views are that spent adsorbents with adsorbed pollutants may be turned into cement composite, and that the exhausted adsorbents or catalysts used in wastewater treatment due to their inorganic components, may improve the quality of cement composite materials in biomass-derived ash [53].

4.3. Stimuli-responsive Materials

In the past two decades, studies have been conducted to enable regeneration of saturated adsorbents with minimal damage to the morphology of the adsorbent. These efforts were achieved through the development of stimulus-sensitive systems. These kinds of adsorbents that respond to stimuli enhance controlled desorption, allowing individual pollutants to be detached from the spent adsorbent separately. There are single-stimuli responsive adsorbents and multi-stimuli responsive adsorbents. Single-stimuli responsive adsorbents respond to one stimulus for desorption. Multi-stimuli responsive adsorbents react to two or more stimuli [27].

5. Conclusions

The state of clean aquatic and drinking water, sanitation, and hygiene is still challenging in sub-Saharan Africa (SSA). However, robust research in low-cost adsorbents can lead to indigenous sustainable low-cost solutions to address Clean Water and Sanitation (SDG 6) and Life on Land (SDG 15). Successful application of low-cost adsorbents in wastewater remediation has the potential to protect ecosystems, leading to their ecological resilience. It is in protecting the ecosystems that those ecosystems will be able to provide ecosystem services, such as providing food, water, and therapy to humankind.

This study has observed the latest trends towards the development of low-cost materials from biomaterials, nanomaterials, and stimuli-responsive materials. These three types of materials make biosorbents, nanosorbents, and stimuli-responsive sorbents that are low-cost compared to conventional methods. They are emerging as groundbreaking innovative solutions in the field of wastewater remediation in different aspects, including their multi-functionality, targeted pollutant removal, sequential desorption, and tailored recycling, portraying their adaptive nature. They each have special properties, which can be merged to give an ultimate solution to the complex composition of wastewaters.

Multi-functionality

- Stimuli-responsive adsorbents are those adsorbents with the ability to modify their chemical or physical characteristics in response to stimuli like light and pH. This unique ability to respond to external stimuli can enhance the selectivity of these stimuli-responsive adsorbents. Functional groups can be added to their structures to enhance their affinity towards pollutants, including metal ions or organic pollutants as contaminants. In this way, stimuli-responsive adsorbents can be used to remove multiple contaminants from wastewater at the same time, overcoming the challenge of the complex nature of wastewaters.
- Multifunctional adsorbents are adsorbents characterised with high efficiency and extraordinary specificity to sense and capture contaminants, in addition to removing pollutants from wastewater systems due to their dynamic behaviour. This can allow real-time detection and removal of pollutants in a complex wastewater treatment, allowing multifunctional adsorbents to address a diversity of water quality challenges with high efficiency while decreasing environmental impact.
- Stimuli-responsive adsorbents allow for tailored recycling due to the possibility of sequential desorption occurring in an organized manner. This can allow for recovery of some useful compounds. Tailored recycling allows for the manufacturing of low-cost adsorbents with their secondary application in mind. This can solve the problem of spent adsorbents' disposal that threatens environmental safety.
- In recent developments, functionalizing biomaterials by incorporating other particles to give them distinct functions while affording them the capacity to adsorb multiple pollutants has become common. This has brought about multifunctional biosorbents that simultaneously remove bacteria, organic, and inorganic pollutants from wastewaters.
- Finally, designing multipurpose (composite) adsorbents that integrate several functions into one system can be a breakthrough in the field of wastewater remediation. An example is designing an adsorbent with enabled antibacterial, catalytic, and adsorption competencies. Such adsorbents would provide an advanced resolution to water treatment.

6. Further Developments

6.1. Ecological Implications and Future Directions

This study, however, does recognize that publications on the practical application of these low-cost adsorbents to restore ecosystems and promote public health are still rare. In the meantime, water pollution continues to cause public health threats and ecosystem degradation. Ecosystem degradability interferes with the ecosystem's health, functionality, and ability to provide ecosystem services like food security, thereby denying communities and habitats essential biodiversity benefits. Future research should therefore focus on bridging economic gaps, sustainability in disposal methods, pilot studies of these adsorbents in real settings through enabling technologies as methods of deployment, to enable scalability and performance monitoring for further improvements, as summarized in **Figure 12**.

