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Review Article 

Comparative Analysis of Natural and Synthetic Materials for Wastewater Treatment: Plant Powders, Activated Carbon, Biochar, Zeolite, and Nanomaterials

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ABSTRACT

The world faces numerous problems related to water scarcity and pollution, largely due to inefficient wastewater treatment and inadequate methods. A comparative account of five widely known adsorbents-plant powders, activated carbon, biochar, zeolite, and nanomaterials-includes a comparative analysis of their adsorption capacities, cost-effectiveness, and environmental sustainability. On one side, plant powders, being cheap and eco-friendly, on the other side, show lesser performance or lower adsorption capacity, particularly with heavy metals. Activated carbon shows a good degree of adsorption, but its production is costlier and energy-intensive. Due to its moderate performance, biochar also allows carbon sequestration. Zeolites are highly low in their lowness during the ion exchange process and removal of metals, and nanomaterials are good in both adsorption and catalytic activity, though costs and environmental risks delay their applications. This review also emphasizes the case for hybrid systems combining the strengths of different materials and their application in efficient and friendly wastewater treatment.



Jana Rammal: She is a PhD student and researcher at the Lebanese University, specializing in environmental plant physiology. She holds an agricultural engineering and biochemistry degree, and she is also a water activist and climate activist who advocates for sustainability and environmental awareness. Her research entails coming up with creative solutions to wastewater treatment and green pest control measures. Besides the academic setting, she is an ambassador for GreenAura and participates in global environmental activities, advocating for climate action, and water sustainability. Through her activism and efforts, Jana is making a significant contribution in the fields of environmental science and sustainability.

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Akram Hijazi: He is an associate professor at the Doctorate School of Science and Technology in the Lebanese University, specializing in organic and organometallic chemistry, environmental sciences, and natural product chemistry. He is the author of more than 180 articles and has been cited more than 3,750 times. He has conducted research on water treatment, bioactive compounds, catalysis, and waste management. He has collaborated with international scientists to develop sustainable chemistry and solutions for the environment. His work has greatly benefited the academic fraternity, and he is one of the leading experts in his field of study.



Salem Darwich: He has authored over 20 papers in high-ranked journals and books. His areas of research cover Middle East politics and society, agriculture and rural development, remote sensing in agriculture, and the impacts of climate change on agriculture. As a United Nations Convention to Combat Desertification (UNCCD) Science and Technology Correspondent, he brings his expertise in desertification, agricultural sciences, environmental economics, and forestry. He establishes professional connections with the Faculty of Agriculture at the Lebanese University and the Ministry of Agriculture, where he provides strategic council on environmental and agricultural matters.



Zaher Abdel Baki: He is an associate professor in the College of Engineering of the American University of the Middle East. His areas of research include green and alternative chemistry, refinery and conversion of biomass, and treatment of wastewater. Dr. Abdel Baki has written 21 papers, which have been cited a total of 114 times and have more than 1,800 reads, as an indication of the relevance of his contributions to the scientific world.



Dalia El Badan: He is an accomplished associate professor of Microbiology with a distinguished academic and research career spanning several core disciplines, including Environmental Microbiology, Food Microbiology, Marine Microbiology, and Biotechnology. Her interdisciplinary expertise bridges fundamental and applied sciences, with a focus on understanding and harnessing the microbial world. Dr. El Badan has contributed significantly to the study of marine microbial communities and their roles in ecological balance and biotechnological innovation. Her skills in microbial culture, isolation, and characterization have enabled her to uncover novel microorganisms with potential applications in environmental sustainability and food safety. Through her teaching, mentorship, and research, Dr. El Badan continues to inspire the next generation of scientists while advancing the understanding of microbial life in both natural and engineered ecosystems.



Wassim Rammal: He earned his PhD in Bioinorganic Chemistry (2005) and a Master's in Molecular Chemistry (2001) from Joseph Fourier University – Grenoble, France, following a Bachelor and Master in Chemistry from the Lebanese University (2000). He has been a lecturer at the Lebanese University since 2005 and currently serves as Director of the Faculty of Science (Branch 5) as of March 2024, a position he also held from 2018 to 2021. Appointed Professor in 2023, Dr. Rammal has held key academic roles, including Head of the Chemistry and Biochemistry Department and member of various faculty councils. He was an active member of the Rammal Rammal Laboratory and has published around twenty peer-reviewed papers in biochemistry. He also taught at Joseph Fourier University from 2002 to 2005



Anis Daou: He is a lecturer in Pharmaceutical Sciences at Qatar University. He holds a Ph.D. in Pharmaceutical Sciences from Kingston University in London. His research primarily focuses on the development of boron-containing compounds for Boron Neutron Capture Therapy (BNCT), a targeted cancer treatment. His work aims to enhance the selective delivery of therapeutic agents to tumor cells using nanocarriers and other advanced drug delivery systems. Dr. Daou's research interests include drug development, nanotechnology, theranostics, drug discovery, and pharmaceutical dosage form design. With over 265 citations on Google Scholar, his work contributes significantly to the fields of targeted cancer therapy and pharmaceutical innovation. He actively shares his research through academic platforms such as ResearchGate and engages with the scientific community on advancements in pharmaceutical science.

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1. Introduction

Access to clean water is essential to human health, economic development, and environmental balance [1,2]. Industrial growth, urbanization, and agricultural intensification have significantly contributed to the quantity and complexity of wastewater globally [3,4]. Domestic and industrial effluents may contain different contaminants, including organic compounds, heavy metals, lead ions, nutrients, and suspended particulates. These pollutants pose significant risks to aquatic ecosystems and human health. Heavy metals such as lead, cadmium, chromium, mercury, and arsenic are hazardous as they are poisonous, non-biodegradable, and accumulate in living organisms [5,6]. They are involved in various medical diseases, including neurological, gastrointestinal, renal, and cancerous conditions. Their environmental longevity makes extraction and recovery even tougher. Additionally, more than 700 organic and inorganic pollutants have been detected in global water systems, as indicated by recent estimates [7]. Dyes, pesticides, drugs, surfactants, radioactive substances, and other chemicals discharged by industries such as textiles, metallurgy, agriculture, and electronics are some of the contaminants [8-10]. Conventional treatment technologies, including membrane filtration, advanced oxidation

processes, ion exchange, electrochemical treatments, coagulation, flocculation, and chemical precipitation are widely used but have many disadvantages, including high operational cost, energy demands, and toxic residues [11-13]. However, the majority of them are bedeviled by their high cost of operation, energy requirement, generation of toxic sludge, or high infrastructure. Therefore, the quest for low-cost, sustainable, and scalable technology is increasing [7,14,15]. Adsorption has been identified as the most effective and environmentally sustainable method for water treatment [9]. This preference is due to its operational simplicity, low energy requirements, minimal chemical usage, and the potential for adsorbent regeneration [2]. The extensive research has been conducted on various adsorbent materials, including activated carbon, zeolite, biochar, nanomaterials, and plant powders [7,16,17]. Recent studies have also added to this field by exploring advanced adsorption and photocatalytic processes, such as the use of tiger nut with TiO_2 , natural clay-based adsorbents for pharmaceutical contaminants [18], and polyaniline (PANI)-based nanocomposites for dye removal [19]. Studies on heavy metal toxins in industrial wastewater [20] and solar UV-assisted photocatalysis of organic contaminants [21] also indicate the growing trend towards hybrid and sustainable treatment processes.

This review assesses five critical categories of adsorbents: plant powders, activated carbon, biochar, zeolite, and nanomaterials. Focus is placed on their removal efficiency, adsorption mechanism, recoverability, cost-effectiveness, and sustainability. The aim is to present a comprehensive global account of each material's merits and demerits and to build promising hybrid solutions for efficient and sustainable wastewater treatment.

2. Plant Powder

Plant-based powders, sourced from agricultural wastes such as *Moringa oleifera*, psyllium husk, banana peel, and rice husk, are abundant in cellulose, lignin, and other organic compounds [22]. These materials exhibit high surface areas and possess various functional groups, which significantly enhance their adsorption capacity for the removal of heavy metals, dyes, and organic pollutants [2].

2.1. Mechanisms of action

Table 1 indicates the wide range of adsorption capacities of plant adsorbents, from the lowest value of 0.5 mg/g for almond shells to the highest value of more than 237.9 mg/g for banana peel for lead adsorption. Psyllium husk and *Moringa oleifera* are repeatedly high-performing materials for all contaminants and are good options for low-cost processes. In contrast, typical agro-wastes, such as rice husk and orange peel, exhibit poor to moderate adsorption efficiency. These differences stem from the impact of material constitution, treatment protocol, and operation conditions on adsorption traits. In most cases, the table indicates raw agricultural waste's potential but states the need to optimize the level of performance of commercial adsorbents.

2.2. Effectiveness of plant powder

Plant powders have shown considerable potential to remove different impurities, including heavy metals and colorants. However, its adsorption capacity is lower than that of more advanced materials like activated carbon

or engineered nanomaterials. Due to its high porosity, excellent adsorption capacity, and superior surface reactivity, activated carbon has been widely used as an adsorbent commercially [16].

Besides conventional sources, activated carbon has also been produced using agricultural by-products (such as olive, apricot, and peach fruit seeds), as well as almond, hazelnut and coconut shells [30]. As an environmentally friendly substance that has shown promise in various fields, biochar, which is made from various agricultural wastes, has attracted the attention of numerous researchers [9,31,33] (**Figure 1**). Some improvement can be achieved through surface modification techniques or integration with other materials hull was treated with a sodium nitrate solution [34]. Teff husk was treated with alkali, followed by carbonization at 550 °C [35], and the calabash peel was treated with nitric acid and formaldehyde [36]. *Senna siamea* seedpods impregnated with zinc chloride were activated by thermal treatment at 550 °C [37]. Dead palm leaves were impregnated with ferric chloride in an alkaline medium and then treated at 600 °C to develop a nanocomposite [37].

