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Sawdust as an Environmentally Friendly Adsorbent

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ABSTRACT

Sawdust, an abundant byproduct of the wood processing industry, has gained attention as a sustainable, low-cost adsorbent for water and wastewater treatment. Its lignocellulosic composition—rich in cellulose, hemicellulose, and lignin—provides a variety of functional groups capable of binding a wide range of contaminants, including heavy metals, synthetic dyes, and organic pollutants. This review synthesizes current knowledge on the sources and characteristics of sawdust, modification techniques to enhance adsorption performance, mechanisms of pollutant removal, and applications across different wastewater types. Comparative analyses with conventional and other bio-based adsorbents highlight its economic and environmental advantages. Limitations and challenges for large-scale implementation are discussed, along with future research priorities to optimize performance, regeneration, and integration into hybrid treatment systems. The findings reinforce sawdust's role as a promising material in advancing sustainable and circular water treatment technologies.

Keywords: Sawdust; Adsorption; Wastewater Treatment; Bio-Based Adsorbent; Environmental Sustainability

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1. Introduction

Environmental contamination has emerged as one of the most critical challenges of the modern era, driven largely by rapid industrialization, urban growth, and population expansion. Industrial effluents are a significant source of hazardous contaminants, often containing heavy metals, synthetic dyes, phenolic compounds, pesticides, and other persistent organic pollutants that pose severe threats to ecosystems and human health. Heavy metals such as lead, cadmium, mercury, and chromium are particularly problematic because they are non-biodegradable, accumulate in living organisms, and can cause chronic toxicity even at trace concentrations. Likewise, synthetic dyes from textile, leather, and paper industries not only alter the aesthetic quality of water bodies but also interfere with light penetration, disrupt aquatic photosynthesis, and can generate carcinogenic or mutagenic byproducts during degradation. These environmental hazards have spurred the search for effective, sustainable, and economically viable wastewater treatment methods [1].

Among the various treatment technologies available, adsorption has attracted significant attention because of its versatility, cost-effectiveness, and relative simplicity of design and operation. The adsorption process is versatile and can be modified to detoxify a broad array of pollutants in aqueous solution; this will largely rely on the character of the adsorbent material. The effectiveness of conventional adsorbents and especially activated carbon is determined by the large surface area and binding capacity. The expensive nature of production and the complexities of regeneration have however led to researchers seeking alternative materials which besides being cheap are renewable or waste materials. This has two ways of treating the environment, water pollution and waste management of the solid waste [2].

One such alternative is sawdust; finely particulate biomaterial produced as a byproduct of the mechanical working of wood. Highly manufactured by sawmills, carpentry shops, and furniture production factories, the sawdust has always been thought to be waste material and it has been disposed of either by open burning or by landfill. Such disposal mechanisms may add to the air pollution and emission of greenhouse gases and other environmental issues. Comparatively, the reuse of sawdust as an adsorbent would be of immense value in a model of waste valorisation, which upcycles a common byproduct, usually used unproductively, into a tool of environmental cleanup [3].

Sawdust composition consists mainly of natural polymers used to provide it with a rich functional group, consisting of hydroxyls, methoxy, and carbinol groups. Such functional groups have the ability to interact pollutants in processes like ion exchange, complexation, hydrogen bonding and hydrophobic interactions. Moreover, sawdust structure can be physiochemically or thermally treated to increase its surface area, porosity and chemical activity, and their significant effect on adsorption performance. It can easily withstand the test of biodegradability, is readily available in most parts of the world and is, in some cases, free or can be easily obtained at low cost, thereby making it an interesting candidate in large scale use in resource constrained environments.

Using sawdust as a pollutant adsorbent correlates well with the idea of the circular economy and green chemistry. It deals with the necessity to have affordable, renewable adsorbents and at the same time decrease the environmental impact of both waste disposal process and water treatment process. During the last twenty years, there have been many studies that looked at the potential of sawdust in the removal of heavy metals, dyes and organic contaminants in water. Although laboratory studies have shown encouraging results, progress should continue with the goal of optimising preparation procedures, performance in more realistic effluents, retention procedures and consideration of the technicalities of scaling up to large-scale application.

This review is aimed at discussing in detail sawdust as a green adsorbent in wastewater treatment. It shall attempt to examine the source and nature of sawdust applicable to adsorption, examine the methods of modifying sawdust and their effect on adsorption capacity, examine the way the mechanism behind pollutant removal works, a summary of the performance statistics of the few studies relevant so far, and determine the key gaps in knowledge that will require attention. This review will provide a synthesis of extant literature in an effort to point out the strong potential of sawdust as a cost-effective solution to curbing water pollution due to its sustainability.

2. Sources and Characteristics of Sawdust

2.1. Sources and Generation of Sawdust

Sawdust is generated as a fine particulate byproduct during various wood processing activities, including sawing, milling, planing, drilling, sanding, and turning [3,4]. The extent and nature of sawdust production depend on the type of processing equipment, the intended product, and the mechanical properties of the wood being processed. Large-scale sawmills can produce several tonnes of sawdust daily, while smaller carpentry and joinery workshops contribute smaller yet significant amounts. Globally, the total annual production of sawdust is immense, with some estimates placing it at several hundred million tonnes. This abundance is partly due to the high proportion of wood mass lost as residue during mechanical conversion — in some milling processes, waste materials such as sawdust, wood chips, and bark can account for up to 50% of the initial log mass.

The source of sawdust strongly influences its properties. Hardwood sawdust, derived from species such as oak, teak, maple, or mahogany, is generally denser and often contains a slightly higher lignin content compared to softwood sawdust from species like pine, spruce, or fir. Hardwood sawdust tends to be more mechanically robust, while softwood sawdust often has a higher resin content, which can affect surface chemistry and adsorption performance. The geographical origin of the wood, environmental growth conditions, and forestry practices also contribute to differences in density, porosity, and chemical makeup [5].

2.2. Environmental and Economic Context

Historically, sawdust has been considered a waste product, with limited utilization in applications such as animal bedding, composting, or as a fuel source for low-efficiency burners. In many regions, large accumulations of sawdust at sawmills or furniture manufacturing sites present environmental challenges. Open burning of sawdust releases particulate matter, carbon monoxide, volatile organic compounds, and greenhouse gases into the atmosphere. If landfilled, sawdust can decompose under anaerobic conditions to produce methane, a potent greenhouse gas [6].