6.2. Scalability

Scalability is still challenging because it is dependent on large-scale production of the adsorbents, well-developed disposal mechanisms, or secondary applications of exhausted adsorbents, as well as established deployment methods. Also, to justify the application of all adsorbents industrially, reliance on maximum batch adsorption capacities is not recommended.

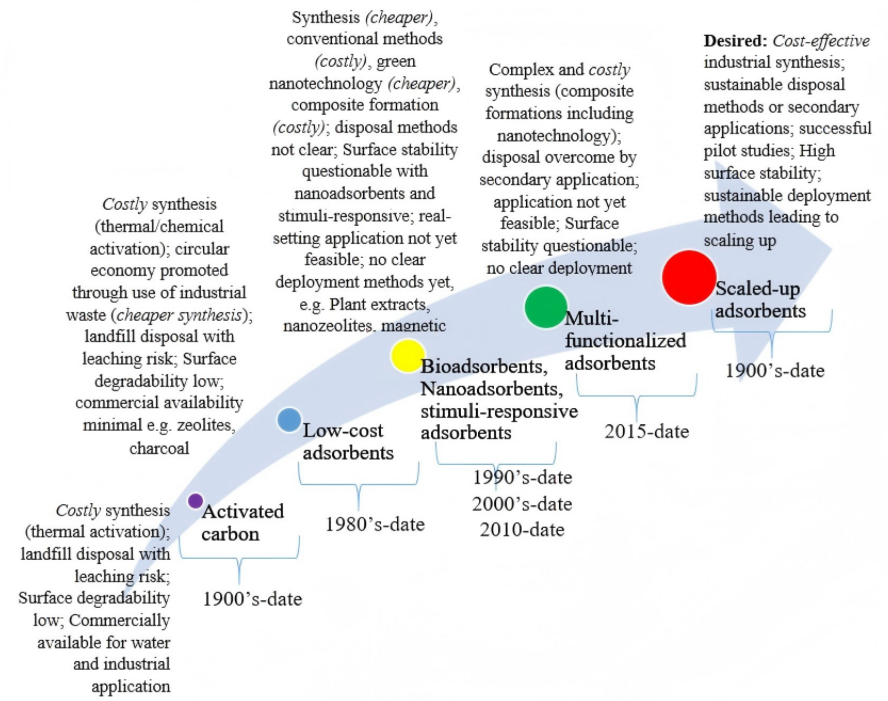

Figure 12. Evolution of adsorbents and desired future outcomes.

6.2.1. Large-scale Synthesis of the Adsorbents

One of the biggest challenges to the successful application of low-cost adsorbents in water treatment is the large-scale synthesis of these technologies.

·For biosorbents, there is no record of a commercial-scale product being found. Large-scale synthesis means an increased amount of chemicals for activation, which might have negative environmental implications. The abundance of natural materials to make biosorbents makes biosorbents economically competitive compared to the commercial adsorbents in the market.

·Stimuli-responsive adsorbents, multi-functionalized adsorbents, and nanoadsorbents require complex, costly, and energy-intensive processes. However, these costs can be reduced through bulk production. Additionally, special reagents are needed for the successful recovery of adsorbents to enable multiple regeneration cycles. Further research is necessary to assess these materials' ability to maintain their structural integrity and functionality over repeated regenerations. Nanosorbents can also lower costs when scaling up because they need less space for production. The synthesis of nanosorbents and multi-functional adsorbents provides a variety of products with customizable structural properties.

6.2.2. Disposal Mechanisms

Disposal of spent low-cost adsorbents remains challenging to scale up unless specific recycling methods are used. Although landfills are applicable in this regard, greener methods need to be in place. Developing low-cost adsorbents with secondary uses or ways to recover both the pollutant and the spent adsorbent for recycling will greatly improve scalability. Therefore, further research is needed in this area.