Poplar sawdust was used to develop activated carbon by impregnating it in potassium hydroxide and zinc chloride separately under different conditions and then pyrolyzing at 300-600 °C [38]. Jackfruit peel was impregnated in concentrated sulphuric acid, rinsed with distilled water, soaked in sodium carbonate solution, pyrolyzed at 400-600 °C, and subjected to microwave pyrolysis at 200 W for 10 min. to prepare a biochar [38,39].

The study by [40] established that *Moringa oleifera* seeds deflocculated turbidity and removed pathogens in water. A typical example of a low-cost natural biosorbent, this is an exemplary display of eco-friendly and efficiency factors of water treatment, especially in terms of cost in developing countries. However, the reality remains that the ability to recycle plant powders still poses challenges, with several reuses being limited. Numerous cost-effective biosorbents derived from agricultural waste have been documented for their efficacy in

Table 1. Summary of plant-based adsorbents used for the removal of organic and inorganic pollutants from aqueous solutions

Adsorbents	Adsorbates	Max adsorption capacity (mg/g)	Key operating conditions			Ref.
			Time (h)	pH	T (°C)	
Moringa Oleifera Powder	Lead (Pb ²⁺)	132.0	2	6	25	[23]
Psyllium Husk Powder	Methylene Blue	156.0	3	6	30	[24]
Coconut shell-based biochar	methylene blue (MB)	33.1 and 9.2	48		25	[17]
Bannan Peel powder	Cd ²⁺ and Pb ²⁺	84.25 for Cd ²⁺ and 237.90 for Pb ²⁺				[25]
Orange Peel Powder	Cu (II) and Cd (II)	2.78 for Cu (II) 2.57 for Cd (II)	2		25	[5]
Almond shell powder	Pb (II)	0.5		6.0		[26]
Rice husk	Lead ions	28.6	7	3.9	25	[27]
Wheat shells	Cd ²⁺ and Pb ²⁺	62.49 149.33	0.5	Wide range		[28]
Chestnut shell	Cu (II)	200.3	24	6	25	[29]
Sunflower Staks	Cd ²⁺ and Pb ²⁺	Cd 8.42×10^{-2} Pb 8.95×10^{-2}	2.5	5	25	[30]
Guar gum Powder	Chromium (Cr ⁶⁺)	100.0	4	4.5	30	[31]
Psyllium husk powder	Methylene Blue	206.6	0.6	4	30	[32]

removing heavy metals [41]. These biosorbents typically require minimal pre-treatment processes, such as washing, drying, grinding, or mild acid or alkali treatment, thereby eliminating the need for extensive physical or chemical modifications.

2.3. Limitations of the plant powder

Despite their economic and environmental benefits, plant-based powder adsorbents face

several limitations, especially in large-scale or industrial wastewater treatment applications. These limitations include:

Lower adsorption capacity: Compared to advanced materials like activated carbon or nanomaterials, plant-based adsorbents generally have lower surface areas, porosity, and fewer reactive functional groups, resulting in inferior adsorption capacity [42].

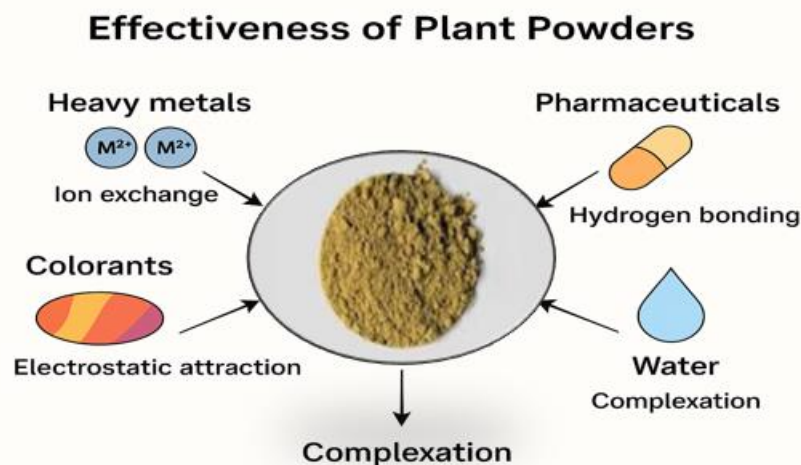


Figure 1. Effectiveness of plant powders

Poor selectivity: These biosorbents often exhibit poor selectivity when treating composite wastewater that contains multiple pollutants, which reduces their overall efficiency.

Low regeneration capacity: Most plant powders are used in a single treatment process and are not easily reusable, making them less sustainable over time.

Performance variability: The chemical composition of agricultural residues can vary depending on the type of plant, growing conditions, and processing methods, leading to inconsistencies in performance.

Susceptibility to biodegradation: Raw plant materials are prone to biodegradation and microbial infection during storage or prolonged use, compromising their stability and operational efficiency.

These challenges underscore the need for further research and development to improve the structural and functional properties of plant-based adsorbents through modification and hybridization approaches [22].

2.4. Enhancement of plant powder

Plant adsorbents have gained increasing attention as low-cost and environmentally friendly adsorbents for wastewater treatment. Being by-products of agricultural waste such as *Moringa oleifera*, banana peel, psyllium husk, rice husk, and orange peel, these adsorbents are rich in lignocellulosic content and contain a variety of functional groups (e.g., hydroxyl and

carboxyl) that facilitate the adsorption of contaminants [9,31,33].

The mechanism of action is often ion exchange, complexation, hydrogen bonding, and electrostatic attraction. Biodegradability and their local availability make them particularly attractive to use in low-resource and rural communities [43].

However, despite their versatility, raw plant powder adsorption capacity is typically lower than that of advanced materials such as activated carbon and nanomaterials. For instance, while *Moringa oleifera* or *Psyllium* husk has a high capacity for some dyes and metals, their overall capacity and selectivity may not be as good as synthetic analogs under complex water conditions.

3. Activated Carbon

Activated carbon is a type of carbonaceous tool that has an abnormally large surface area and porosity and is primarily made from organic materials such as coconut endocarp, and rice husk. It has traditionally been the standard in the area of water treatment industry [44].

When designing pyrolysis conversions, it is crucial to consider various parameters, as changes in preparation conditions can impact the effectiveness of activated carbon (AC) [45]. The two main methods for converting lignocellulosic biomass (LB) to AC are activation and pyrolysis [46]. This section explores the operational factors that influence

the yield and quality of AC produced through biomass pyrolysis and activation, including pre-treatment techniques, activation procedures, reaction temperature, and heating technology. A visual summary of the activated carbon production and activation process is provided (Figure 2).

3.1. Mechanisms of adsorption

Carbon had to be carbonized at temperatures as high as 900 °C. For the activation step, the carbon is then crushed to the appropriate size [44]. Chemical, physical, or a mixture of chemical and physical activation known as physiochemical activation can all be used to activate carbon. The mechanism of AC adsorption is typically attributed to the carbon micropore or weak van der Waals forces that might draw impurities [47].

Natural active monomeric molecules separated from herbal medicines have emerged as the most effective option in recent years for minimizing adverse effects of preparation and creating high-value products [47-49].

The primary active component of *Andrographis paniculata* (*A. paniculata*), andrographolide, is already sold in China and Southeast Asia and is used as a natural antibiotic to treat a variety of conditions, including sore throats, chills, influenza, and other illnesses. The steps involved in extracting andrographolide from *A. paniculata* are extraction, decolorization, concentration, removal of impurities, and crystallization [50]. An abundance of chlorophyll, primarily chlorophyll a (Chl a) and

chlorophyll b (Chl b), is typically present in extracts of *A. paniculata*. Direct concentration of the extract will result in a thick, dark green lump that will interfere with the separation and purification process that follows. Furthermore, a lack of chlorophyll during the crystallization process gives andrographolide crystals a green appearance, which detracts from the product's purity, worth, and biological activity. Consequently, decolorization is crucial [51].

In fact, several countries have made it their standard procedure for decolorization. However, it was discovered that the removal rates of Chl a and Chl b from AC made by various manufacturers varied significantly, even if they had comparable adsorption values of iodine and methylene blue, which are often used to evaluate the adsorption effectiveness of AC [52].

There are currently few studies on the removal of Chl a and Chl b from herbal extracts using AC microstructure and adsorption mechanisms, and the majority of AC studies focus mainly on dyes and metal ions [52-53]. A higher specific surface area or micropore volume can enhance adsorption performance by providing more adsorption sites [4]. The pore size must be sufficiently large to accommodate the dimensions of the adsorbed molecules [52]. Mesopores (2-50 nm) are primarily responsible for adsorbing large molecular weight organic molecules, macropores (> 50 nm) are suitable for the adsorption of microorganisms, and micropores (0-2 nm) mainly adsorb compounds of low molecular weight [54].

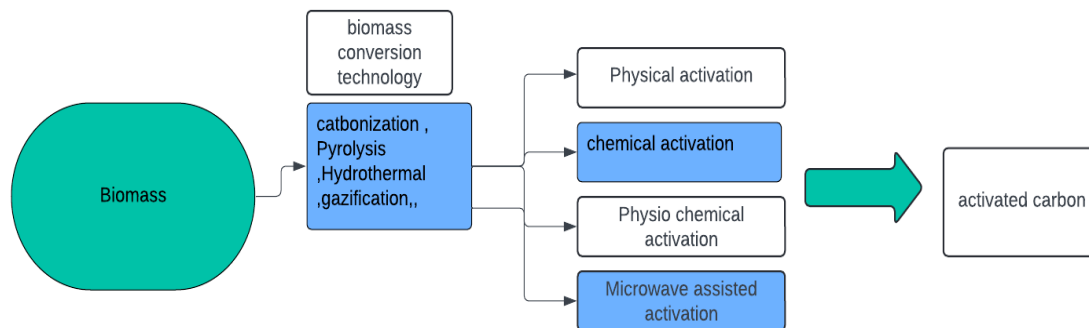


Figure 2. Primary techniques for producing activated carbon from biomass

3.2. Effectiveness of activated carbon

Adsorption is a promising technique for removing various pollutants from wastewater [45]. The use of inexpensive adsorbents derived from sources such as agricultural waste can effectively eliminate contaminants [15]. Extensive studies have been conducted on the adsorption of pollutants in activated carbon [55], which can be produced from various agricultural wastes and has a high surface area [56].

