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From Ancient Wisdom To Green Chemistry: Unveiling The Magic Of Natural Adsorbents For Water Purification.

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ABSTRACT

This comprehensive review explores the historical evolution, advantages, types, efficiency factors, enhancement techniques, challenges, and future prospects of natural adsorbents for water pollutants removal. The use of natural adsorbents, derived from diverse sources like activated carbon, clay minerals, chitosan, agricultural by-products, and aquatic plants, is rooted in centuries-old practices and aligns with contemporary goals of environmental sustainability. The advantages of natural adsorbents, including environmental friendliness, cost-effectiveness, abundance, versatility, and community involvement, underscore their significance in green chemistry and sustainable water purification. Key types of natural adsorbents and their applications are detailed, emphasizing their ability to address a spectrum of pollutants. Factors affecting the efficiency of natural adsorbents, such as surface area, chemical composition, pH, temperature, and regeneration potential, are elucidated. Techniques to improve efficiency, including activation, surface modification, composite materials, and nanostructures, are discussed. Challenges, such as variable adsorption capacities, specificity, regeneration efficiency, and scale-up issues, are identified, alongside future prospects like advanced characterization techniques, nanotechnology integration, and community engagement. The review emphasizes the need for addressing standardization, mechanical stability, long-term performance, and certification to promote wider acceptance. The collective insights from this review provide a roadmap for researchers, policymakers, and practitioners, guiding the continued development and application of natural adsorbents in water treatment. The evolving landscape of natural adsorbents presents exciting opportunities for sustainable and effective solutions to address contemporary water quality challenges.

Keywords: Activated carbon; Agricultural by-products; Environmental sustainability; Enhancement techniques; Pollutant removal; Sustainable water management

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INTRODUCTION

Natural adsorbents are materials derived from natural sources that have the ability to adsorb (or trap) pollutants from water. These materials are environmentally friendly and can be an effective and economical solution for water purification. The use of natural adsorbents for water purification has a long history, dating back centuries. Ancient civilizations, including the Egyptians and Greeks, used charcoal as a water purification method. They recognized its ability to adsorb impurities and improve water taste. Indigenous cultures in various regions used clay vessels for water storage and noticed the water purification benefits of clay, which could adsorb contaminants. The concept of activated carbon emerged in the 18th century [1].

Activated carbon, produced by heating materials like wood or coconut shells, gained popularity for its ability to adsorb a wide range of pollutants. It was used in water treatment in Europe during the 19th century. Activated carbon became a common adsorbent in water treatment plants worldwide during the 20th century. Its use expanded due to its effectiveness in removing organic compounds, odors, and color from water. Natural zeolites, such as clinoptilolite, gained attention for their ion-exchange and adsorption properties. They were utilized for the removal of heavy metals and ammonium from water. In recent decades, there has been extensive research on various natural adsorbents derived from agricultural by-products, waste materials, and plants [2, 3].

Researchers have explored materials like chitosan, rice husk, peat moss, and fruit peels for their adsorption capabilities. The use of certain plants and algae for phytoremediation, a process where plants absorb and accumulate pollutants from water, gained attention. Water hyacinth and duckweed, for example, were studied for their ability to remove heavy metals from water bodies. As environmental concerns grew in the 21st century, there has been a renewed focus on sustainable and eco-friendly water treatment methods. Natural adsorbents align with these goals by being renewable, biodegradable, and often derived from waste materials. Advances in material science have led to the development of new natural adsorbents with enhanced properties [4-6].

Researchers continue to explore and optimize these materials for improved water treatment efficiency. The history of natural adsorbents for water pollutants reflects a continuous evolution driven by a growing understanding of adsorption processes, advancements in technology, and a shift toward more sustainable and environmentally friendly water treatment practices. Ongoing research and innovation in this field aim to further improve the efficacy and applicability of natural adsorbents in addressing diverse water quality challenges [7, 8].

Advantages for the use of natural adsorbents for water pollutants removal

The use of natural adsorbents for water pollutants is important for several reasons, emphasizing environmental sustainability, cost-effectiveness, and versatility. Their use aligns with the principles of green chemistry and sustainable development, contributing to a more environmentally responsible approach to water purification [9]. Some of these advantages are listed as follows:

Environmental Friendliness: Natural adsorbents are derived from renewable resources and are often biodegradable, making them environmentally friendly alternatives to synthetic materials. This minimizes the environmental impact associated with the production, use, and disposal of adsorbents [10,11].

Cost-Effectiveness: Many natural adsorbents are readily available and often come from waste or by-products of agricultural, forestry, or food processing industries. Utilizing these materials can be cost-effective, especially when compared to the production and use of synthetic adsorbents [12,13].

Abundance and Availability: Natural adsorbents are abundant and widely available in various forms, such as activated carbon from coconut shells, clay minerals, agricultural residues, and plant materials. This accessibility makes them attractive for water treatment applications, especially in regions where other treatment methods may be cost-prohibitive [14].