6.2.3. Deployment Methods

The integration of low-cost adsorbents into current water treatment systems does not seem straightforward. It may need broad modification to incorporate adsorbents into the existing water treatment facilities. New systems that will act as vehicles or anchors to properly deploy low-cost adsorbents on a pilot scale are therefore needed. Some studies have shown that stimuli-responsive polymers can be integrated into hydrogels or membranes, thereby enabling a higher surface area for adsorption, filtration, and photocatalysis. The integration of some adsorbents into membrane materials and photocatalysts, combined with permanent magnets on fiber optics, has been reported. It has been observed that such integrations can enhance wastewater purification. Hybrid systems can also be explored on a broader scale. These are systems in which a low-cost adsorbent is coupled with another technology to enable their application in real settings. Deployment through enabling technologies such as 3D devices is another promising way forward in the application to a real-world setting.

Author Contributions

S.O. supervised and reviewed the paper. T.G. co-supervised and co-reviewed the paper. R.H. contributed to the writing of the paper. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Ahmed, S.F., Kumar, P.S., Kabir, M., et al., 2022. Threats, challenges and sustainable conservation strategies for freshwater biodiversity. Environmental Research. 214(1), 113808. DOI: https://doi.org/10.1016/j.envres.2022.113808

[2] Cernev, T., Fenner, R., 2020. The importance of achieving foundational sustainable development goals in reducing global risk. Futures. 115(1), 102492. DOI: https://doi.org/10.1016/j.futures.2019.102492

[3] Meftah, S., Meftah, K., Drissi, M., et al., 2025. Heavy metal polluted water: Effects and sustainable treatment solutions using bio-adsorbents aligned with the SDGs. Discover Sustainability. 6(1). DOI: https://doi.org/10.1007/s43621-025-00895-6

[4] Jones, E.R., Bierkens, M.F.P., Wanders, N., et al., 2022. Current wastewater treatment targets are insufficient to protect surface water quality. Communications Earth & Environment. 3(1). DOI: https://doi.org/10.1038/s43247-022-00554-y

[5] Badawi, A.K., Zaher, K., 2021. Hybrid treatment system for real textile wastewater remediation based on coagulation/flocculation, adsorption and filtration processes: Performance and economic evaluation. Journal of Water Process Engineering. 40, 101963. DOI: https://doi.org/10.1016/j.jwpe.2021.101963

[6] Homaeigohar, S., 2020. The nanosized dye adsorbents for water treatment. Nanomaterials. 10(2), 295. DOI: https://doi.org/10.3390/nano10020295

[7] Bilal, M., Ihsanullah, I., Shah, M.U.H., et al., 2022. Recent advances in the removal of dyes from wastewater using low-cost adsorbents. Journal of Environmental Management. 321, 115981. DOI: https://doi.org/10.1016/j.jenvman.2022.115981

[8] Bilal, M., Ihsanullah, I., Younas, M., et al., 2021. Recent advances in applications of low-cost adsorbents for the removal of heavy metals from water: A critical review. Separation and Purification Technology. 278, 119510. DOI: https://doi.org/10.1016/j.seppur.2021.119510

[9] Bej, S., Swain, S., Bishoyi, A.K., et al., 2023. Wastewater-associated infections: A public health concern. Water, Air, & Soil Pollution. 234(7). DOI: https://doi.org/10.1007/s11270-023-06431-4

[10] Vera, M., Juela, D.M., Cruzat, C., et al., 2021. Modeling and computational fluid dynamic simulation of acetaminophen adsorption using sugarcane bagasse. Journal of Environmental Chemical Engineering. 9(2), 105056. DOI: https://doi.org/10.1016/j.jece.2021.105056

[11] Mishra, R.K., Mentha, S.S., Misra, Y., et al., 2023. Emerging pollutants of severe environmental concern in water and wastewater: A comprehensive review on current developments and future research. Water-Energy Nexus. 6, 74–95. DOI: https://doi.org/10.1016/j.wen.2023.08.002