Activated carbon obtained by biomass pyrolysis is effective in removing a wide range of contaminants, including Pb, Hg, Cu, Ar, Cd, Cr, Fe, and Ni. There is a growing demand for environmentally friendly solutions to address heavy metal-induced river contamination.

Traditional methods of removing metal ions from wastewater include ion exchange, membrane filtration, electrochemical treatment, precipitation, electrodialysis, reverse osmosis, and adsorption. Despite the significant overhead and capital expenses associated with other technologies, adsorption is preferred due to its versatility in handling, design, and operation [45,57,58].

Flexible surface functional groups in carbon-based materials facilitate the adsorption of HM ions. The efficiency of carbon-based compounds in adsorbing metal particles has been confirmed by research. The capacity of a carbon-based adsorbent (CBA) to adsorb chemical constituents depends on the adsorbate's properties (pore size, polarity, molecular weight (MWs), and functionality), and the solution environment's (acidity, ionic strength, and temperature) [59], [60].

Chemicals bind and aggregate on different adsorbents in the aqueous phase due to donor-acceptor forces such as hydrogen bonding, induced dipole, van der Waals, and dipole-dipole. Important adsorption activities include the hydrophobic effect, covalent and electrostatic interactions, hydrogen, and π - π bonding [61]. Typically, biomass pyrolysis is used to create AC, which is then activated to increase the active surface area [60,62].

The activation pathway is selected based on the properties of the raw material, including

density, size, and heating value. During the pyrolysis process, a designated reactor is selected and rapidly heated to the target temperature while surrounded by an inert atmosphere [63]. Pyrolysis is crucial because it removes moisture and volatile biomass components [64]. Pyrolytic variables, which encompass temperature, feed content, reactor types, and heating rate, have a considerable impact on the AC properties. The biomass pyrolysis into AC has been the subject of extensive research. However, the majority of applications and research so far have been on the use of AC in fertilizers and soil amendments. Review publications have addressed the subject of AC adsorption on numerous occasions [11,45,55,58].

4. Biochar

The porous product rich in carbon obtained from the pyrolysis of biomass in a limited oxygen atmosphere is biochar [65,66]. Although it lacks a universally accepted definition, biochar is generally described as a particular kind of charcoal, which mainly consists of amorphous carbon and is derived from organic raw materials such as wood residues, agricultural waste, sewage sludge, and animal manure [67,68]. The promising applicability in environmental remediation by recent studies is, particularly, wastewater treatment and soil fertilization [7,69].

4.1. Mechanism of biochar

The ability of biochar to remove pollutants is largely dependent on its surface chemistry and porous structure [2]. In the absence of oxygen, biomass is thermally broken-down during pyrolysis to produce a substance high in carbon and functional groups like carboxyl and hydroxyl. Because of these characteristics, biochar can adsorb organic contaminants (such as dyes and pesticides), heavy metals (such as lead and cadmium), and nutrients (such as phosphate and nitrogen). The technique to produce biochar and its adsorption mechanism is depicted in (Figure 3).

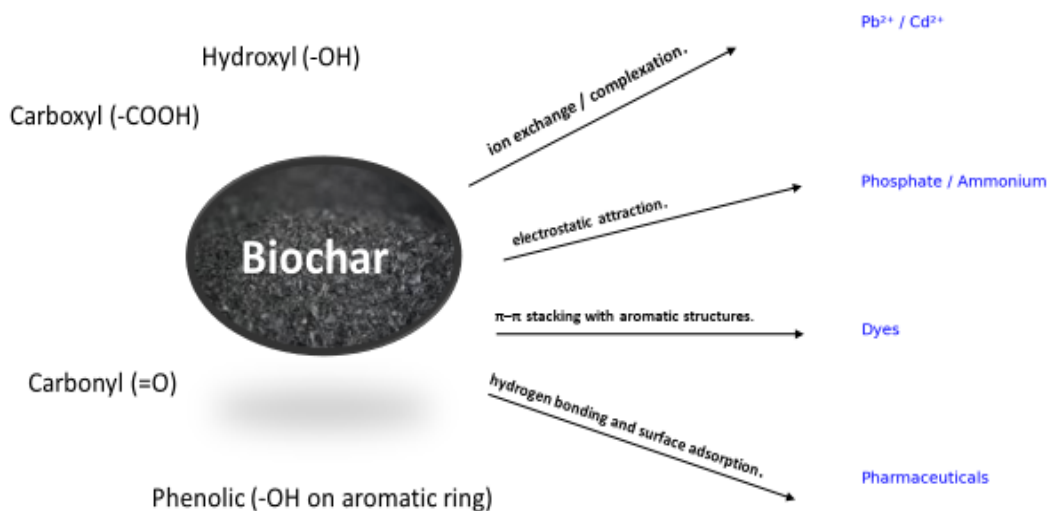


Figure 3. Biochar production and adsorption mechanism

Table 2. Applications of biochar in wastewater treatment and key supporting studies

Application	Pollutants removed	Key studies
Nutrient removal	Phosphorus and nitrogen	[68,70]
Heavy metal adsorption	Lead, cadmium, and arsenic	[71,72]
Organic pollutant removal	Dyes and pesticides	[68,70]

4.2. Advantages of biochar

Biochar offers numerous benefits, making it one of the most sustainable and economical materials for wastewater treatment (Table 2). Its production from renewable resources such as agricultural residues and forest waste enhances biomass utilization and reduces waste [73]. Biochar converts biomass into stable carbon, helping to sequester carbon and mitigating climate change [74].

Other significant advantages include its low production cost compared to conventional adsorbents such as activated carbon and nanomaterials [75]. This affordability improves accessibility, especially in developing countries with limited resources for wastewater treatment [75]. Biochar's physical and chemical properties, such as high porosity and

abundance of functional groups, make it highly effective against various contaminants [76].

Research by Osman *et al.* (2023) investigates the development of biochar from agricultural wastes like jackfruit peels and poplar sawdust for the removal of heavy metals from wastewater [37]. Biochar regeneration cycles are crucial to its economic viability. Studies indicate that biochar can be regenerated using thermal processes, which must be evaluated in terms of capital expenditure (CAPEX) and operational expenditure (OPEX) [77].

4.3. Limitations of biochar

Despite its growing popularity as a sustainable and low-cost adsorbent, biochar has some limitations in wastewater treatment. Its performance is highly dependent on the

feedstock type and pyrolysis conditions, resulting in differing physicochemical characteristics such as surface area, porosity, and functional group content [76]. Such variability leads to inconsistent adsorption efficiency and limits standardization for large-scale applications. Additionally, biochar has been observed to exhibit moderate adsorption capacity compared to advanced materials like activated carbon or engineered nanomaterials and is generally not selective in treating complex or multi-pollutant wastewater. Biochar regeneration and reuse is also an issue, as thermal or chemical regeneration processes could damage its structure or be costly [72]. In other cases, biochar can leach undesired chemicals, such as heavy metals or polyaromatic hydrocarbons, especially when it is produced from contaminated or improperly managed feedstocks. Its adsorption behavior is also affected by environmental conditions like pH, temperature, and ionic strength, which can detract from its dependability in fluctuating field conditions. Besides, diminished adsorption kinetics and scalability issues of production also reduce its useful application. These issues emphasize the need for novel modification techniques and hybrid technologies to enhance the efficiency and reliability of biochar in wastewater treatment operations [65,67].

5. Zeolite

Zeolite is a crystalline microporous material extensively utilized in wastewater treatment due to its exceptional ion exchange and adsorption properties. Its framework consists of aluminosilicate tetrahedra arranged in a regular lattice, which facilitates the selective adsorption of pollutants [22,78].

Zeolitic tuffs have been discovered globally since the initial identification of zeolitic minerals in volcanogenic sedimentary rocks. Over the last few decades, natural zeolites have found numerous applications in the construction industry, agriculture, adsorption, soil remediation, energy, and catalysis [79].

Natural zeolites are porous, hydrated aluminosilicate minerals with valuable physicochemical properties, including sorption,

catalysis, molecular sieving, and cation exchange [80]. Due to these properties and their widespread availability, natural zeolites are increasingly popular for environmental applications [81].

5.1. Mechanism of zeolite synthesis and application in wastewater treatment

The synthesis of aluminosilicate zeolites primarily involves hydrothermal synthesis, a thermally activated process carried out in an alkaline supersaturated solution [82]. The transformation of a mixture containing silicon, aluminum, metal cations, organic molecules, and water into a crystalline microporous aluminosilicate occurs in three major steps:

Preparation: A highly concentrated solution of silica, alumina, and other constituents is prepared in an alkaline environment.

Nucleation: It begins when supersaturation is achieved. At this stage, the initial entities that form the building blocks of the zeolite lattice start to assemble. These nuclei act as seeds for the formation of crystalline structures.

Crystalline growth: following nucleation, crystalline growth develops the microporous zeolite. Crystallization is temperature-dependent, with higher temperatures enhancing the growth and yield of the crystals. Before crystallization, the gel was aged at sub-crystallization temperatures to stabilize it and ensure the quality of the crystals in the final synthesis phase.

5.2 Application of zeolite

The applications of zeolites in wastewater treatment are based on their microporous crystalline structure and ion exchange capabilities (Figure 4). These properties are directly related to the process of synthesizing zeolites, which determines the size of the pores that the material will have, its chemical composition, and its adsorption efficiency [22,83-84].

Adsorption and molecular sieving: The microporous framework traps molecules based on size, thus enabling the removal of organic pollutants and specific nutrients such as ammonium and phosphorus.