Economically, developing sustainable and value-added utilization of sawdust offers businesses a means through which they can cut down on the expenses of disposal besides generating additional income. The use of sawdust as an adsorbent to wastewater treatment systems falls in line with the ethos of a circular economy which is to create value out of an underutilized waste product to create a valuable resource in the remediation of the environment. It is especially attractive in resource-limited, poorer, rural circumstances where it is cheap and readily available to decentralize or small-scale treatment cases.

2.3. Physical Properties

Sawdust physical properties are also important in defining the adsorption capacity. Sawdust are irregular shaped particles that were created in the course of mechanical processing of wood. Ranged widely in particle size, particle sizes may range up to fine dust-like debris with a diameter few micrometres in diameter to coarse splinters of several millimetres' length. Such heterogeneity affects the available surface area as well as pores on which adsorption occurs. Does it represent a greater surface area-to-volume so that there are more available binding sites and thus adsorption kinetics are faster? Too small particles can however interfere with the separation of the solids and liquids once it is treated and may involve subsequent filtering or settling processes that may increase the operational costs.

Another key property is bulk density, which varies between 160 and 320 kg/m 3 between air-dried sawdust, type of wood, moisture content and structure of the sawdust. This is because lower bulk density would tend to be associated with greater porosity that can enhance intraparticle pollutant diffusion. Sawdust with their fibrous nature and cellular arrangement (tracheids, vessels, and rays) generates a system of channels and pores through which fluids can easily enter the interior of the product.

A large parameter is also moisture content. Newly produced sawdust can be composed of high-water content thus inhibits the uptake of hydrophobic compounds and accelerates microbial growth during the storage process. Stabilization of the material, prior to use is commonly achieved through air drying or oven drying. Moreover, the microstructural study by means of scanning electron microscopy (SEM) often demonstrates complex surface topography which has pits, ridge, and micro voids that are also contributing to adsorption capacity due to increasing the available surface area and offering the pathways of molecular diffusion. **Table 1** presents an overview of important properties of sawdust [7–9].

Table 1. Key physical properties of sawdust influencing adsorption performance.

Property	Typical Range/Description	Influence on Adsorption
Particle size	Few µm to several mm	Smaller particles increase surface area but may cause separation challenges
Bulk density	160–320 kg/m³ (air-dried)	Lower density often correlates with higher porosity and better diffusion
Porosity	Varies with wood type and processing method	High porosity improves intraparticle diffusion of pollutants
Surface texture	Irregular, fibrous, with pits and microvoids (seen in SEM)	Increases available binding sites and fluid contact
Moisture content	5–15% after drying; can be >40% in fresh sawdust	High moisture may reduce hydrophobic pollutant adsorption
Color/appearance	Light yellow to brown, depending on wood species	Related to lignin content and possible extractives

2.4. Chemical Composition

Lignocellulosic biomass is mostly consisted of Sawdust that contains three primary polymeric components-cellulose, hemicellulose, lignin-, and small quantities of extractives as well as inorganic minerals.

Approximately 40 to 50% of sawdust are cellulose content per weight. It is a straight long chain polysaccharide made up of 2-D glucose units that are bonded by 1, 4-glycosidic bonds into crystalline and amorphous polysaccharide. The amorphous areas expose reactive hydroxyl (-OH) groups (-OH) to hydrogen bonding or ion-exchange with pollutants with the crystalline areas offering mechanical strength. Cellulose is in large part responsible to the hydrophilic character of sawdust and its adsorptive behavior toward polar compounds and metal ions attributable to its vast quantity of hydroxyl groups [10].

Hemicellulose is an amorphous heteropolymer derived of different sugar monomers in which xylose, mannose, galactose, arabinose, and glucose are the key elements and has an approximate percentage of 20–35 in sawdust. Its complex branched and less-ordered structure is more chemically reactive and available in comparison with cellulose. Hemicellulose has hydroxyls and acetyl functional groups capable of adsorption due to the ability to form hydrogen bonds, or once hydrolyzed or modified, a carboxyl group formed to bind with cation.

Lignin constitutes approximately 15–30% of sawdust and is a complex, three-dimensional, cross-linked phenolic polymer built from guaiacyl, syringyl, and p-hydroxyphenyl units. Lignin's aromatic rings and methoxy groups contribute hydrophobic and π–π interaction capabilities, making it particularly effective for adsorbing non-polar organic pollutants and aromatic dyes. Additionally, phenolic hydroxyl groups in lignin can form complexes with certain metal ions.

Minor components of sawdust include extractives (such as tannins, resins, fats, and waxes) and ash content (silica, calcium, potassium, and other minerals). Extractives can block adsorption sites or interfere with adsorption processes, though in some cases they may enhance affinity for specific hydrophobic contaminants [11,12].

Overall, the interplay of these chemical constituents results in a heterogeneous adsorbent surface containing both hydrophilic and hydrophobic domains, enabling sawdust to interact with a diverse range of pollutants. The balance between cellulose, hemicellulose, and lignin—determined largely by wood species—has a direct influence on adsorption efficiency and selectivity. Key chemical constituents of sawdust are summarised in **Table 2**.

Table 2. Typical chemical composition of sawdust from lignocellulosic biomass.

Component	Approximate Content (% Dry Weight)	Functional Groups Present	Role in Adsorption
Cellulose	40–50%	Hydroxyl (-OH)	Hydrogen bonding, ion exchange with metals
Hemicellulose	20–35%	Hydroxyl (-OH), acetyl (-$COCH_3$)	Hydrogen bonding, carboxyl group generation after modification
Lignin	15–30%	Aromatic rings, methoxy (-OCH_3), phenolic (-OH)	Hydrophobic interactions, π–π stacking, metal complexation
Extractives	1–5%	Tannins, resins, waxes	Can enhance hydrophobic pollutant adsorption or block sites
Ash (minerals)	0.5–2%	Silica, Ca, K, Mg, Fe	May contribute to ion exchange or surface precipitation

2.5. Functional Groups and Adsorption Potential

The adsorption potential of sawdust is intimately linked to the variety, density, and accessibility of functional groups present in its lignocellulosic matrix. These functional groups originate from the primary constituents—cellulose, hemicellulose, and lignin—and they serve as the active sites for interactions with pollutants. Understanding their nature and chemical reactivity is essential for explaining and predicting adsorption performance under different conditions.