[12] Rashid, R., Shafiq, I., Akhter, P., et al., 2021. A state-of-the-art review on wastewater treatment techniques: The effectiveness of adsorption method. Environmental Science and Pollution Research. 28(8), 9050–9066. DOI: https://doi.org/10.1007/s11356-021-12395-x

[13] Rathi, B.S., Kumar, P.S., Show, P.-L., 2020. A review on effective removal of emerging contaminants from aquatic systems: Current trends and scope for further research. Journal of Hazardous Materials. 409, 124413. DOI: https://doi.org/10.1016/j.jhazmat.2020.124413

[14] Satyam, S., Patra, S., 2024. Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. Heliyon. 10(9), e29573. DOI: https://doi.org/10.1016/j.heliyon.2024.e29573

[15] Dutta, S., Gupta, B., Srivastava, S.K., et al., 2021. Recent advances on the removal of dyes from wastewater using various adsorbents: A critical review. Materials Advances. 2(14), 4497–4531. DOI: https://doi.org/10.1039/D1MA00354B

[16] Gang, D., Ahmad, Z.U., Lian, Q., et al., 2021. A review of adsorptive remediation of environmental pollutants from aqueous phase by ordered mesoporous carbon. Chemical Engineering Journal. 403, 126286. DOI: https://doi.org/10.1016/j.cej.2020.126286

[17] Bekchanov, D., Mukhamediev, M., Yarmanov, S., et al., 2024. Functionalizing natural polymers to develop green adsorbents for wastewater treatment applications. Carbohydrate Polymers. 323, 121397. DOI: https://doi.org/10.1016/j.carbpol.2023.121397

[18] Tony, M.A., 2019. An industrial ecology approach: Green cellulose-based bio-adsorbent from sugar industry residue for treating textile industry wastewater effluent. International Journal of Environmental Analytical Chemistry. 1–17. DOI: https://doi.org/10.1080/03067319.2019.1661397

[19] Das, O., et al., 2022. Natural and industrial wastes for sustainable and renewable polymer composites. Renewable and Sustainable Energy Reviews. 158, 112054. DOI: https://doi.org/10.1016/j.rser.2021.112054

[20] Alsawy, T., Rashad, E., El-Qelish, M., et al., 2022. A comprehensive review on the chemical regeneration of biochar adsorbent for sustainable wastewater treatment. Clean Water. 5(1). DOI: https://doi.org/10.1038/s41545-022-00172-3

[21] Osman, A.I., et al., 2023. Methods to prepare biosorbents and magnetic sorbents for water treatment: A review. Environmental Chemistry Letters. DOI: https://doi.org/10.1007/s10311-023-01603-4

[22] Rangappa, H.S., Herath, I., Lin, C., et al., 2024. Industrial waste-based adsorbents as a new trend for removal of water-borne emerging contaminants. Environmental Pollution. 343, 123140. DOI: https://doi.org/10.1016/j.envpol.2023.123140

[23] Karthik, R.M., Philip, L., 2021. Sorption of pharmaceutical compounds and nutrients by various porous low-cost adsorbents. Journal of Environmental Chemical Engineering. 9(1), 104916. DOI: https://doi.org/10.1016/j.jece.2020.104916

[24] Sun, J., Zhou, C., Shen, H., et al., 2022. Green synthesis of ceramsite from industrial wastes and its application in selective adsorption: Performance and mechanism. Environmental Research. 214, 113786. DOI: https://doi.org/10.1016/j.envres.2022.113786

[25] Neeti, K., Singh, R., Ahmad, S., 2022. The role of green nanomaterials as effective adsorbents and applications in wastewater treatment. Materials Today: Proceedings. DOI: https://doi.org/10.1016/j.matpr.2022.11.300

[26] Vishnu, D., Dhandapani, B., 2021. A review on the synergetic effect of plant extracts on nanomaterials for the removal of metals in industrial effluents. Current Analytical Chemistry. 17(2), 260–271. DOI: https://doi.org/10.2174/1573411016666200110090607