Figure 4. Zeolite synthesis and application

Ion exchange: Zeolites exchange their intrinsic cations, such as Na⁺ and K⁺, with contaminants including heavy metals like Pb²⁺ and Cd²⁺ and ammonium ions, NH₄⁺, thus purifying the water.

Catalysis: Acid-base properties of zeolites derived from their synthesis promote chemical reactions in wastewater treatment, such as partial decomposition of complex pollutants.

5.3. Advantages of zeolites

Zeolites are naturally abundant minerals that can be synthesized at relatively low costs, particularly in resource-poor regions [85]. Their ion exchange capacity and molecular sieving properties enable the selective removal of specific contaminants, including ammonium, phosphorus, and heavy metals such as lead, cadmium, and arsenic [86].

Zeolites have low environmental impacts during use and at the end of their lifecycle, as their regeneration produces less waste compared to synthetic adsorbents, enhancing sustainability in environmental applications [86].

Munir *et al.* (2024) explores the use of zeolite nanocomposites to remove microplastics, ammonia, and trace metals from wastewater, emphasizing their efficiency and cost-effectiveness.

5.4. Limitations of zeolites in waste-water treatment

Natural zeolites also vary in composition and purity, leading to inconsistent performance in

wastewater treatment processes [71,76,87]. This variability makes it challenging to achieve predictable outcomes in different treatment systems [14,22].

Overcoming these shortcomings requires further development, either by modifying the structure of zeolites or incorporating them with other materials to extend their applicability and improve efficiency in complex wastewater cases [22,86,88-89].

6. Nanomaterials

Nanomaterials are materials engineered at the nanoscale, typically ranging from 1 to 100 nanometers. The small size makes them unique in many properties compared to their bulk counterparts. It is these unique properties that make them so useful in many applications in various fields [90,91].

6.1. Application of nanomaterials

Nanomaterials are highly effective in wastewater treatment due to their extraordinary physical, chemical, and optical properties [90]. With sizes less than 100 nm, they have a high surface area-to-volume ratio, exceptional reactivity, and multifunctionality. These nanomaterials are prepared through adsorption, photocatalysis, or antimicrobial activity. For instance, carbon-based nanomaterials, such as graphene oxide and carbon nanotubes, effectively adsorb heavy metals and organic pollutants, while metal nanoparticles, including silver and copper,

exhibit strong antimicrobial properties, and are capable of inactivating pathogens present in water. According to MDPI-Nanomaterials, semiconductor nanoparticles such as TiO_2 and ZnO are among the most popular photocatalytic materials for the degradation of organic pollutants, leading to the decomposition of complex compounds into harmless substances [1].

Nanomaterials have indeed transformed wastewater treatment by offering innovative solutions for multiple processes. Their high surface area and reactivity make them effective in adsorbing heavy metals and dyes. Advanced oxidation is possible with catalysts such as ZnO and TiO_2 . Nanocomposite membranes can improve filtration efficiency, whereas silver nanoparticles provide potent disinfection properties. Magnetic nanoparticles are effective in heavy metal removal, and superhydrophobic materials allow efficient oil-water separation. Additionally, nano biosensors detect pollutants more precisely, while nanomaterials in microbial fuel cells enhance energy production during wastewater treatment. This indicates that nanotechnology has the potential to revolutionize water management, making it cleaner and more sustainable (Table 3).

6.2. Advantages of nanomaterials

Nanomaterials are significantly more effective in adsorption and catalytic efficiency, and hence very efficient in wastewater treatment. With a high surface area, they can selectively adsorb

various pollutants, such as heavy metals and organic contaminants. Moreover, nanomaterials can be prepared for multifunctional applications, such as combining adsorption with catalytic degradation, thereby improving overall treatment efficiency [92].

Although nanomaterials such as CNTs and metal nanoparticles have excellent adsorption and catalytic activity, they are costly to produce and hence not affordable for daily use. Studies such as [92] present the cost barriers of the use of nanomaterials for wastewater treatment. For example, [57] describes the use of graphene oxide and silver nanoparticles for the removal of heavy metals and pathogens from water. However, scalability is an issue due to the high cost of production and the potential environmental impact of nanoparticle waste disposal.

6.3. Limitations of nanomaterials

As nanomaterials have become more affordable, they are now more competitive for cleaning up water and wastewater. However, there are some challenges in using these nanoparticles directly in water and wastewater treatment processes [93,94]. First, in a fluidized system or a rigid bed, nanoparticles have a tendency to aggregate, which causes a considerable decrease in efficiency and increases pressure drop.

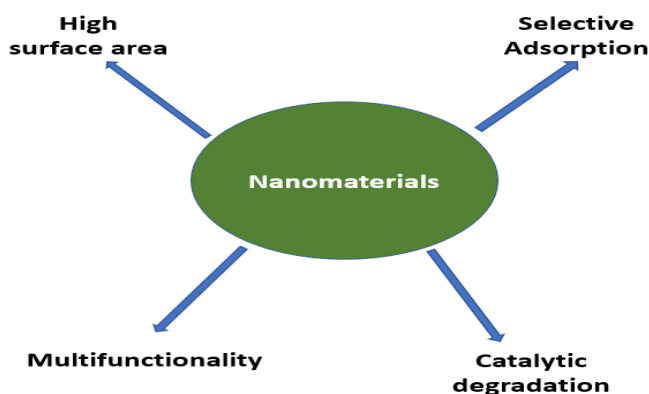


Figure 5. Functional benefits of nanomaterials in wastewater remediation

Table 3. The applications of nanomaterials in wastewater treatment

Application	Description	Example	Ref.
Adsorption	Nanomaterials, especially carbon nanotubes, provide a huge surface area-to mass ratio and are extremely effective in adsorbing contaminant species such as toxic heavy metals and dyes onto their surfaces, which are normally difficult to remove from wastewater.	CNTs have been widely researched in the removal of heavy metal ions and dyes in wastewater.	[92]
Catalysis	Nano-catalysts, metal or metal oxide nanoparticles, promote the oxidation of organic pollutants through advanced oxidation processes, hence enhancing the breaking down of harmful substances.	ZnO nanoparticles have been utilized in organic pollutant degradation in wastewater.	[97]
Membrane filtration	The integration of nanomaterials into membranes enhances their filtration efficiency and selectivity for the effective removal of pathogens, organic compounds, and heavy metals from wastewater.	These nanocomposite membranes, with embedded nanoparticles, enhance the separation of contaminants.	[88]
Disinfection	Silver nanoparticles are highly effective in their antimicrobial action by inactivating bacteria and viruses in water, thus serving as a strong disinfectant.	The silver nanoparticles serve in water disinfection because of their antimicrobial properties.	[97]
Heavy metal removal	Magnetic nanoparticles can be functionalized to bind selectively and remove toxic heavy metals such as arsenic and lead in contaminated water, hence facilitating the extraction.	The application of functionalized magnetic nanoparticles removes heavy metals from water.	[92]
Oil-water separation	Nanostructured material with superhydrophobicity has been employed for separating oil from water and thus may find application in treating industrial effluents and oil spills.	Superhydrophobic nano coatings can help separate oil from water in industrial wastewater.	[97]
Sensors	Nanomaterial-based sensors detect trace amounts of pollutants, enabling sensitive monitoring of water quality and helping in the early detection of contaminants.	Nano-biosensors are being developed to detect contaminants such as nitrates and phosphates in water.	[97]
Energy recovery	Nanomaterials increase the efficiency of microbial fuel cells to effectively deal with wastewater treatments along with power generation, primarily through their enhancement of electron transfer processes.	Nanomaterials are being used in microbial fuel cells to treat wastewater while generating electricity.	[97]

Second, it is still challenging to separate the majority of exhausted nanoparticles (apart from magnetic nanoparticles) from the treated water. From a financial perspective, it is economically unfeasible [95]. Third, there is uncertainty about the effects of nanomaterials on human health and the aquatic environment, as well as the behavior and long-term impacts of nanoparticles in water and wastewater treatment processes [96].

7. Comparative Analysis of Materials in Wastewater Treatment

The selection of the appropriate material for wastewater treatment should be based on its efficiency, cost, and environmental impact. Different materials are used for various types of treatment, from simple turbidity and pathogen removal to complicated contaminant degradation. This section compares the use and performance of five key materials: plant powders, activated carbon, biochar, zeolite, and

nanomaterials, highlighting their strengths, limitations, and market trends to extract insight on their practical applications (Figure 4).

Plant-derived powders, such as *Moringa oleifera*, represent natural and ecological materials that are widely used in wastewater treatment. They are highly effective coagulants, which can efficiently remove turbidity and pathogens [40]. However, their adsorption capacity for heavy metals and organic pollutants is relatively low compared to synthetic materials [98]. Although they are biodegradable and cost-effective, the potential for regeneration of plant powders is limited, as they are mostly single-use and then discarded [99,100].

Activated carbon is an established material in wastewater treatment due to its large surface area and porosity, which provide excellent performance in the adsorption of organic pollutants and heavy metals [55,101]. It is versatile and efficient; however, its production involves moderate to high costs, and thermal regeneration is energy-intensive [102]. The carbon footprint of its production and disposal is also a concern for the environment. However, activated carbon remains one of the most widely used materials for the treatment of many contaminants [103].

Biochar, produced through the pyrolysis of organic biomass, offers a sustainable and cost-effective alternative to wastewater treatment [103]. Its adsorption capacity, influenced by the type of feedstock and pyrolysis conditions, is generally moderate, making it promising for the recovery of nutrients and the removal of organic pollutants [77]. Additionally, biochar contributes to sustainability through carbon sequestration [94,104,105]. However, the current methods are still underdeveloped, and their performance is generally lower compared to activated carbon [62,76].