Other most notable functional groups include hydroxyl (-OH) moieties that are highly common in cellulose and hemicellulose. The nature of hydroxyl groups is polar and thus able to form hydrogen bond to the molecules of water and polar solutes. They also have pairs of unpaired electrons on the oxygen that can coordinate with positively charged reagents, e.g. heavy metal cations. In water, the hydroxyl binding sites may be nucleophilic sites, which may be involved in ligand-metal binding or ion exchange equations. An example here is the adsorption of Pb^{2+} or Cu^{2+} ions on sawdust surfaces where there is a tendency of the adsorption of the ions to dislodge protons on the hydroxyl sites to give stable adsorbate complexes at the surface.

Hemicellulose also contains carboxyl (-COOH) groups, in lesser amounts, and these are produced in larger amounts by oxidatively treating sawdust, which is seen to help bind the cations. In water, these groups are able to detach and form carboxylate anions (-COOH), which exhibit a great electrostatic pull, to metal cations. The ionization level is regulated by the pH of the solution, at higher values it favors its dissociation, and increases the adsorption of species with positive charges.

The carbonyl (C=O) groups typical of ketones, aldehydes, or esters appear in the lignocellulosic framework and add to the adsorption via dipolar dipolar interaction, or where multiple groups of oxygen are involved, coordination chemistry. They have the ability to interact with some of the polar organic molecules, dyes, or the use of metal ions through electron delivery of the oxygen atom to the electrophilic sites through donation.

They are not as reactive as the hydroxyl or carboxyl groups (although often the other methoxy (-OCH_3) groups of lignin, in large quantities, may affect the hydrophobicity of the sawdust surface), probably due to the fact that they all bear an oxygen atom. The lignin aromatic ring in combination with this hydrophobic nature renders sawdust suited to interacting with non-polar or aromatic pollutants through hydrophobic partitioning or 3-hydrophobic partitioning interactions. As an illustration, this may be the absorption of phenolic compounds, aromatic dyes, and some pesticides on the sawdust surfaces [13,14].

Aromatic phenolic (-OH attached to benzene rings) structures in lignin may have two functions: they may be used to donate hydrogen bonds to polar substances, or to behavior as weak acids, giving off protons in an unattached form, which then may be used as a cation source. The conjugated pi-electron system of aromatic backbone of lignin also has potential of pi-pi interaction with the other aromatic compounds like synthetic dyes or organic pollutants.

The synergistic existence of these functional groups produces an uneven adsorption surface which can participate in two or more mechanisms concurrently. In the case of heavy metals, ion exchange predominates (frequently with hydroxyl, carboxyl, and phenolic groups) and complexation. In the case of dyes, the hydrophobic effect is also a significant factor in addition to electrostatic interaction (between the charged dye molecules and those on the sawdust containing the opposite charge). In the case of organic pollutants (e.g., phenols or hydrocarbons), pi- pi bonding with the aromatic regions of lignin as well as hydrophobic distribution also plays a greater role.

Nevertheless, the availability of the functional groups is not only dependent on chemical composition essentially, but also on the surface morphology as well as in porosity of sawdust. Most functional groups could be buried in the interior of the material mass, which are inaccessible to large pollutant molecules, unless the structure is physically or chemically altered. That is why various modification treatments, including acid washing, alkaline treatment, thermal activation, or others usually improve the adsorption capability: presenting more reactive sites, growing the surface area, and in some cases, adding new functional groups [15,16].

Thanks to the balanced hydrophilic and hydrophobic domains that sawdust is characterized by in untreated form, the substance can be utilized to treat both non-polar and polar pollutants. It has been successfully used in the adsorption of a great number of pollutants such as toxic metals, synthetic dyes, oil residues and phenolic compounds among others, and this versatility is attributed to one of its reasons. Potential of the sawdust to be used as a multi-purpose adsorbent with the surface chemistry providing the multiple functionalities makes sawdust an environmentally friendly and flexible material with potential of optimization.

2.6. Influence of Source and Pre-Treatment

The source of sawdust, the type of wood it is obtained and the form of processing/treatment of the wood before its transformation to sawdust, may be significant factors in changing its physical and chemical properties and, hence, its performance in terms of adsorption.

There is a variation in the lignocellulosic composition, density, and extractives in species of wood. Hardwood like oak, maple, and teak tend to have a slightly higher cellulose and lower lignin content as compared to softwood, i.e. pine, fir or spruce. These variations result in the ratio of hydroxyl in comparison to aromatic regions in the sawdust and this factors into its attraction towards various kinds of pollutants. Such as, sawdust of hardwood with a greater fraction of cellulose is perhaps more efficient in adsorbing heavy metals using hydroxyl-mediated complexation, and lignin-rich sawdust of softwood may be more effective in aromatic dyes, hydrophobic organic contaminants using 1, p-interactions.

Several factors may also support wood chemistry, including environmental conditions during its growth (soil make-up, water content, and exposure to other forms of environmental stress). Crystallinity of cellulose and cross-linking of lignin as well as age of the tree and its maturity influence the availability of functional group which form part of the adsorption [3,17].

Another important issue is the history of the wood before its use. Untreated, natural wood Sawdust can be prepared with some minimal preparation typically and used in chemical or environmental applications. But the sawdust produced through wood treated with chemicals, e.g. pressure-treated timber, could have preservatives (metallic based compounds, arsenic or chromated copper arsenate (CCA). Such chemicals may be leached into treated water, which causes secondary contamination. Wood painted, varnished, or coated in resin may also add synthetic organic chemicals to the sawdust that may hamper adsorption or present health risks.

To ensure safe and effective use, pre-treatment steps are commonly performed. These include:

- Distilled or deionized water washing to get rid of soluble impurities e.g. tannins, sugars or dust on the surface.
- Sieving to create a monodisperse particle size distribution and enhance reproducibility of adsorption experiments(more) and eliminate clogging in the packed bed systems.
- Controlled drying to minimize moisture down to the maximum, microbial growth and stabilizing the physical form.
- Potential prior chemical clean up e.g. acid or base wash to remove other residual contaminants or functionalize the surface prior to the main modification procedure [18].

Through careful sourcing and pre-treatment, the variability in adsorption performance due to feedstock differences can be reduced, making sawdust a more consistent and reliable adsorbent material.

2.7. Advantages for Environmental Applications

There are a number of reasonable benefits that can be cited using sawdust as an adsorbent in environmental clean-up, both ecologically and financially.