[27] Faheem, M., Hassan, M.A., Du, J., et al., 2024. Harnessing potential of smart and conventional spent adsorbents: Global practices and sustainable approaches through regeneration and tailored recycling. Separation and Purification Technology. 354, 128907. DOI: https://doi.org/10.1016/j.seppur.2024.128907

[28] Chua, S.F., Nouri, A., Ang, W.L., et al., 2021. The emergence of multifunctional adsorbents and their role in environmental remediation. Journal of Environmental Chemical Engineering. 9(1), 104793. DOI: https://doi.org/10.1016/j.jece.2020.104793

[29] Madima, N., Mishra, S.B., Inamuddin, I., et al., 2020. Carbon-based nanomaterials for remediation of organic and inorganic pollutants from wastewater: A review. Environmental Chemistry Letters. 18(4), 1169–1191. DOI: https://doi.org/10.1007/s10311-020-01001-0

[30] Uddin, M.N., Desai, F., Asmatulu, E., 2020. Engineered nanomaterials in the environment: Bioaccumulation, biomagnification and biotransformation. Environmental Chemistry Letters. 18(4), 1073–1083.

DOI: https://doi.org/10.1007/s10311-019-00947-0

[31] Chai, W.S., Cheun, J.Y., Kumar, P.S., et al., 2021. A review on conventional and novel materials towards heavy metal adsorption in wastewater treatment application. Journal of Cleaner Production. 296, 126589. DOI: https://doi.org/10.1016/j.jclepro.2021.126589

[32] Wang, J., Guo, X., 2020. Adsorption isotherm models: Classification, physical meaning, application and solving method. Chemosphere. 258, 127279. DOI: https://doi.org/10.1016/j.chemosphere.2020.127279

[33] Manchisi, J., Matinde, E., Rowson, N.A., et al., 2020. Ironmaking and Steelmaking Slags as Sustainable Adsorbents for Industrial Effluents and Wastewater Treatment: A Critical Review of Properties, Performance, Challenges and Opportunities. Sustainability. 12(5), 2118. DOI: https://doi.org/10.3390/su12052118

[34] Iwanow, M., Gärtner, T., Sieber, V., et al., 2020. Activated Carbon as Catalyst Support: Precursors, Preparation, Modification and Characterization. Beilstein Journal of Organic Chemistry. 16, 1188–1202. DOI: https://doi.org/10.3762/bjoc.16.104

[35] Gao, Y., Yue, Q., Gao, B., et al., 2020. Insight into Activated Carbon from Different Kinds of Chemical Activating Agents: A Review. Science of the Total Environment. 746, 141094. DOI: https://doi.org/10.1016/j.scitotenv.2020.141094

[36] Rehman, A., Park, M., Park, S.J., 2019. Current Progress on the Surface Chemical Modification of Carbonaceous Materials. Coatings. 9(2), 103. DOI: https://doi.org/10.3390/coatings9020103

[37] Devi, N.S., Hariram, M., Vivekanandhan, S., 2021. Modification Techniques to Improve the Capacitive Performance of Biocarbon Materials. Journal of Energy Storage. 33, 101870. DOI: https://doi.org/10.1016/j.est.2020.101870

[38] Aruna, B.N., Sharma, A.K., Kumar, S., 2021. A Review on Modified Sugarcane Bagasse Biosorbent for Removal of Dyes. Chemosphere. 268, 129309. DOI: https://doi.org/10.1016/j.chemosphere.2020.129309

[39] Grassi, P., Drumm, F.C., Georgin, J., et al., 2020. Application of Cordia Trichotoma Sawdust as an Effective Biosorbent for Removal of Crystal Violet from Aqueous Solution in Batch System and Fixed-Bed Column. Environmental Science and Pollution Research. 28(6), 6771–6783. DOI: https://doi.org/10.1007/s11356-020-11005-6