Both natural and synthetic zeolites exhibit excellent selective adsorption, particularly for cations and small molecules [22]. Their ion-exchange properties make them ideal for removing ammonia and heavy metals [85,106-107]. Zeolites are moderately priced and have a high regeneration potential through ion

exchange [85]. Their lower environmental impact improves their attractiveness for wastewater treatment applications [78,86,108]. Nanomaterials are at the forefront of wastewater treatment due to their catalytic properties and their excellent adsorption [109]. The high surface area-to-volume ratio enables advanced treatment processes such as photocatalysis and disinfection. However, high production costs and limited regeneration methods hinder practical applications, raising concerns about toxicity and environmental persistence. Despite these challenges, nanomaterials have great potential to address complex and advanced contaminants in wastewater [92,110,111].

Due to high costs and environmental concerns, nanomaterials make up only 10% of the wastewater treatment market, despite their high adsorption capacities [112,113]. On the other hand, activated carbon, with proven efficiency, is the market leader at 40%, while zeolite takes second place at 25%. Therefore, the trends in use underscore the need for balancing efficiency, sustainability and cost in material selection (Figure 7).

The choice in wastewater treatment depends on efficacy, cost-effectiveness, and scalability. Activated carbon leads with a market share of about 40% due to its high adsorption efficiency and versatility [55,114]. Zeolite enjoys a market share of 25%, especially because of its ion-exchange properties in the removal of ammonia and heavy metals [22,115]. Biochar, which takes 15%, is the upcoming green alternative [116-118]; nanomaterials hold 10% due to market share due to high production cost and environmental concerns [119,120]. Plant powders also account for 10% and are mainly used in regions that focus on low-cost solutions [42] (Figure 5).

Each material has its strengths and limitations, and the choice of material depends on specific treatment objectives, economic feasibility, and environmental impact considerations. Hybrid systems could optimize the combined benefits of multiple materials, allowing sustainable and efficient wastewater treatment solutions (Figure 6).

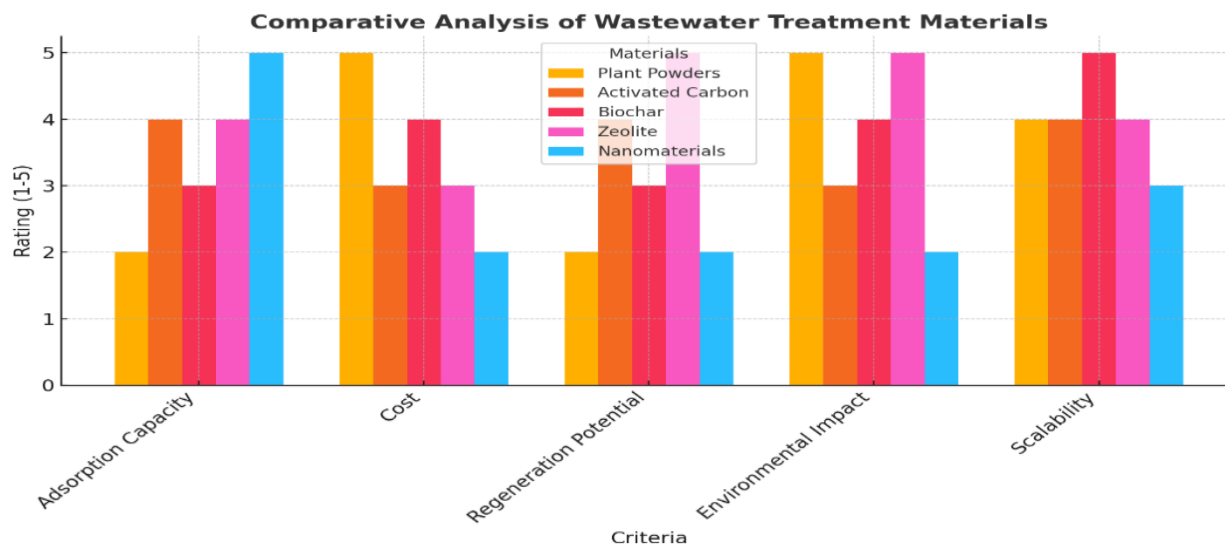


Figure 6. Comparison of plant powders, activated carbon, biochar, zeolite, and nanomaterials based on adsorption capacity, cost, regeneration potential, environmental impact, and scalability

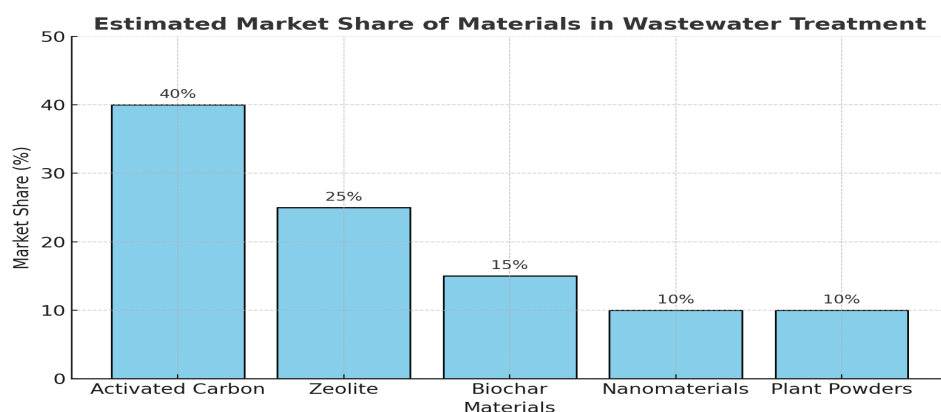


Figure 7. Estimated percentages of market share for various materials in wastewater treatment

8. Conclusion

This review highlights the distinctive advantages and limitations of various materials used in wastewater treatment. Every material has particular merits applicable to specific environmental, technical, and financial situations. Plant powders are inexpensive, sustainable materials best adapted to turbidity and pathogen removal in low-resource settings, yet their adsorption capacity is usually low. Activated carbon remains one of the best and most widely used adsorbents for organic pollutants and heavy metals, but its high regeneration and production costs is an environmental and economic concerns. Biochar

provides a sustainable alternative with moderate adsorption capacity and other benefits such as carbon sequestration. Zeolites, by their selective ion exchange capability, are particularly effective for ammonia and heavy metal removal. Nanomaterials, despite offering increased efficiency and multifunctionality, are constrained by large barriers like high expense, potential environmental toxicity, and reduced scalability.

Future research needs to focus on further developing hybrid systems that combine the low cost and environmental sustainability of natural materials with the efficiency of advanced technologies such as nanomaterials. This course of action will be crucial in shaping

the future of sustainable, scalable, and high-performance wastewater treatment technology.

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Conflicts of Interest

The authors declared that there are no conflicts of interest in this study.

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References

- [1]. a) O.P. Egwuatu, M.O. Ori, H.S. Samuel, F.M. Ekpan, AI-enabled diagnostics and monitoring in nanomedicine, *Eurasian Journal of Science and Technology*, **2024**, *4*, 208-229. [Crossref], [Google Scholar], [Publisher] b) S.T. Khan, A. Malik, Engineered nanomaterials for water decontamination and purification: From lab to products, *Journal of Hazardous Materials*, **2019**, *363*, 295-308. [Crossref], [Google Scholar], [Publisher]
- [2]. B.S. Rathi, P.S. Kumar, Application of adsorption process for effective removal of emerging contaminants from water and wastewater, *Environmental Pollution*, **2021**,

280, 116995. [Crossref], [Google Scholar], [Publisher]

- [3]. A.P. Tom, J.S. Jayakumar, M. Biju, J. Somarajan, M.A. Ibrahim, Aquaculture wastewater treatment technologies and their sustainability: A review, *Energy Nexus*, **2021**, *4*, 100022. [Crossref], [Google Scholar], [Publisher]

- [4]. Y. Wei, J. Wang, C. Gu, Z. Ma, The Relationship between CO₂ Adsorption and Microporous Volume in a Porous Carbon Material, *Chemistry and Technology of Fuels and Oils*, **2021**, *56*, 932-940. [Crossref], [Google Scholar], [Publisher]

- [5]. A. Yirga, O.P. Yadav, T. Dey, Waste orange peel adsorbent for heavy metal removal from water, *Pollution*, **2022**, *8*, 553-566. [Crossref], [Google Scholar], [Publisher]

- [6]. M.O. Raimi, O.T. Vivien, Measures of harm from heavy metal contents (lead and cadmium) in women's lipstick and lipgloss in Yenagoa Metropolis, Bayelsa State, Nigeria, *International Journal of Petrochemistry and Research*, **2018**, *2*, 236-242. [Crossref], [Google Scholar], [Publisher]

- [7]. Y. Wang, L. Chen, Y. Zhu, W. Fang, Y. Tan, Z. He, H. Liao, Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: A scientometric review, *Environmental Sciences Europe*, **2024**, *36*, 25. [Crossref], [Google Scholar], [Publisher]

- [8]. A. Harper, L. Leatherbury, A. Machuca, J. Phillips, The impact of switching to international financial reporting standards on United States businesses, *Journal of International Education Research*, **2012**, *8*, 467-472. [Crossref], [Google Scholar], [Publisher]

- [9]. N. Singh, G. Nagpal, S. Agrawal, Water purification by using adsorbents: a review, *Environmental technology & innovation*, **2018**, *11*, 187-240. [Crossref], [Google Scholar], [Publisher]

- [10]. S. Mitra, A.J. Chakraborty, A.M. Tareq, T.B. Emran, F. Nainu, A. Khusro, A.M. Idris, M.U. Khandaker, H. Osman, F.A. Alhumaydhi, Impact of heavy metals on the environment and human