The most irresistible advantages include plentitude and affordability. Production of sawdust is massive all over the world due to its unavoidable consequence that accompanies wood processing companies such as sawmills, carpentry shops, and furniture industries. It is also free or comparatively inexpensive in most instances and could, by extension, be used as a very readily accessible item in the low resource setting applications.

The other strengths include sustainability and valorisation of waste. Using sawdust as a pollutant removal agent solves two environmental issues simultaneously by offloading the solid waste networks and offering a become-zero solution to the use of commercial adsorbents such as activated carbon whose supply is expensive to the economy. Industries have the potential to do their part by recycling sawdust into the water treatment system and thus obtaining a part of a circular economy aim, namely, using waste materials to create valuable resources.

Technically, the lignocellulosic structure of sawdust offers a broader range of functional groups, hence; it can relate with a broad range of substances contaminants- both inorganic and organic through various absorption methods. Such versatility is unusual to low-cost adsorbents many of which are specific to a type of pollutant.

Sawdust also has low weight, and is easily worked on due to its fibrous nature which could be layered into filters or columns and even in the case of batch reactor. It can be used as raw material or can be processed to granules, pellets or biochar to match various treatment systems designs. Moreover, it can be processed by easy chemical or thermal adjustments to enhance its performance relatively, and the facility to do so does not need sophisticated or expensive facilities [19].

Lastly, sawdust is very appealing as it is biodegradable and compatible with the environment. Spent sawdust may be disposable at the end of its service life with low environmental penalties subject to the adsorption of highly toxic and hazardous substances. It is actually reusable and can be regenerated in certain instances thus adding to its sustainability rating.

Combing these features, sawdust appears among a comfortable, environmentally friendly, and scalable solution to various water treatment purposes and more specifically in regions where costs and material accessibility are significant impediments.

3. Modification and Treatment of Sawdust for Adsorption

Although raw sawdust is blessed with diverse functional groups (that can react with the pollutants), there are inherent drawbacks given that raw sawdust has a limited adsorption capacity because of the low surface area, insufficient porosity, and inaccessibility of the active sites. Moreover, it might possess superior natural surface chemistry to other classes of contaminant rather than others. With a view to incorporating these shortcomings and manipulating sawdust to meet particularized ventures, numerous strategies of physical, chemical, and thermal alterations have been established. The purpose of such treatment is to make the pollutant-binding ability higher, enlarging surface area, functional groups, or increasing the strength of the material to be reused in the treatment systems [20,21].

3.1. Physical Modifications

Sawdust is usually subjected to physical modification, which may include size reduction, classification and cleaning of surface, but not the chemicals in sawdust. Reductive size of the particles by grinding or milling is the most common one. A smaller particle has a greater surface area-to- volume ratio and will result in an augmented number of exposed locations of adsorption. But the over-fine particles may pose operational problems like excessive pressure drop in packed column systems or trouble in extracting the adsorbent out of treated water. Thus, smaller-sized particles are very essential in offering optimum particle sizes that do not compromise hydraulic performance accompanying an increase of the surface area.

Sieving and classification may be used to yield constant particle size distributions and may enhance repeatability of adsorption experiments and predictable flow behavior in filtration devices.

Pre-treatment pre-requisites include washing and drying to eliminate dusts, loosely bound extractives and other adsorption-blocking constituents on the surface. To remove tannins, sugars or other interferents, washing with distilled water may be done. This is then followed by the drying that is usually done in the oven at temperature ranging between 60-105 degrees to lessen moisture or inhibit microbial proliferation [22].

3.2. Chemical Modifications

Chemical modification of sawdust involves the deliberate alteration of its surface chemistry to enhance adsorption performance. While raw sawdust contains a variety of functional groups such as hydroxyl, methoxy, and phenolic moieties, these groups are often partially blocked by impurities, embedded within inaccessible microstructures, or insufficiently reactive toward certain pollutants. Chemical treatments aim to remove these limitations by (i) cleaning the surface, (ii) introducing new functional groups, (iii) enhancing surface charge characteristics, and (iv) increasing porosity and accessibility of binding sites.

Such treatments can be broadly categorized into acid modification, alkaline modification, salt impregnation or metal loading, and oxidative treatments. In many studies, combinations of these approaches are applied to achieve synergistic improvements [23].

3.2.1. Acid Treatment

Acid treatment is commonly performed using mineral acids such as hydrochloric acid (HCl), nitric acid (HNO_3), or sulfuric acid (H_2SO_4). The primary purposes of acid washing are to:

- Remove mineral impurities and inorganic ash content from the sawdust matrix.
- Increase surface roughness by partially hydrolyzing hemicellulose and amorphous cellulose regions.
- Protonate surface functional groups, enhancing their attraction toward anionic contaminants.

When an acid interacts with lignocellulosic biomass, partial hydrolysis of glycosidic bonds can occur in the hemicellulose component, loosening the fibrous structure and exposing buried hydroxyl and carboxyl sites. This process may also open micro-pores, increasing the available surface area for adsorption.

For anionic dyes (e.g., Congo red) or negatively charged organic species, protonation of hydroxyl (-OH) and carboxyl (-COOH) groups produces a net positive surface charge, strengthening electrostatic attraction. However, care must be taken to avoid excessive degradation; harsh acid conditions can lead to significant mass loss, cellulose depolymerization, and reduced mechanical stability of the adsorbent [24].

3.2.2. Alkaline Treatment

Alkaline treatment is widely regarded as one of the most effective chemical modifications for heavy metal and cationic dye adsorption. Sodium hydroxide (NaOH) and potassium hydroxide (KOH) are the most frequently used reagents.

The mechanism involves:

- Saponification of ester linkages between lignin and hemicellulose, breaking down the lignin–carbohydrate complex.
- Swelling of cellulose fibers, which increases internal surface accessibility.
- Deprotonation of phenolic and carboxylic groups, resulting in a more negatively charged surface that enhances electrostatic attraction to cations.

NaOH treatment can also remove certain extractives (e.g., tannins, fats, resins) that may block active sites. The process typically leads to an increase in BET surface area, improved wettability, and a more open pore structure. However, overly concentrated alkali solutions or prolonged exposure can degrade cellulose chains, reducing material integrity [25].

3.2.3. Salt Impregnation and Metal Loading

Salt impregnation involves soaking sawdust in solutions of metal salts such as calcium chloride ($CaCl_2$), ferric chloride ($FeCl_3$), aluminum chloride ($AlCl_3$), or magnesium chloride ($MgCl_2$). This technique introduces metal ions that serve as active centers for adsorption, particularly of negatively charged species like phosphate, fluoride, and anionic dyes.