[40] Namdeti, R., Rao, G.B., Lakkimsetty, N.R., et al., 2024. Innovative Approaches in Water Decontamination: A Critical Analysis of Biomaterials, Nanocomposites, and Stimuli-Responsive Polymers for Effective Solutions. Journal of Environmental & Earth Sciences. 7(1), 92–102. DOI: https://doi.org/10.30564/jees.v7i1.7476

[41] Prem, R., 2025. Green nanomaterial-based sustainable analysis of contaminant-remediation in wastewater: A bird's-eye view on recent advances and limitations. Sustainable Chemistry for the Environment. 10, 100238. DOI: https://doi.org/10.1016/j.scenv.2025.100238

[42] Figueiredo, B., Maria, C., Castro, A., et al., 2021. Adsorption of Reactive Black 5 and Basic Blue 12 using biochar from gasification residues: Batch tests and fixed-bed breakthrough predictions for wastewater treatment. Bioresource Technology Reports. 15, 100767. DOI: https://doi.org/10.1016/j.biteb.2021.100767

[43] Miao, Q., Li, G., 2021. Potassium phosphate/magnesium oxide modified biochars: Interfacial chemical behaviours and Pb binding performance. Science of the Total Environment. 759, 143452. DOI: https://doi.org/10.1016/j.scitotenv.2020.143452

[44] Ma, Y., Li, M., Li, P., et al., 2021. Hydrothermal synthesis of magnetic sludge biochar for tetracycline and ciprofloxacin adsorptive removal. Bioresource Technology. 319, 124199. DOI: https://doi.org/10.1016/j.biortech.2020.124199

[45] Jabar, J.M., Odusote, Y.A., 2020. Removal of cibacron blue 3G-A (CB) dye from aqueous solution using chemo-physically activated biochar from oil palm empty fruit bunch fiber. Arabian Journal of Chemistry. 13(5), 5417–5429. DOI: https://doi.org/10.1016/j.arabjc.2020.03.020

[46] Herath, A., Layne, C.A., Perez, F., et al., 2021. KOH-activated high surface area Douglas Fir biochar for adsorbing aqueous Cr(VI), Pb(II) and Cd(II). Chemosphere. 269, 128409. DOI: https://doi.org/10.1016/j.chemosphere.2020.128409

[47] Li, J., Zhou, B., Chang J., et al., 2022. Evolution of the physicochemical properties and SO2 adsorption performance of powdered activated coke during adsorption–desorption cycle. Journal of Analytical and Applied Pyrolysis. 167, 105671. DOI: https://doi.org/10.1016/j.jaap.2022.105671

[48] Renu, N., Sithole, T., 2024. A review on regeneration of adsorbent and recovery of metals: Adsorbent disposal and regeneration mechanism. South African Journal of Chemical Engineering. 50, 39–50. DOI: https://doi.org/10.1016/j.sajce.2024.07.006

[49] Hassan, M., Naidu, R., Du, J., et al., 2020. Critical review of magnetic biosorbents: Their preparation, application, and regeneration for wastewater treatment. Science of the Total Environment. 702, 134893. DOI:

https://doi.org/10.1016/j.scitotenv.2019.134893

[50] Baskar, A.V., Bolan, N., Hoang, S.A., et al., 2022. Recovery, regeneration and sustainable management of spent adsorbents from wastewater treatment streams: A review. Science of the Total Environment. 822, 153555. DOI: https://doi.org/10.1016/j.scitotenv.2022.153555

[51] Zielecka, R., Cygańczuk, K., Pastuszka, Ł., et al., 2021. Nanometals-Containing Polymeric Membranes for Purification Processes. Materials. 14(3), 513. DOI: https://doi.org/10.3390/ma14030513

[52] Blagojev, N., Šćiban, M., Vasić, V., et al., 2022. Use of exhausted biosorbent ash as eco-friendly filler in natural rubber. Polymer International. 71(11), 1267–1277. DOI: https://doi.org/10.1002/pi.6423

[53] Rial, J.B., Ferreira, M.L., 2022. Potential applications of spent adsorbents and catalysts: Re-valorization of waste. Science of the Total Environment. 823, 153370. DOI: https://doi.org/10.1016/j.scitotenv.2022.153370