- health: Novel therapeutic insights to counter the toxicity, *Journal of King Saud University-Science*, **2022**, *34*, 101865. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [11]. Y. Xu, Y. Zhu, Z. Chen, J. Zhu, G. Chen, A comprehensive review on forward osmosis water treatment: Recent advances and prospects of membranes and draw solutes, *International Journal of Environmental Research and Public Health*, **2022**, *19*, 8215. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [12]. S. Boinpally, A. Kolla, J. Kainthola, R. Kodali, J. Vemuri, A state-of-the-art review of the electrocoagulation technology for wastewater treatment, *Water Cycle*, **2023**, *4*, 26-36. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [13]. C.K. Mbamba, D.J. Batstone, X. Flores-Alsina, S. Tait, A generalised chemical precipitation modelling approach in wastewater treatment applied to calcite, *Water Research*, **2015**, *68*, 342-353. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [14]. G. Crini, E. Lichtfouse, Advantages and disadvantages of techniques used for wastewater treatment, *Environmental Chemistry Letters*, **2019**, *17*, 145-155. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [15]. N. Karić, A.S. Maia, A. Teodorović, N. Atanasova, G. Langergraber, G. Crini, A.R. Ribeiro, M. Đolić, Bio-waste valorisation: Agricultural wastes as biosorbents for removal of (in) organic pollutants in wastewater treatment, *Chemical Engineering Journal Advances*, **2022**, *9*, 100239. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [16]. Y.A. Neolaka, A.A. Riwu, U.O. Aigbe, K.E. Ukhurebor, R.B. Onyancha, H. Darmokoesoemo, H.S. Kusuma, Potential of activated carbon from various sources as a low-cost adsorbent to remove heavy metals and synthetic dyes, *Results in Chemistry*, **2023**, *5*, 100711. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [17]. N.E.P. da Silva, L.C.A. Bezerra, R.F. Araújo, T.A. Moura, L.H.S. Vieira, S.B.S. Alves, L.G. Fregolente, O.P. Ferreira, F. Avelino, Coconut shell-based biochars produced by an innovative thermochemical process for obtaining improved lignocellulose-based adsorbents, *International Journal of Biological Macromolecules*, **2024**, *275*, 133685. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [18] D.E. Obasi , M.F. Ajayi , N.N. Chimezie , A.R. Afuape , M.G. Udoisoh , O.J. Edun, C.C. Ezeoma, S. U. Aiso ,D.T. Menankiti , A.G. Oluchukwu, I.E. Akemu, U.D. Donatus, C. Allan-Gyimah , C.O. Njoku, J.I. Ojeniran, Optimization of Pharmaceutical Wastewater Treatment Using Tiger Nut and TiO₂: A comparative study of photocatalytic degradation and adsorption efficiency, *Progress in Chemical and Biochemical Research*, **2024**, *8*, 1-21. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [19]. F. Ali, S. Fazal, N. Iqbal, A. Zia, F. Ahmad, PANI-based nanocomposites for the removal of dye from wastewater, *Journal of Medicinal and Nanomaterials Chemistry*, **2023**, *5*, 106-124. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [20] S. Nozariamini, R. Rahimiyan, and S. Miryousefi ata, Investigation of metal toxins in industrial wastewater, *Progress in Chemical and Biochemical Research*, **2020**, *3*, 377-389. [[Crossref](#)], [[Publisher](#)]
- [21]. F. Ghanaat, L. Vafajoo, M. Haddadi, Affecting parameters on photocatalytic degradation of organic contaminants in a synthesized wastewater utilizing concentrated solar UV, *Progress in Chemical and Biochemical Research*, **2022**, *5*, 331-337. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [22]. S. Kumari, J. Chowdhry, M. Kumar, M.C. Garg, Zeolites in wastewater treatment: A comprehensive review on scientometric analysis, adsorption mechanisms, and future prospects, *Environmental Research*, **2024**, 119782. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [23]. M. Liu, X. Xue, B. Zhou, Y. Zhang, B. Sun, J. Chen, X. Li, Population susceptibility differences and effects of air pollution on cardiovascular mortality: epidemiological evidence from a time-series study, *Environmental Science and Pollution Research*, **2019**, *26*, 15943-15952. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

- [24]. K. Kaur, R. Jindal, Synergistic effect of organic-inorganic hybrid nanocomposite ion exchanger on photocatalytic degradation of Rhodamine-B dye and heavy metal ion removal from industrial effluents, *Journal of environmental chemical engineering*, **2018**, *6*, 7091-7101. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [25]. Q. Ge, Q. Tian, S. Wang, J. Zhang, R. Hou, Highly efficient removal of lead/cadmium by phosphoric acid-modified hydrochar prepared from fresh banana peels: Adsorption mechanisms and environmental application, *Langmuir*, **2022**, *38*, 15394-15403. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [26]. P.V. Thitame, S.R. Shukla, Removal of lead (II) from synthetic solution and industry wastewater using almond shell activated carbon, *Environmental Progress & Sustainable Energy*, **2017**, *36*, 1628-1633. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [27]. I.W. Almanassra, M.I. Khan, M.A. Atieh, A. Shanableh, Adsorption of lead ions from an aqueous solution onto NaOH-modified rice husk, *Desalination and Water Treatment*, **2022**, *262*, 152-167. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [28]. Y. Zhang, J. Qu, Y. Yuan, H. Song, Y. Liu, S. Wang, Y. Tao, Y. Zhao, Z. Li, Simultaneous scavenging of Cd (II) and Pb (II) from water by sulfide-modified magnetic pinecone-derived hydrochar, *Journal of Cleaner Production*, **2022**, *341*, 130758. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [29]. H. Zhang, G.W. Li, W. Feng, Z.Y. Yao, Cu (II) Adsorption from aqueous solution onto poly (acrylic acid/chestnut shell pigment) hydrogel, *Water*, **2022**, *14*, 3500. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [30]. M. Jalali, F. Aboulghazi, Sunflower stalk, an agricultural waste, as an adsorbent for the removal of lead and cadmium from aqueous solutions, *Journal of Material Cycles and Waste Management*, **2013**, *15*, 548-555. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [31]. S. Mandal, S. Hwang, S.Q. Shi, Guar gum, a low-cost sustainable biopolymer, for wastewater treatment: A review, *International Journal of Biological Macromolecules*, **2023**, *226*, 368-382. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [32]. M. Malakootian, M.R. Heidari, Reactive orange 16 dye adsorption from aqueous solutions by psyllium seed powder as a low-cost biosorbent: kinetic and equilibrium studies, *Applied Water Science*, **2018**, *8*, 1-9. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [33]. S.N. Zulkifli, H.A. Rahim, W.-J. Lau, Detection of contaminants in water supply: A review on state-of-the-art monitoring technologies and their applications, *Sensors and Actuators B: Chemical*, **2018**, *255*, 2657-2689. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [34]. M. Espindola-Rodriguez, Y. Sanchez, S. López-Marino, D. Sylla, M. Placidi, M. Neuschitzer, H. Xie, V. Izquierdo-Roca, O. Vigil-Galán, E. Saucedo, Selenization of Cu₂₂nSnS₄ thin films obtained by pneumatic spray pyrolysis, *Journal of Analytical and Applied Pyrolysis*, **2016**, *120*, 45-51. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [35]. X. Tang, G. Ran, J. Li, Z. Zhang, C. Xiang, Extremely efficient and rapidly adsorb methylene blue using porous adsorbent prepared from waste paper: Kinetics and equilibrium studies, *Journal of hazardous materials*, **2021**, *402*, 123579. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [36]. J. Lee, E. Kim, G. Han, J.V. Tongco, S.G. Shin, S. Hwang, Microbial communities underpinning mesophilic anaerobic digesters treating food wastewater or sewage sludge: a full-scale study, *Bioresource technology*, **2018**, *259*, 388-397. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [37]. M. Imran-Shaukat, R. Wahi, Z. Ngaini, The application of agricultural wastes for heavy metals adsorption: A meta-analysis of recent studies, *Bioresource Technology Reports*, **2022**, *17*, 100902. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

- [38]. J. Song, L. Chen, Y. Zhou, Z. Yuan, Y. Niu, Z. Wei, Efficient adsorptive separation of Cu (II) from Ph by ZIF-8 constructed with sodium alginate polymer backbone, *International Journal of Biological Macromolecules*, **2024**, *279*, 135501. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [39]. A.I. Osman, E.M.A. El-Monaem, A.M. Elgarahy, C.O. Aniagor, M. Hosny, M. Farghali, E. Rashad, M.I. Ejimofor, E.A. López-Maldonado, I. Ihara, Methods to prepare biosorbents and magnetic sorbents for water treatment: a review, *Environmental Chemistry Letters*, **2023**, *21*, 2337-2398. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [40]. W.M. Desta, M.E. Bote, Wastewater treatment using a natural coagulant (Moringa oleifera seeds): optimization through response surface methodology, *Heliyon*, **2021**, *7*. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [41]. B. Alyüz, S. Veli, Kinetics and equilibrium studies for the removal of nickel and zinc from aqueous solutions by ion exchange resins, *Journal of hazardous materials*, **2009**, *167*, 482-488. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [42]. C. Mayer-Laigle, J. Beaugrand, A. Bourmaud, L. Brionne, T. Colinart, S. Dervaux, C. Fabre, M.-J. Le Guen, K. Kenschak, G. Paës, Datasets on the production routes and the properties of plant powders for manufacturing of green products, *Data in Brief*, **2024**, *56*, 110787. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [43]. K.H.D. Tang, Valorization of organic waste as biosorbents for wastewater treatment, *Water Emerging Contaminants & Nanoplastics*, **2024**, *3*, N/A-N/A. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [44]. F.C. Moura, R.D. Rios, B.R. Galvão, Emerging contaminants removal by granular activated carbon obtained from residual Macauba biomass, *Environmental Science and Pollution Research*, **2018**, *25*, 26482-26492. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [45]. M. Gutiérrez, V. Grillini, D.M. Pavlović, P. Verlicchi, Activated carbon coupled with advanced biological wastewater treatment: A review of the enhancement in micropollutant removal, *Science of the Total Environment*, **2021**, *790*, 148050. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [46]. D. Duan, D. Chen, L. Huang, Y. Zhang, Y. Zhang, Q. Wang, G. Xiao, W. Zhang, H. Lei, R. Ruan, Activated carbon from lignocellulosic biomass as catalyst: A review of the applications in fast pyrolysis process, *Journal of Analytical and Applied Pyrolysis*, **2021**, *158*, 105246. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [47]. M.S. Muzarpar, A. Leman, N. Maghpor, N.N.M. Hassan, N. Misdana, the adsorption mechanism of activated carbon and its application-A review, *International Journal of Advanced Technology in Mechanical, Mechatronics and Materials*, **2020**, *1*, 118-124. [[Google Scholar](#)], [[Publisher](#)]
- [48]. L.S. Chua, N. Abd Latiff, M. Mohamad, Reflux extraction and cleanup process by column chromatography for high yield of andrographolide enriched extract, *Journal of applied research on medicinal and aromatic plants*, **2016**, *3*, 64-70. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [49]. G. Li, J. Li, W. Tan, M. Yang, H. Wang, X. Wang, Effectiveness and mechanisms of the adsorption of carbendazim from wastewater onto commercial activated carbon, *Chemosphere*, **2022**, *304*, 135231. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [50]. D.P. Gonde, B.K. Bhole, K.S. Kakad, Andrographolide, diterpenoid constituent of *Andrographis paniculata*: Review on botany, phytochemistry, molecular docking analysis, and pharmacology, *Annales Pharmaceutiques Francaises*, **2024**, 15-43. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [51]. D. Wu, X. Cao, S. Wu, Overlapping elution-extrusion counter-current chromatography: A novel method for efficient purification of natural cytotoxic andrographolides from *Andrographis paniculata*, *Journal of Chromatography A*, **2012**, *1223*, 53-63. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

