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REVIEW ARTICLE

Sustainable biowaste activated carbons for cleaner wastewater treatment by adsorption: A review

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ABSTRACT

The rapid expansion of industrial activities alongside the depletion of natural resources has intensified the global demand for sustainable wastewater treatment technologies. Activated carbon derived from biowaste precursors presents a superior eco-friendly and economically viable alternative to conventional fossil-based materials while advancing the strategic goals of a circular economy. This comprehensive review evaluates synthesis pathways encompassing conventional and hydrothermal carbonization, physical and chemical activation mechanisms, and the technical advantages offered by microwave-assisted heating. Systematic synthesis of literature demonstrates that biowaste-based activated carbon possesses exceptional morphological characteristics and adsorption capacities that frequently surpass commercial standards for the remediation of synthetic dyes, heavy metals, and pharmaceutical contaminants. Despite these advancements, this review identifies a critical research gap regarding the persistent difficulty in standardizing final product quality due to the inherent chemical and structural variability of diverse biomass precursors. Furthermore, the lack of performance evaluation in multi-component pollutant systems fails to accurately reflect the complex chemical interactions of real-world industrial wastewater streams. This fundamental discrepancy between controlled experimental success and rigorous industrial requirements continues to be the primary obstacle preventing the widespread implementation of biowaste-derived adsorbents.

Keywords: activated carbon; adsorption; biomass; circular economy; waste; wastewater treatment

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1. Introduction

Global freshwater consumption has demonstrated a sustained annual growth of approximately 1% since 1980, as detailed in the 2021 World Water Development Report by UNESCO. This persistent increase in demand concerns a resource that is essential for human survival[1]. This poses a serious challenge in maintaining water quality, especially in water pollution. According to a 2017 report by the World Water Assessment Program, 80% of global wastewater is discharged undergoing treatment, causing pollution of various water sources and groundwater, which leads to eutrophication[2]. The increasing amount of pollutants has led to a scarcity of clean water, thereby disrupting food security[3].

Water contamination occurs due to several main factors, namely industrial waste disposal, agriculture, illegal waste disposal, and leachate leakage from landfills[4]. Wastewater contains excess nutrients, organic compounds, and heavy metals from anthropogenic activities[5].

These hazardous substances tend to bioaccumulate in aquatic organisms and biomagnify along the food chain[6]. Therefore, these toxic agents compromise the integrity of aquatic ecosystems and, by extension, public health. The latter is endangered via consumption pathways involving tainted water, fish, and agricultural produce[7]. As pollutant concentrations increase across trophic levels, it becomes crucial to implement stricter control and mitigation measures to reduce the discharge of toxic substances into natural water bodies by regulating industrial and domestic waste disposal[8].

Wastewater remediation is accomplished using multiple techniques, notably adsorption, membrane filtration, and advanced oxidation processes[9]. Among these methods, adsorption is notable due to its simplicity, efficiency, and adaptability for the removal of various pollutants[10]. However, activated carbon produced through chemical activation tends to be expensive[11]. This makes the use of commercial activated carbon less economical, especially for large-scale applications.

Biowaste is a promising source of raw materials as a sustainable and economical alternative[12]. Global waste generation is projected to increase from 2 billion tons in 2016 to 3.8 billion tons annually by 2050, as detailed in the World Bank's "What a Waste 2.0" report. Biowaste, which consists of food waste, agricultural residues, and organic household waste, constitutes a significant 40% of this total waste stream[13]. This data shows that biowaste is the most dominant type of waste and has great potential for reuse, one of which is as an activated carbon material[14]. The high carbon content in this waste has the potential to be used as raw material for activated carbon for sustainable wastewater treatment[15]. In addition, converting biowaste into adsorbents offers various advantages, such as increased economic value, environmental friendliness, and low cost[16]. This application not only transforms waste materials into commercially viable products but also reinforces the core concepts of a circular economy and zero waste[17].

This sustainable methodology is intrinsically aligned with circular economy principles and contributes to several Sustainable Development Goals (SDGs). Its primary impact is on SDG 12 (Responsible Consumption and Production), achieved by valorizing organic waste into useful products and thus minimizing environmental disposal. This waste diversion also indirectly supports SDG 13 (Climate Action) by curbing emissions from conventional waste disposal. Furthermore, the approach directly enhances SDG 6 (Clean Water and Sanitation) by reducing harmful pollutants in liquid waste. This improvement in water quality provides a co-benefit for SDG 3 (Good Health and Well-Being) by mitigating public health risks associated with pollutant exposure. Finally, if implemented at an industrial scale, this local-resource-based solution has the potential to advance SDG 9 (Industry, Innovation, and Infrastructure).