The mechanism typically relies on:

- Electrostatic attraction between the impregnated metal cations on the surface and the target anions in solution.
- Ligand exchange processes, where hydroxyl groups bound to the metal center are replaced by the target anion.

Metal-loaded sawdust can also exhibit catalytic properties, allowing for the simultaneous adsorption and degradation of certain organic pollutants through Fenton-like reactions (in the case of Fe^{3+} loading).

3.2.4. Oxidative Treatments

Oxidizing agents such as hydrogen peroxide (H_2O_2), potassium permanganate ($KMnO_4$), ozone (O_3), or nitric acid (in oxidative mode) can be used to introduce oxygen-containing functional groups onto the sawdust surface.

For example:

- H_2O_2 treatment can open lignin aromatic rings and introduce carboxyl (-COOH) and carbonyl (C=O) groups, increasing polarity and cation-binding capacity.
- $KMnO_4$ treatment can deposit MnO_2 nanoparticles on the surface, providing additional adsorption sites and potential redox reactivity toward organic contaminants.

Oxidative treatments can also partially degrade lignin, increasing porosity and surface roughness. The tradeoff is that aggressive oxidation can weaken the structure or produce soluble degradation products that must be removed before use.

3.2.5. Combination and Sequential Treatments

Combining chemical modifications often yields superior performance compared to single-step treatments. For instance:

- Acid washing followed by $FeCl_3$ impregnation can ensure better metal ion distribution and enhance anionic dye removal.
- NaOH treatment followed by oxidative modification can produce surfaces rich in both negatively charged sites and oxygen-containing functional groups, suitable for a wider range of pollutants [26].

The sequence of treatments matters; performing oxidation before alkali treatment may lead to different surface chemistry than the reverse order.

3.2.6. Environmental and Economic Considerations

The chemical modification enhances adsorption capacity, it also raises issues of cost, reagent consumption, and secondary waste generation. The selection of reagents should balance performance gains against potential environmental impacts. Mild conditions, lower reagent concentrations, and short treatment times are preferred for sustainable operation. Wastewater generated from chemical modification processes must be neutralized and treated before discharge to avoid secondary pollution.

In low-resource settings, the use of locally available benign chemicals—such as lime ($Ca(OH)_2$) for alkaline modification or vinegar (acetic acid) for mild acid treatment—can be explored to reduce costs and environmental risks [27].

3.3. Thermal Treatments

Thermal treatments are used to convert sawdust into carbon-rich, porous adsorbents with significantly improved surface area, porosity, and stability. Heating in an oxygen-limited environment alters the lignocellulosic matrix, producing biochar or activated carbon-like materials that can effectively adsorb a wide range of pollutants.

Carbonization (Pyrolysis)

Conducted at 300–600 °C in an inert or oxygen-limited atmosphere, carbonization drives off volatile compounds, concentrates fixed carbon, and develops a microporous structure. Lower pyrolysis temperatures retain more oxygen-containing functional groups—beneficial for metal ion binding—while higher temperatures enhance hydrophobicity and surface area, favoring organic pollutant adsorption.

Physical Activation

A two-step process where sawdust is first carbonized, then activated at 700–900 °C using oxidizing gases such as steam or CO_2. This etches the carbon matrix, widening pores and often achieving surface areas between 500–900 m²/g. It produces high-capacity adsorbents but requires more energy and controlled conditions [28].

Chemical Activation

Involves impregnating sawdust with activating agents like phosphoric acid (H_3PO_4) or potassium hydroxide (KOH) before heating at 400–800 °C. The chemicals dehydrate and partially oxidize the biomass, generating extensive microporosity (often >1000 m²/g) and introducing functional groups tailored to target pollutants. A summary of thermal treatment methods is given in **Table 3**.

Table 3. Summary of thermal treatment methods for sawdust.

Method	Temp (°C)	Activating Agent	Surface Area (m²/g)	Key Benefit	Main Limitation
Carbonization	300–600	None	50–300	Preserves functional groups	Lower surface area
Physical activation	700–900	Steam, CO_2	500–900	High porosity & surface area	High energy demand
Chemical activation	400–800	H_3PO_4, KOH	800–1500	Very high capacity & tailored chemistry	Chemical handling needed

Advantages:

- High adsorption capacity and broad applicability for metals, dyes, and organics
- Improved reusability and resistance to microbial degradation
- Tunable surface chemistry through activation choice

Limitations:

- Energy-intensive processes (especially physical activation)
- Equipment and process control requirements
- Management of off-gases and residual chemicals from activation [29]

3.4. Combined Physical–Chemical Approaches

In many cases, the most effective improvements are obtained by combining physical and chemical treatments. For example, grinding and sieving followed by alkaline treatment can produce sawdust with increased surface area and enhanced functional group exposure. Similarly, acid washing prior to metal loading can improve the distribution of impregnated ions across the surface. Sequential treatments can be tailored to target specific pollutants—for instance, oxidizing followed by alkaline modification for heavy metal adsorption, or alkaline followed by cation impregnation for anionic dye removal.

3.5. Impact of Modification on Adsorption Performance

Numerous studies have reported significant improvements in adsorption capacity following modification. Alkaline-treated sawdust, for instance, can exhibit two to five times greater uptake of Pb^{2+} or Cu^{2+} compared to raw sawdust. Acid treatment has been shown to improve dye adsorption by increasing positive surface charge under acidic conditions. Thermal activation can yield materials with surface areas exceeding 500 m²/g, rivaling commercial activated carbon in some cases.

However, the selection of a modification method should consider factors beyond adsorption performance, including cost, environmental safety, and the potential for regeneration and reuse. Harsh chemicals may require neutralization or disposal measures, and energy-intensive processes may reduce the sustainability benefits of using sawdust in the first place [30].

3.6. Environmental and Practical Considerations

Although enhancement of adsorption characteristics can be achieved via modification, there are trade-offs, which may arise to environmental issues. The proper disposal and use of chemical reagents should be done without causing secondary pollution. Renewable biomass-derived fuel or wastes (or by-products) of other processes can also be used to provide energy in thermal treatments to reduce its use. Practically speaking, modification should be chosen according to the scale and context vulnerability proposed, at least in the case of small-scale modifications, such as simple physical treatments applied along rural water filtration, and more serious modifications can be justified in the case of larger-scale and more valuable water filtration (eg when industrial waste water has to be treated) [31].