- [52]. E.I. Ugwu, J.C. Agunwamba, A review on the applicability of activated carbon derived from plant biomass in adsorption of chromium, copper, and zinc from industrial wastewater, *Environmental monitoring and assessment*, **2020**, *192*, 240. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [53]. K.S. Fisher, A.J. Vreugdenhil, Adsorption of chromium (VI) using an activated carbon derived from petroleum coke feedstock, *International Journal of Molecular Sciences*, **2022**, *23*, 16172. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [54]. P.S. Kumar, L. Korving, K.J. Keesman, M.C. van Loosdrecht, G.-J. Witkamp, Effect of pore size distribution and particle size of porous metal oxides on phosphate adsorption capacity and kinetics, *Chemical Engineering Journal*, **2019**, *358*, 160-169. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [55]. S. Wong, N. Ngadi, I.M. Inuwa, O. Hassan, Recent advances in applications of activated carbon from biowaste for wastewater treatment: a short review, *Journal of Cleaner Production*, **2018**, *175*, 361-375. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [56]. H. Laksaci, B. Belhamdi, O. Khelifi, A. Khelifi, M. Trari, Elimination of amoxicillin by adsorption on coffee waste based activated carbon, *Journal of Molecular Structure*, **2023**, *1274*, 134500. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [57]. E. Singh, A. Kumar, R. Mishra, S. You, L. Singh, S. Kumar, R. Kumar, Pyrolysis of waste biomass and plastics for production of biochar and its use for removal of heavy metals from aqueous solution, *Bioresource Technology*, **2021**, *320*, 124278. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [58]. Y. Shao, J. Li, X. Fang, Z. Yang, Y. Qu, M. Yang, W. Tan, G. Li, H. Wang, Chemical modification of bamboo activated carbon surface and its adsorption property of simultaneous removal of phosphate and nitrate, *Chemosphere*, **2022**, *287*, 132118. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [59]. M.M. Sabzehmeidani, S. Mahnaee, M. Ghaedi, H. Heidari, V.A. Roy, Carbon based materials: a review of adsorbents for inorganic and organic compounds, *Materials Advances*, **2021**, *2*, 598-627. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [60]. P. Nume, T. Sangtawesin, M. Yilmaz, K. Kanjana, Activated carbon derived from radiation-processed durian shell for energy storage application, *Carbon Resources Conversion*, **2024**, *7*, 100192. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [61]. Z. Dehgani, M. Ghaedi, M.M. Sabzehmeidani, E. Adhami, Removal of paraquat from aqueous solutions by a bentonite modified zero-valent iron adsorbent, *New Journal of Chemistry*, **2020**, *44*, 13368-13376. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [62]. Q. Zhou, W. Yang, L. Wang, H. Lu, S. Nie, L. Xu, W. Yang, C. Wei, Biomass carbon materials for high-performance secondary battery electrodes: A review, *Resources Chemicals and Materials*, **2024**, *3*, 123-145. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [63]. J. Speight, Production of fuels from nonfossil fuel feedstocks, *The Refinery of the Future*, **2020**, 391-426. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [64]. J.M. Illingworth, B. Rand, P.T. Williams, Understanding the mechanism of two-step, pyrolysis-alkali chemical activation of fibrous biomass for the production of activated carbon fibre matting, *Fuel Processing Technology*, **2022**, *235*, 107348. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [65]. K. Abhishek, A. Shrivastava, V. Vimal, A.K. Gupta, S.K. Bhujbal, J.K. Biswas, L. Singh, P. Ghosh, A. Pandey, P. Sharma, Biochar application for greenhouse gas mitigation, contaminants immobilization and soil fertility enhancement: A state-of-the-art review, *Science of The Total Environment*, **2022**, *853*, 158562. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [66]. N.A.M. Castillo, L.A.G. Fernández, B. Thiodjio-Sendja, M.M. Aguilera-Flores, R. Leyva-Ramos, S.Y. Reyes-López, L.D. de León-Martínez,

- J.M. Dias, Bone char for water treatment and environmental applications: A review, *Journal of Analytical and Applied Pyrolysis*, **2023**, *175*, 106161. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [67]. M.O. Omondi, X. Xia, A. Nahayo, X. Liu, P.K. Korai, G. Pan, Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data, *Geoderma*, **2016**, *274*, 28-34. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [68]. Q. Yin, B. Zhang, R. Wang, Z. Zhao, Biochar as an adsorbent for inorganic nitrogen and phosphorus removal from water: A review, *Environmental Science and Pollution Research*, **2017**, *24*, 26297-26309. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [69]. M.A. Al Masud, W.S. Shin, A. Sarker, A. Septian, K. Das, D.M. Deepo, M.A. Iqbal, A.R.M.T. Islam, G. Malafaia, A critical review of sustainable application of biochar for green remediation: Research uncertainty and future directions, *Science of The Total Environment*, **2023**, *904*, 166813. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [70]. T.G. Ambaye, M. Vaccari, E.D. van Hullebusch, A. Amrane, S. Rtimi, Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater, *International Journal of Environmental Science and Technology*, **2021**, *18*, 3273-3294. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [71]. G. Zeng, M. Si, C. Dong, Q. Liao, F. He, V.E. Johnson, C. Arinzechi, W. Yang, Z. Yang, Adsorption behavior of lead, cadmium, and arsenic on manganese-modified biochar: competition and promotion, *Environmental Geochemistry and Health*, **2024**, *46*, 86. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [72]. X. Shi, W. Yang, J. Li, Z. Yao, The application of biochar as heavy metals adsorbent: The preparation, mechanism, and perspectives, *International Journal of Environmental Research*, **2024**, *18*, 41. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [73]. J. Lehmann, S. Joseph, Biochar for environmental management: science, technology and implementation, *Taylor & Francis*, **2024**. [[Google Scholar](#)], [[Publisher](#)]
- [74]. M. Ahmad, A.U. Rajapaksha, J.E. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S.S. Lee, Y.S. Ok, Biochar as a sorbent for contaminant management in soil and water: a review, *Chemosphere*, **2014**, *99*, 19-33. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [75]. A. Shah, J. Zakharova, M. Batool, M.P. Coley, A. Arjunan, A.J. Hawkins, T. Bolarinwa, S. Devi, A. Thumma, C. Williams, Removal of cadmium and zinc from water using sewage sludge-derived biochar, *Sustainable Chemistry for the Environment*, **2024**, *6*, 100118. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [76]. Y. Wang, L. Chen, Y. Zhu, W. Fang, Y. Tan, Z. He, H. Liao, Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: a scientometric review, *Environmental Sciences Europe*, **2024**, *36*, 25. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [77]. M. Afshar, S. Mofatteh, Biochar for a sustainable future: Environmentally friendly production and diverse applications, *Results in Engineering*, **2024**, 102433. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [78]. S. Wang, Y. Peng, Natural zeolites as effective adsorbents in water and wastewater treatment, *Chemical engineering journal*, **2010**, *156*, 11-24. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [79]. C. Colella, W.S. Wise, The IZA Handbook of Natural Zeolites: A tool of knowledge on the most important family of porous minerals, *Microporous and mesoporous materials*, **2014**, *189*, 4-10. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [80]. a) Mohsen Doust Mohammadi, Hewa Y Abdullah, Vijayanand Kalamse, Ajay Chaudhari, Interaction of Fluorouracil drug with boron nitride nanotube, Al doped boron nitride nanotube and BC2N nanotube, *Computational and Theoretical Chemistry*, **2022**, *1212*, 113699. [[Crossref](#)], [[Google Scholar](#)],