Recognizing the critical importance of developing sustainable adsorbents, extensive research has emerged focusing on biowaste-derived materials including activated carbons. However, this significant research gap persists due to the inherent chemical and structural variability of biomass precursors which complicates the standardization of final product quality. Consequently, this paper provides a strategic review of outstanding publications regarding activated carbons synthesized from biowaste for the removal of dyes, heavy metal ions, and pharmaceutical compounds from both simulated and real wastewater. By synthesizing these recent advancements, this review aims to bridge the fundamental discrepancy between academic findings and the rigorous requirements of industrial-scale water purification systems.

2. Application of activated carbon derived from biowaste

The utilization of activated carbon derived from biowaste offers significant advantages in integrated wastewater management. For instance, the synergy between ozonation and adsorption processes effectively boosts leachate treatment performance and biodegradability[18]. While high ozone requirements make the treatment of raw leachate expensive in real-world scenarios, coupling these methods can reduce ozone usage and minimize operational costs, providing both economic and environmental benefits.

Integrating biowaste-derived activated carbon with the Fenton reaction (AOP) enables effective degradation of organic pollutants using H_2O_2 and Fe^{2+} in acidic conditions. It offers simple operation, rapid kinetics, and high efficiency, but its disadvantages include strict pH control and iron sludge generation. Despite this, the approach remains a viable solution for sustainable water purification[19].

Commercial production of activated carbon has traditionally relied on a range of raw materials including various grades of coal and related by-products (e.g., pitch), petroleum coke, wood, coconut shells, nut shells, fruit pits, and sawdust[18]. These materials were selected due to their high carbon content and pore structure, which supports the efficiency of the activation process[19]. Among them, coconut shells are widely used because they have high density, low ash content, and ability to yield activated carbon with a large specific surface area[20]. Several studies confirm that coconut-shell-based activated carbon exhibits excellent adsorption capacity[21]. Especially for heavy metal and organic compound filtration and adsorption applications, with microstructural pore characteristics that support the activation process and optimal adsorbent performance[22]. Therefore, although coconut shells are an ideal material from a technical and ecological standpoint, efforts to develop alternative raw materials and innovative activation techniques are needed to maintain the sustainability of high-quality activated carbon production on an industrial scale[25]. In addition, dependence on limited natural resources will raise concerns about supply sustainability and increased production costs.

Conventional feedstocks like coal, lignite, and coconut shells are increasingly being replaced by renewable and sustainable alternatives. In this regard, waste biomass (biowaste) has emerged as an environmentally benign and cost-effective source for activated carbon production[24]. Biowaste includes various agricultural residues and organic waste, such as bagasse, fruit peels, wood waste, rice husks, straw, and food waste[25]. This source generally has high carbon content, a lignocellulose structure that is conducive to pore formation, and abundant availability throughout the year[26]. The use of biowaste not only reduces dependence on limited and costly fossil raw materials[27]. It also provides added value by reducing the volume of organic waste that has the potential to pollute the environment[28]. In addition, transforming low-value biowaste into functional adsorbent materials aligns with circular economy principles by converting discarded organic matter into useful products applicable in water purification[29], industrial wastewater treatment[30], and air pollutant control[31]. As illustrated in **Figure 1**, the synthesis routes of activated carbons from biowaste generally involve pretreatment, carbonization, and activation processes before obtaining the final adsorbent material.

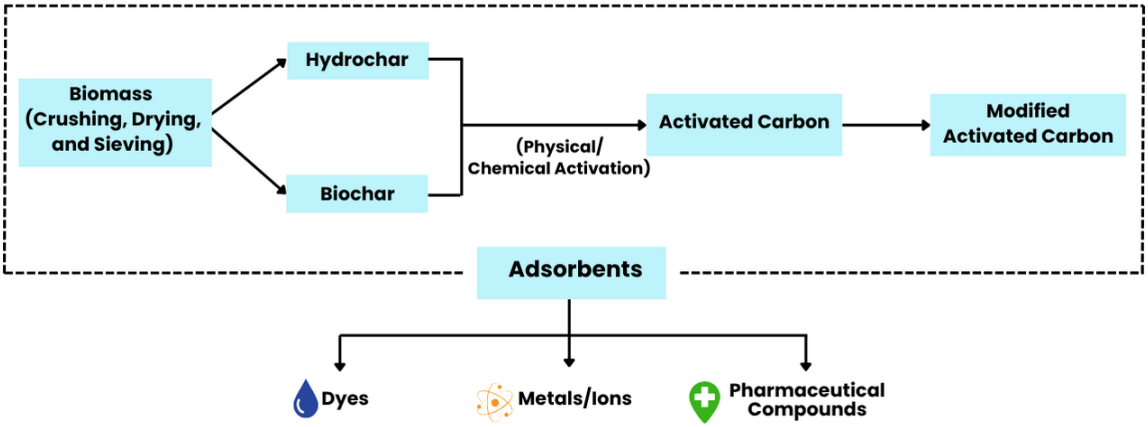

Figure 1. Synthesis routes of activated carbons from biowaste.