4. Adsorption Mechanisms and Kinetics

The effectiveness of sawdust adsorption is based on the relationship between its physical form, its surface chemistry and that of the contaminants it is dealing with. The process of adsorption mechanisms is extremely important in understanding the results of an experimental work, improving conditions of operation and developing changes to make the process more efficient. The section provides the details of the basic adsorption mechanisms, the pathways of interaction with the pollutants, and kinetics, and equilibrium theories widely used to characterize the properties of adsorption of sawdust.

4.1. Overview of Adsorption Processes

Adsorption is a process during which the molecules or ions (adsorbates), are deposited on the surface of a solid or porous substance (adsorbent). When discussing sawdust, adsorption may take place via: physisorption, or chemisorption.

- Angstrom Physisorption entails weak intermolecular forces between molecules around van der Waals and hydrogen bonding. It is normally reversible, presents no significant changes to either the adsorbent or adsorbate and is also preferred at low temperatures. The lignocellulosic surface of the sawdust has many physisorption sites, especially organic substances and polar materials.
- Chemisorption entails formation of stronger chemical bonds namely covalent or ionic interaction between adsorbates and adsorbents. It can be very slow compared to physisorption, and even irreversible, although it can often depend on some activation energy. Chemisorption in sawdust usually takes place in the form of ion exchange, surface complexation and interactions that involve chemical reactions between functional groups and pollutant species [22].

In actual wastewater treatment processes, both physisorption and chemisorption may be used in series or in parallel, the degree to which these processes contribute being controlled by such factors as pH hardness, and pollutant chemistry.

4.2. Pollutant-Specific Interaction Mechanisms

4.2.1. Heavy Metals

Sawdust is rich in functional groups—hydroxyl, carboxyl, phenolic, and methoxy—that can bind metal ions through several mechanisms:

- **Ion exchange**: Metal cations in solution replace protons or other cations (e.g., Na^+, Ca^{2+}) bound to functional groups on the sawdust surface.
- **Complexation/chelation**: Metal ions form coordinate bonds with oxygen atoms in hydroxyl or carboxyl groups, producing stable surface complexes.
- **Precipitation**: In certain pH ranges, metal hydroxides may form on the sawdust surface, contributing to apparent adsorption.

4.2.2. Synthetic Dyes

The adsorption of dyes depends heavily on the charge and molecular structure of the dye:

- Cationic dyes (e.g., methylene blue) are attracted to negatively charged sites on sawdust, particularly after alkaline modification.
- Anionic dyes (e.g., Congo red) can bind to protonated functional groups under acidic conditions or interact with metal-loaded sawdust through electrostatic attraction.
- Aromatic dyes may also interact with lignin's aromatic rings via π–π stacking interactions [20].

4.2.3. Organic Pollutants

Non-polar organics (e.g., phenols, hydrocarbons) can adsorb onto sawdust through hydrophobic partitioning into lignin-rich regions. Aromatic pollutants can also bind through π–π interactions, while polar organics may form hydrogen bonds with hydroxyl or carbonyl groups.

4.3. Influence of Environmental Factors

- pH: One of the most important parameters. pH affects both the surface charge of sawdust and the ionization state of the pollutants. For example, higher pH generally increases negative surface charge, enhancing cation adsorption but reducing anion adsorption.
- Ionic strength: High concentrations of background electrolytes can compete with target ions for adsorption sites, reducing capacity.
- Temperature: Higher temperatures may increase adsorption capacity for endothermic chemisorption processes but decrease capacity for exothermic physisorption processes.
- Contact time: Determines how quickly equilibrium is reached. Some adsorption occurs within minutes, while other systems require hours due to slow diffusion into internal pores [32].

4.4. Adsorption Isotherm Models

Adsorption isotherm models are essential for understanding how pollutants interact with sawdust surfaces during the adsorption process. They describe the equilibrium relationship between the concentration of adsorbates in the liquid phase and the amount retained on the solid phase at a constant temperature. By applying these models, researchers can determine the adsorption capacity of sawdust, the nature of the adsorption surface, and whether the process is monolayer, multilayer, homogeneous, or heterogeneous. Three main isotherm models have been widely applied in sawdust studies.

The Langmuir isotherm assumes that adsorption occurs on a uniform surface with finite identical sites, leading to the formation of a monolayer. Once a site is occupied, no further adsorption can occur there, and interactions between adsorbed molecules are not considered. The Langmuir equation is expressed as:

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e}$$

where qe is the adsorption capacity at equilibrium, q_{max} is the maximum adsorption capacity, KL is the Langmuir constant, and Ce is the equilibrium concentration of the adsorbate. For example, a study on methylene blue dye adsorption using sawdust reported that the Langmuir model provided the best fit, indicating monolayer coverage with a maximum capacity of over 100 mg/g. This suggests that the dye molecules uniformly occupied active sites on the sawdust surface.

The Freundlich isotherm, on the other hand, is an empirical model that assumes adsorption takes place on a heterogeneous surface with sites of varying affinities. Unlike the Langmuir model, it does not restrict adsorption to a monolayer and allows for multilayer adsorption. The equation is expressed as:

$$q_e = K_F C_e^{1/n}$$

where KF is the Freundlich constant related to adsorption capacity and 1/n is the heterogeneity factor. When $1 / n<1$ adsorption is favorable, while values greater than 1 suggest unfavorable adsorption. In a study involving chromium (VI) removal by sawdust, the Freundlich isotherm gave the best correlation, indicating that adsorption occurred on a heterogeneous surface with multiple types of binding sites. This reflects the complex nature of sawdust, which contains cellulose, hemicellulose, and lignin with diverse functional groups.

The Temkin isotherm introduces the concept of adsorbate–adsorbent interactions, assuming that the heat of adsorption decreases linearly with increasing surface coverage. The Temkin model is expressed as:

$$q_e = B \ln(A C_e)$$

where A is the binding constant, and B is related to adsorption heat. For instance, studies on copper ion adsorption onto modified sawdust showed that the Temkin model adequately explained the reduction in adsorption energy as more sites became occupied, highlighting the role of adsorbate–adsorbent interactions in the process [33–36].

Overall, the application of isotherm models provides a clearer understanding of how pollutants interact with sawdust, with different models fitting best depending on the type of contaminant and the modification of sawdust.

4.5. Adsorption Kinetic Models

While isotherm models explain equilibrium interactions, adsorption kinetic models describe how quickly adsorption occurs and provide insights into the underlying mechanism. They help determine whether adsorption is controlled by physical forces, chemical bonding, or diffusion processes.