- [Publisher] b) V. GirijaVenii, K.S. Reddy, K. Sharma, K.S. Shankar, J. Rohit, Role of zeolites in improving nutrient and water storage capacity of soil and their impact on overall soil quality and crop performance, *Soil Science: Fundamentals to Recent Advances*, **2021**, 449-467. [Crossref], [Google Scholar], [Publisher]
- [81]. I. El Bojaddayni, M.E. Küçük, Y. El Ouardi, I. Jilal, S. El Barkany, K. Moradi, E. Repo, K. Laatikainen, A. Ouammou, A review on synthesis of zeolites from natural clay resources and waste ash: Recent approaches and progress, *Minerals Engineering*, **2023**, *198*, 108086. [Crossref], [Google Scholar], [Publisher]
- [82]. L.D. Youcef, A. López-Galindo, C. Verdugo-Escamilla, L.S. Belaroui, Synthesis and characterization of zeolite LTA by hydrothermal transformation of a natural Algerian palygorskite, *Applied Clay Science*, **2020**, *193*, 105690. [Crossref], [Google Scholar], [Publisher]
- [83]. D. Kallo, Applications of natural zeolites in water and wastewater treatment, *Reviews in mineralogy and geochemistry*, **2001**, *45*, 519-550. [Crossref], [Google Scholar], [Publisher]
- [84]. E.J. Feijen, J.A. Martens, P.A. Jacobs, Zeolites and their mechanism of synthesis, *Studies in Surface Science and Catalysis*, Elsevier 1994, pp. 3-21. [Crossref], [Google Scholar], [Publisher]
- [85]. A. Khaleque, M.M. Alam, M. Hoque, S. Mondal, J.B. Haider, B. Xu, M. Jahir, A.K. Karmakar, J. Zhou, M.B. Ahmed, Zeolite synthesis from low-cost materials and environmental applications: A review, *Environmental advances*, **2020**, *2*, 100019. [Crossref], [Google Scholar], [Publisher]
- [86]. N. Munir, A. Javaid, Z. Abideen, B. Duarte, H. Jarar, A. El-Keblawy, M.S. Sheteiwy, The potential of zeolite nanocomposites in removing microplastics, ammonia, and trace metals from wastewater and their role in phytoremediation, *Environmental Science and Pollution Research*, **2024**, *31*, 1695-1718. [Crossref], [Google Scholar], [Publisher]
- [87]. J. Wen, H. Dong, G. Zeng, application of zeolite in removing salinity/sodicity from wastewater: A review of mechanisms, challenges and opportunities, *Journal of Cleaner Production*, **2018**, *197*, 1435-1446. [Crossref], [Google Scholar], [Publisher]
- [88]. Á. de Jesús Ruíz-Baltazar, Advancements in nanoparticle-modified zeolites for sustainable water treatment: An interdisciplinary review, *Science of The Total Environment*, **2024**, 174373. [Crossref], [Google Scholar], [Publisher]
- [89]. M. Parmar, M. Bandyopadhyay, R. Gaur, S. Shahabuddin, Synthesis and Characterization of Amine-Functionalized Zeolite 4A for Wastewater Treatment, *International Conference on Advances in Water Treatment and Management*, **2023**, 19-29. [Crossref], [Google Scholar], [Publisher]
- [90]. M. Sajid, Nanomaterials: types, properties, recent advances, and toxicity concerns, *Current Opinion in Environmental Science & Health*, **2022**, *25*, 100319. [Crossref], [Google Scholar], [Publisher]
- [91] K. T. Ramesh and K. Ramesh, *Nanomaterials*, Springer, **2009**. [Google Scholar], [Publisher]
- [92]. H. Sadegh, G.A. Ali, V.K. Gupta, A.S.H. Makhlof, R. Shahryari-Ghoshekandi, M.N. Nadagouda, M. Sillanpää, E. Megiel, The role of nanomaterials as effective adsorbents and their applications in wastewater treatment, *Journal of Nanostructure in Chemistry*, **2017**, *7*, 1-14. [Crossref], [Google Scholar], [Publisher]
- [93]. M.A. Makhesana, K.M. Patel, A. Nyabadza, Applicability of nanomaterials in water and waste-water treatment: A state-of-the-art review and future perspectives, *Materials Today: Proceedings*, **2024**. [Crossref], [Google Scholar], [Publisher]
- [94] Y. Zhang, B. Wu, H. Xu, H. Liu, M. Wang, Y. He, B. Pan, Nanomaterials-enabled water and wastewater treatment, *NanoImpact*, **2016**, *3*, 22-39. [Crossref], [Google Scholar], [Publisher]
- [95]. H. Sari Erkan, N. Bakaraki Turan, G. Onkal Engin, M. Bilgili, A review of advantages and

- challenges of using engineered nanoparticles for waste and wastewater treatments, *International Journal of Environmental Science and Technology*, **2021**, *18*, 3295-3306. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [96]. A. Malakar, S.R. Kanel, C. Ray, D.D. Snow, M.N. Nadagouda, Nanomaterials in the environment, human exposure pathway, and health effects: A review, *Science of the Total Environment*, **2021**, *759*, 143470. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [97]. S. Singh, V. Kumar, R. Romero, K. Sharma, J. Singh, Applications of nanoparticles in wastewater treatment, *Nanobiotechnology in Bioformulations*, **2019**, 395-418. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [98]. A.E. Burakov, E.V. Galunin, I.V. Burakova, A.E. Kucherova, S. Agarwal, A.G. Tkachev, V.K. Gupta, Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review, *Ecotoxicology and environmental safety*, **2018**, *148*, 702-712. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [99]. J.X. Liao, P.S. So, S. Bordoloi, D.N. Li, H.R. Yuan, Y. Chen, L.Q. Xin, Plant performance and soil-plant carbon relationship response to different biochar types, *Biochar*, **2024**, *6*, 75. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [100]. F. Haq, M. Kiran, I.A. Khan, S. Mehmood, T. Aziz, M. Haroon, Exploring the Pathways to Sustainability: A Comprehensive Review of Biodegradable Plastics in the Circular Economy, *Materials Today Sustainability*, **2024**, 101067. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [101]. A. Larasati, G.D. Fowler, N.J. Graham, Insights into chemical regeneration of activated carbon for water treatment, *Journal of Environmental Chemical Engineering*, **2021**, *9*, 105555. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [102]. I. Pet, M.N. Sanad, M. Farouz, M.M. ElFaham, A. El-Hussein, M.A. El-Sadek, R.A. Althobiti, A. Ioanid, Recent Developments in the Implementation of Activated Carbon as Heavy Metal Removal Management, *Water Conservation Science and Engineering*, **2024**, *9*, 62. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [103]. M.Z. Yameen, S.R. Naqvi, D. Juchelková, M.N.A. Khan, Harnessing the power of functionalized biochar: Progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability, *Biochar*, **2024**, *6*, 25. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [104]. B.A. Oni, O. Oziegbe, O.O. Olawole, Significance of biochar application to the environment and economy, *Annals of Agricultural Sciences*, **2019**, *64*, 222-236. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [105]. L. Gogoi, N. Baruah, P. Taifa, N. Gogoi, Use of Biochar for Mitigating Greenhouse Gas Emission in Agriculture, *Agricultural Greenhouse Gas Emissions: Problems and Solutions*, **2024**, 173-204. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [106]. C. Feng, E. Jiaqiang, W. Han, Y. Deng, B. Zhang, X. Zhao, D. Han, Key technology and application analysis of zeolite adsorption for energy storage and heat-mass transfer process: A review, *Renewable and sustainable energy reviews*, **2021**, *144*, 110954. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [107]. B. Yue, S. Liu, Y. Chai, G. Wu, N. Guan, L. Li, Zeolites for separation: Fundamental and application, *Journal of Energy Chemistry*, **2022**, *71*, 288-303. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [108]. M.H. Saleem, M.F.B. Mfarrej, K.A. Khan, S.A. Alharthy, Emerging trends in wastewater treatment: Addressing microorganic pollutants and environmental impacts, *Science of the Total Environment*, **2024**, *913*, 169755. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [109]. Y. Devarajan, Nanomaterials-Based Wastewater Treatment: Addressing Challenges and Advancing Sustainable Solutions, *BioNanoScience*, **2025**, *15*, 1-14. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [110]. A. Sharma, H. Goel, S. Sharma, H.S. Rathore, I. Jamir, A. Kumar, S.C. Thimmappa, K.K. Kesari, B.K. Kashyap, Cutting edge

- technology for wastewater treatment using smart nanomaterials: recent trends and futuristic advancements, *Environmental Science and Pollution Research*, **2024**, *31*, 58263-58293. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [111]. S. Tyagi, R.T. Kapoor, S. Solanki, A. Goyal, R. Singh, Nanomaterial mediated wastewater treatment: a new frontier in environmental remediation, *Microbiome-Based Decontamination of Environmental Pollutants*, **2024**, 31-49. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [112]. S. Satyam, S. Patra, Innovations and challenges in adsorption-based wastewater remediation: a comprehensive review, *Heliyon*, **2024**. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [113]. S. Zahmatkesh, M. Hajiaghaei-Keshteli, A. Bokhari, S. Sundaramurthy, B. Panneerselvam, Y. Rezakhani, Wastewater treatment with nanomaterials for the future: A state-of-the-art review, *Environmental Research*, **2023**, *216*, 114652. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [114]. N.N. de Lima, J.R.M. de Souza, A. de Cássia Oliveira Carneiro, Í.L. Nunes, A.B.T. Viana, M.L. da Silva, Production, application and market of activated carbon in Brazil: A review, *International Wood Products Journal*, **2021**, *12*, 240-248. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [115]. R.O.A. Rahman, A.M. El-Kamash, Y.T. Hung, Applications of nano-zeolite in wastewater treatment: An overview, *Water*, **2022**, *14*, 137. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [116]. S.K. Thengane, K. Kung, J. Hunt, H.R. Gilani, C.J. Lim, S. Sokhansanj, D.L. Sanchez, Market prospects for biochar production and application in California, *Biofuels, Bioproducts and Biorefining*, **2021**, *15*, 1802-1819. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [117]. B. Garcia, O. Alves, B. Rijo, G. Lourinho, C. Nobre, Biochar: production, applications, and market prospects in Portugal, *Environments*, **2022**, *9*, 95. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [118]. J. Maroušek, A. Maroušková, O. Strunecký, B. Minofar, Markets for biochar products and services, *Biochar for Environmental Management*, *Routledge*, **2024**, 805-817. [[Google Scholar](#)], [[Publisher](#)]
- [119]. M. Kamali, K.M. Persson, M.E. Costa, I. Capela, Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: current status and future outlook, *Environment International*, **2019**, *125*, 261-276. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [120]. G. Palani, A. Arputhalatha, K. Kannan, S.K. Lakkaboyana, M.M. Hanafiah, V. Kumar, R.K. Marella, Current trends in the application of nanomaterials for the removal of pollutants from industrial wastewater treatment—a review, *Molecules*, **2021**, *26*, 2799. [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]