Versatility: Natural adsorbents exhibit a broad range of adsorption capabilities, effectively targeting different types of pollutants, including heavy metals, organic compounds, dyes, and various chemicals. This versatility makes them suitable for addressing diverse water quality issues [10,11].

Community Involvement: The use of natural adsorbents can involve local communities in sustainable water management practices. For instance, agricultural residues, such as rice husks or fruit peels, can be sourced locally, providing economic opportunities for farmers and communities [6].

Reduced Energy Consumption: The production of natural adsorbents typically involves lower energy consumption compared to the manufacturing processes associated with synthetic alternatives. This contributes to a more sustainable and energy-efficient approach to water treatment [15].

Regeneration Potential: Some natural adsorbents can be regenerated and reused, extending their lifecycle and reducing the overall cost of water treatment. This regeneration process can involve simple methods such as washing, drying, or other treatment techniques to restore adsorption capacity [16].

Biocompatibility: Natural adsorbents are often biocompatible and pose fewer risks to human health and the environment compared to certain synthetic materials. This characteristic is particularly important in applications where water is used for drinking or agriculture [17].

Phytoremediation: Certain natural adsorbents, such as certain plants and algae, can actively take up pollutants from water through a process called phytoremediation. This approach integrates water treatment with the natural growth and metabolism of these organisms [18].

Types of natural adsorbents for water pollutants removal

Various types of natural adsorbents can be employed for the removal of water pollutants. These materials are derived from natural sources and exhibit adsorption capabilities towards different types of contaminants [14]. Table (1) shows some common types of natural adsorbents used for water pollutants removal.

Table 1: Some common types of natural adsorbents used for water pollutants removal

Natural Adsorbent	Source (Examples)	Application	Reference
Activated Carbon (Charcoal)	Coconut shells, wood, peat, or agricultural residues.	Effective in adsorbing a wide range of pollutants, including organic compounds, odors, and certain chemicals.	[19-23]
Clay Minerals	Bentonite, kaolin, montmorillonite	Adsorption of heavy metals, organic compounds, and dyes	[24-28]
Chitosan	Chitin, found in the exoskeletons of crustaceans	Effective in adsorbing heavy metals and some organic pollutants	[29-32]
Peat Moss	Partially decomposed organic matter	Adsorption of dyes, pesticides, and organic compounds.	[33-36]
Rice Husk	Outer covering of rice grains.	Adsorption of heavy metals, dyes, and organic pollutants.	[37-40]
Sawdust and Wood-Based Materials	Wood chips, sawdust, and shavings	Adsorption of certain chemicals and organic pollutants	[41-43]
Algae and Aquatic Plants	Water hyacinth, duckweed, algae.	Phytoremediation for the removal of heavy metals and nutrients.	[44-47]
Fungi and Mycelium	*Pleurotus ostreatus* (oyster mushroom), mycelium	Adsorption of heavy metals and organic pollutants	[48-51]
Natural Zeolites	Clinoptilolite, chabazite	Adsorption of ammonium, heavy metals, and certain chemicals.	[52-54]
Bone Char	Animal bones.	Adsorption of fluoride, heavy metals, and organic compounds.	[55-58]

Factors affect the efficiency of natural adsorbents for water pollutants removal

The efficiency of natural adsorbents for water pollutants removal can be influenced by various factors. Understanding and controlling these factors are essential for designing efficient water treatment systems using natural adsorbents. Optimization of these parameters can lead to improved pollutant removal efficiency and the development of sustainable water purification technologies [59-60]. Table (2) shows common factors affecting the adsorption efficiency of natural adsorbents.

Table 2: Some common factors affecting the adsorption efficiency of natural adsorbents