The pseudo-first-order model assumes that the rate of adsorption is proportional to the number of available unoccupied sites on the sawdust surface. It is often applied to the early stages of adsorption dominated by physisorption. In one study on the adsorption of phenol by raw sawdust, the data initially followed the pseudo-first-order model, reflecting rapid physical binding through weak forces such as hydrogen bonding. However, deviations at longer contact times indicated the involvement of other mechanisms [37,38].

The pseudo-second-order model assumes that chemisorption is the rate-limiting step. This involves valence forces created by sharing or exchanging electrons between the adsorbent and adsorbate. For example, in studies on lead (Pb^{2+}) and cadmium (Cd^{2+}) adsorption by chemically modified sawdust, the pseudo-second-order model provided the best fit, suggesting strong chemical interactions through ion exchange and complexation. This model often better represents dye and heavy metal adsorption on sawdust compared to the pseudo-first-order model [39].

The intraparticle diffusion model describes adsorption controlled by the diffusion of adsorbates into the internal pores of sawdust. The adsorption process is often multi-staged: an initial phase of external film diffusion followed by a slower stage of intraparticle pore diffusion. For instance, experiments involving Congo red dye adsorption onto sawdust showed a multi-linear intraparticle diffusion plot, indicating that both film diffusion and pore diffusion contributed to the overall adsorption process. The fact that the line did not pass through the origin suggested that intraparticle diffusion was not the sole rate-controlling step [40–42].

In summary, kinetic models provide valuable insights into the mechanisms governing adsorption by sawdust. The pseudo-first-order model is useful in explaining rapid initial uptake through physical forces, while the pseudo-second-order model more accurately describes processes dominated by chemical interactions. The intraparticle diffusion model highlights the importance of pore structure and internal diffusion in determining adsorption efficiency. Together, these models deepen the understanding of how sawdust adsorbs various contaminants and guide optimization strategies for wastewater treatment applications [43].

4.6. Integrated Mechanistic Understanding

In practice, adsorption by sawdust involves a complex interplay of mechanisms. For example, in the removal of Pb^{2+}, initial uptake may occur via electrostatic attraction and ion exchange at the surface, followed by slower diffusion of ions into internal pores where chemisorption locks them in place. For dyes, initial binding might involve rapid electrostatic attraction, followed by slower hydrophobic interactions or π–π stacking with lignin domains. These multi-mechanistic pathways underscore the need for integrated kinetic and equilibrium analyses to fully characterize the adsorption system [44].

5. Applications and Performance Evaluation

Sawdust has been investigated extensively as a low-cost and environmentally friendly adsorbent for the removal of a broad spectrum of pollutants from aqueous environments. Laboratory-scale experiments, pilot plant studies, and limited full-scale applications have all demonstrated its potential under various operational conditions. The following subsections provide a detailed evaluation of its performance across different classes of contaminants, comparisons with other adsorbents, regeneration studies, and the limitations observed in practical use.

5.1. Removal of Heavy Metals

One of the most widely studied applications of sawdust adsorption is the removal of toxic heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr^{6+}), copper (Cu^{2+}), mercury (Hg^{2+}), nickel (Ni^{2+}), and zinc (Zn^{2+}). These metals are persistent in the environment, bioaccumulate in living organisms, and pose severe health risks even at low concentrations.

Studies have shown that both raw and modified sawdust can effectively remove heavy metals from synthetic solutions and industrial wastewater. For example, alkaline-treated sawdust often exhibits significantly enhanced binding capacity for cationic metals, due to increased availability of negatively charged hydroxyl and carboxyl groups. Acid-treated sawdust, conversely, may improve adsorption of metals at low pH by removing surface impurities and increasing porosity.

Performance is influenced by pH, with most heavy metals achieving maximum uptake in the pH range of 4–6, where metal ions are stable in solution and functional groups on sawdust are sufficiently ionized for binding. Removal efficiencies exceeding 90% have been reported in controlled laboratory conditions for metals such as Pb^{2+} and Cu^{2+}, especially when contact times of 60–120 minutes are provided [45,46].

5.2. Removal of Synthetic Dyes

The textile, leather, and paper industries release large volumes of dye-containing wastewater, often characterized by intense color, high chemical oxygen demand, and potential toxicity. Sawdust has been used to adsorb various classes of dyes, including cationic dyes (e.g., methylene blue, crystal violet), anionic dyes (e.g., Congo red, acid orange), and non-ionic dyes [47].

Cationic dyes typically show strong affinity for raw and especially alkaline-treated sawdust due to electrostatic attraction with negatively charged sites. Anionic dyes, on the other hand, adsorb more effectively onto protonated functional groups at low pH or onto sawdust modified with metal salts that introduce positive surface charge. Aromatic dyes also interact with lignin's aromatic rings via π–π stacking, contributing to adsorption beyond electrostatic forces.

Batch studies have reported dye removal efficiencies ranging from 70% to over 95%, depending on initial dye concentration, pH, and adsorbent dosage. Contact times of 30–90 minutes are typically sufficient to reach equilibrium for many dye systems [48].

5.3. Removal of Organic Pollutants

Beyond dyes, sawdust has shown potential for adsorbing various organic pollutants such as phenolic compounds, pesticides, and petroleum hydrocarbons [49]. These compounds can be hydrophobic, aromatic, or polar, and sawdust's lignin-rich domains and multiple functional groups allow for versatile interaction mechanisms.

Phenol adsorption, for example, often involves hydrogen bonding with hydroxyl groups and hydrophobic interactions with lignin. Pesticides, depending on their structure, may bind via hydrophobic partitioning or π–π interactions. Sawdust-based biochar has been especially effective for organic pollutant removal due to its increased surface area and aromatic content.

5.4. Comparative Performance with Other Adsorbents

While commercial activated carbon generally exhibits higher adsorption capacities than raw sawdust, the performance gap narrows when sawdust is chemically or thermally modified. In some cases, metal-loaded or activated sawdust has achieved comparable removal efficiencies at a fraction of the cost.

Compared to other agricultural waste-based adsorbents (e.g., rice husk, coconut shell powder, peanut shells), sawdust often offers higher capacity for certain pollutants due to its diverse functional groups and porous structure. Its availability in large volumes as an industrial byproduct also gives it an economic advantage in many regions [49].

5.5. Regeneration and Reusability

For sawdust to be viable in large-scale applications, it must be regenerable and reusable over multiple cycles. Regeneration can be achieved through chemical desorption (e.g., using dilute acids or bases), solvent washing, or thermal treatment. However, raw sawdust may experience structural degradation after repeated use, reducing its adsorption performance.

Modified sawdust, particularly biochar or metal-loaded variants, tends to retain performance better over multiple cycles. Some studies report effective regeneration for up to 4–6 cycles with minimal loss in capacity, although this depends heavily on the pollutant type and regeneration method used.

5.6. Limitations in Practical Applications

While sawdust has demonstrated strong potential as a low-cost and sustainable adsorbent in laboratory studies, its application under real-world conditions is not without challenges. One of the foremost limitations arises from the complex nature of industrial and municipal wastewater. Unlike the controlled solutions used in laboratory experiments, real wastewater streams contain a mixture of competing ions, dissolved organic matter, oils, and fluctuating pH levels. These components often interfere with adsorption, occupying or blocking binding sites on sawdust surfaces and thereby reducing its efficiency.Another practical issue is related to the separation of sawdust particles after treatment. Because sawdust consists of fine and lightweight particles, it can be difficult to remove them completely from treated water without employing additional filtration or sedimentation processes. This step not only increases operational costs but also complicates system design, particularly in large-scale or continuous flow treatment facilities. Moreover, the mechanical stability of raw sawdust poses an additional concern. Over time, and particularly under conditions of agitation or prolonged use, the particles may break down further into smaller fragments. This breakdown can cause clogging in filtration units or packed bed reactors, making process maintenance more demanding.

A further limitation is the variability in sawdust quality. Since its composition depends heavily on the wood species, age, processing methods, and storage conditions, there can be significant inconsistency in adsorption capacity between different batches of sawdust. For example, hardwood sawdust may have different affinities for contaminants compared to softwood sawdust due to variations in cellulose, hemicellulose, and lignin content. This variability makes it challenging to establish standardized performance parameters for large-scale applications [50].

To overcome these limitations, researchers emphasize the importance of pre-treatment and modification techniques that can enhance the stability, adsorption efficiency, and reusability of sawdust. Pilot-scale testing is also essential to evaluate the performance of sawdust-based systems under realistic conditions before they can be reliably deployed in industrial or municipal wastewater treatment plants. Only through such optimization can sawdust move from being a promising laboratory material to a dependable solution for widespread environmental remediation.

6. Conclusions

The collective body of research reviewed in this article demonstrates that sawdust is a versatile, low-cost, and environmentally friendly adsorbent with significant potential for wastewater treatment. Derived as a byproduct of the wood processing industry, sawdust is abundant in most parts of the world, making it an accessible raw material for pollutant removal, especially in regions where financial and technological resources for advanced treatment systems are limited. Its chemical composition—dominated by cellulose, hemicellulose, and lignin—provides a diverse array of functional groups capable of binding a wide range of contaminants, including heavy metals, synthetic dyes, and organic pollutants.

The adsorption performance of raw sawdust can be significantly enhanced through various modification techniques. Physical treatments such as grinding, sieving, and washing improve particle size uniformity and remove impurities. Chemical modifications, particularly acid, alkali, or oxidative treatments, can increase the availability of functional groups and alter surface charge to target specific pollutants. Thermal activation, meanwhile, can generate high-surface-area biochar-like materials that rival commercial activated carbon in performance. These modifications not only improve adsorption capacity but can also enhance regeneration potential, enabling repeated use and reducing overall operational costs.

Mechanistically, sawdust interacts with contaminants through a complex interplay of adsorption processes. Heavy metals are often removed via ion exchange and surface complexation; dyes through electrostatic attraction, hydrogen bonding, and π–π stacking; and organic pollutants through hydrophobic interactions and aromatic bonding. The multiplicity in adsorption pathways renders sawdust with a broad scope of applicability which is uncommon to mono-material-based adsorbents. Nevertheless, these interactions are highly dependent on the solution-related parameters of chemistry (pH, ionic strength, presence of interfering species, etc.).

Controlled lab applications have demonstrated removal efficiencies of over 90 percent of several target contaminants and equilibrium is commonly reached in 30 to 120 minute range. Compared to other agricultural by-products adsorbents, sawdust can often provide better functions, owing to their large and diverse types of functional groups and porous microscopic structures. However, there are various issues when it comes to scaling up the laboratory to the fields. The complex nature of real wastewater stream is chemically complex as the types of contaminants present in a mixture compete with each other to occupy binding sites as well as disrupt the adsorption process. Fine particles of sawdust are as well not easily removed in the treated water without extra separation processes and this may complicate the operations. Besides, differences in sawdust composition based on wood species and age as well as different processing steps, may affect the adsorption performance unpredictably.

Despite these challenges, the environmental and economic advantages of using sawdust are compelling. Repurposing sawdust for wastewater treatment reduces the environmental burden associated with its disposal, particularly in areas where open burning or landfilling are common practices. It also decreases reliance on costly commercial adsorbents, enabling broader access to clean water technologies in low-income and rural communities. Integrating sawdust-based adsorption into hybrid treatment systems—such as coupling with biological filtration, membrane processes, or advanced oxidation—could further improve removal efficiencies and broaden the spectrum of treatable pollutants.

Future research should focus on several key areas. First, more pilot- and full-scale studies using real industrial wastewater are needed to assess the performance, operational stability, and cost-effectiveness of sawdust-based systems under realistic conditions. Second, regeneration strategies should be optimized to maximize the number of reuse cycles without compromising adsorption capacity or generating secondary pollution. Third, composite materials incorporating sawdust with other functional adsorbents, catalysts, or nanomaterials could be developed to combine adsorption with degradation processes, enabling simultaneous removal and breakdown of persistent contaminants. Lastly, a life-cycle assessment (LCA) approach should be applied to evaluate the overall environmental footprint of sawdust modification, use, and disposal, ensuring that these systems remain sustainable over the long term.

In conclusion, sawdust represents a promising, sustainable solution for water purification in a world increasingly challenged by environmental pollution and resource scarcity. With appropriate modification, system design, and integration into larger treatment frameworks, it can play a significant role in achieving global water quality goals while promoting waste valorization and circular economy principles. Continued interdisciplinary research—bridging materials science, environmental engineering, and industrial ecology—will be critical in translating this abundant byproduct into a mainstream technology for clean water production.

Author Contributions

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