Factor	Impact	Reference
The surface area and porosity of the adsorbent material	Higher surface area and greater porosity typically result in increased adsorption capacity, allowing the adsorbent to capture more pollutants	[61-62]
The particle size of the adsorbent.	Finer particles often provide a larger surface area, which can enhance adsorption efficiency. However, excessively fine particles may lead to compaction and hinder water flow.	[47, 63]
The chemical composition of the natural adsorbent.	The presence of specific functional groups and chemical properties influences the adsorbent's affinity for different types of pollutants. For example, certain materials may be more effective in adsorbing heavy metals, while others may target organic compounds.	[64]
The pH of the water being treated	pH affects the charge of both the adsorbent and the pollutants. Changes in pH can influence the adsorption capacity and selectivity of natural adsorbents	[65, 66]
The temperature of the water and adsorption process.	Temperature can influence the kinetics of adsorption. Generally, higher temperatures may accelerate adsorption, but the impact depends on the specific adsorbent and pollutants.	[67-69]
The initial concentration of pollutants in the water.	Higher pollutant concentrations may lead to saturation of the adsorbent, reducing its effectiveness. Optimal performance is often achieved within a certain concentration range.	[70-72]
The duration of contact between the adsorbent and water.	Adequate contact time is necessary for pollutants to be adsorbed onto the surface of the adsorbent. Insufficient contact time can result in incomplete removal.	[34-38]
The amount of adsorbent added to the water.	The efficiency of pollutant removal often increases with higher adsorbent dosages, up to a point. Beyond that point, excess adsorbent may lead to diminishing returns.	[25-30]
The ability of the adsorbent to be regenerated for reuse.	Adsorbents that can be regenerated and reused offer economic and environmental benefits. The ease and effectiveness of regeneration influence the overall efficiency of the adsorption process.	[73-75]
Presence of other substances in the water.	Some substances may compete with target pollutants for adsorption sites, affecting the overall efficiency. Interference from coexisting substances should be considered in practical applications.	[76,77]
The characteristics of the water matrix.	Properties such as water hardness, organic matter content, and salinity can influence the interactions between the adsorbent and pollutants, impacting efficiency.	[78-80]
The mechanical stability of the adsorbent material.	Mechanical stability is crucial for maintaining the integrity of the adsorbent during the adsorption process and ensuring its effective use over time.	[81-83]
Environmental conditions during the adsorption process.	Factors such as humidity, sunlight, and exposure to air can affect the stability and performance of certain natural adsorbents.	[84,85]

Techniques for improving the efficiency of natural adsorbents for water pollutants removal

Several techniques can be employed to enhance the efficiency of natural adsorbents for water pollutants removal. These methods aim to optimize the adsorption process and improve the overall performance of the adsorbent material. Here are some techniques commonly used for this purpose as shown in Table (3):

Table 3: Some techniques commonly used for improving the efficiency of natural adsorbents for water pollutants removal

Technique	Description	Impact	Reference
Activation	Activation involves the modification of natural adsorbents to increase their surface area and porosity. This is commonly achieved through physical or chemical activation processes.	Increased surface area enhances the adsorption capacity, allowing the adsorbent to capture more pollutants.	[86-90]
Modification of Surface Chemistry	Surface modification involves altering the chemical composition of the adsorbent to introduce specific functional groups. This can be achieved through chemical treatments or functionalization.	Surface modifications can enhance the adsorbent's affinity for certain pollutants, improving its selectivity and overall performance	[91-94]
Composite Materials	Combining natural adsorbents with other materials to form composite structures.	Composite materials may exhibit synergistic effects, combining the strengths of different components to enhance adsorption efficiency.	[95-98]
Nanostructures	Creating nanoscale structures or incorporating nanoparticles into natural adsorbents.	Nanostructures provide increased surface area and reactivity, leading to improved adsorption efficiency.	[99-103]

Technique	Description	Impact	Reference
		Nanoparticles can also enhance selectivity and kinetics.	
Use of Surfactants	Adding surfactants to the adsorption system to modify the surface properties of the adsorbent.	Surfactants can alter the wettability of the adsorbent surface, improving its interaction with pollutants and facilitating adsorption.	[104, 105]
Electrochemical Methods	Applying electrochemical processes to enhance adsorption.	Electrochemical methods can modify the surface charge of the adsorbent, improving its interaction with charged pollutants.	[106-109]
Incorporation into Filtration Systems	Integrating natural adsorbents into filtration systems or fixed-bed columns.	This approach allows for continuous and controlled contact between water and the adsorbent, improving the overall efficiency of pollutant removal.	[1110, 111]
Ultrasonication	Applying ultrasonic waves to the adsorption system	Ultrasonication can enhance mass transfer and improve the distribution of adsorbent particles in the solution, leading to increased efficiency.	[112-114]
Biological Augmentation	Combining biological processes, such as microbial activity, with adsorption.	Biological augmentation can enhance the removal of specific pollutants through microbial degradation or transformation in conjunction with adsorption.	[115-118]

Challenges and Future Prospects for application of natural adsorbents for water pollutants removal

The application of natural adsorbents for water pollutant removal presents challenges and opportunities. Challenges include variable adsorption capacities influenced by source and preparation methods, hindering consistent performance. Achieving high selectivity while avoiding interference from coexisting substances is challenging due to varying specificity. Efficient regeneration methods are crucial, and scaling up to larger treatment systems faces issues like uniformity and mass transfer limitations. Competitiveness against established technologies in terms of cost, efficiency, and scalability is essential. Mechanical stability, long-term performance, and the lack of standardized testing methods also need addressing for widespread acceptance. Future prospects involve advanced characterization techniques, nanotechnology integration, and research on biocompatible materials. Tailoring adsorbents, integrating smart materials for real-time monitoring, conducting environmental impact assessments, and community engagement are crucial for sustainable implementation. Policy support is essential for advancing research and encouraging the use of sustainable water treatment technologies, fostering innovation in the field [6, 119-122]. Addressing these challenges and capitalizing on future prospects can lead to the continued evolution of natural adsorbents, providing sustainable solutions for water treatment challenges.

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