The preparation of raw materials through pretreatment stages is widely used to achieve optimal quality in the carbonization and activation stages in activated carbon production[32]. Drying at an optimal temperature of 100–105°C for 24 hours is effective in removing free moisture without damaging the physical properties of the raw material, thereby supporting the stability of the subsequent thermal process[33]. This removal of

moisture minimizes the formation of water vapor that can interfere with the pyrolysis process, thereby improving the quality of the activated carbon produced[34]. Next is screening, which is done to control the particle size of the raw material so that uniform and fine grains are obtained[35]. Smaller particle sizes result in better activated carbon texture because they increase specific surface area and pore homogeneity[36]. The breakdown of coarse particles through grinding and sieving allows for more effective penetration of the activator during the activation process, which contributes to an increase in the adsorption capacity of activated carbon[37]. Therefore, the combination of drying and sieving methods as a systematic pretreatment stage is key to producing activated carbon with superior physical and chemical characteristics and optimal application performance.

Carbonization is the next important step in the production of activated carbon. Carbonization is a high-temperature thermal process that converts organic material into carbon with a pore structure that supports adsorption capabilities[38]. This process can be carried out using two main methods, namely conventional carbonization and hydrothermal carbonization[39]. Conventional carbonization is carried out by directly heating the raw material at elevated temperatures (400–1000°C) under inert or oxygen-limited conditions[40]. High temperatures serve to remove volatile components and compact the carbon structure[41]. This method is commonly used and effective in producing carbon with a large surface area, but it usually requires a considerable amount of energy and a relatively long processing time[40]. Hydrothermal carbonization is carried out under wet conditions by heating the raw material at moderate pressure and temperature (180–250°C) in a closed environment using water as the reaction medium[42]. This method enables the conversion of raw materials with high moisture content without the need for intensive drying beforehand, resulting in carbon with a distinctive micro- and mesostructure and broader application potential. Hydrothermal carbonization is also considered more environmentally friendly and energy efficient than conventional carbonization[43]. Importantly, these two methods produce carbon materials with distinct physicochemical characteristics. Hydrothermal carbonization typically yields hydrochar enriched with oxygen-containing functional groups such as hydroxyl and carbonyl, but with limited pore development and relatively low surface arean[46]. In contrast, conventional carbonization promotes devolatilization and aromatization, resulting in a more ordered structure with well-developed microporosity and higher surface area, but fewer surface functional groups due to thermal decomposition[47].

The activation process is carried out to develop carbon porosity, increase surface area and enhance the adsorption capacity of activated carbon[44]. Activation can be performed through two main approaches: physical activation and chemical activation. In physical activation, gases such as CO_2, N_2, or steam react with carbon at high temperatures (700–900°C)[45]. This process opens the pores and cleans the surface of the carbon without using additional chemicals, resulting in activated carbon with a stable pore structure[46]. Chemical activation, in contrast, is characterized by the impregnation of the precursor material with a chemical agent (e.g., KOH, H_3PO_4, or $ZnCl_2$) prior to carbonization[47]. This activator helps open pores and induce chemical reactions that significantly increase the surface area of carbon at lower carbonization temperatures compared to physical activation[48]. This activator helps open pores and induce chemical reactions that significantly increase the carbon's surface area at lower carbonization temperatures compared to physical activation[49]. The selected carbonization and activation methods strongly influence the physicochemical properties of the resultant activated carbon, along with the overall efficiency and sustainability of the production processs[39]. The optimal integration of pretreatment steps, such as drying and screening, with appropriate carbonization and activation methods is crucial for yielding activated carbon with tailored properties and high efficacy. This allows for its use in diverse industrial applications, including water purification, pollutant control, and energy storage. Such a holistic methodology ensures a balanced optimization of product performance, production costs, and environmental impact for industrial-scale activated carbon manufacturing[50].

Heating using microwaves allows for rapid and uniform energy absorption directly into the precursor material matrix[51]. This, it accelerates the carbonization rate compared to conventional conduction- and convection-based heating methods. Activated carbon produced through microwave heating shows an increase in specific surface area of up to 15–25% higher than conventional carbonization under similar process conditions[52]. In addition, the total porosity and micro-pore volume of microwave-activated carbon consistently exceed the porosity values achieved by conventional heating, resulting in a more open and evenly distributed pore structure[53]. Microwave-heated activated carbon can reduce the concentration of organic pollutants such as methylene blue by up to 98%, indicating that microwave radiation increases the local temperature on the surface of activated carbon, which accelerates pore formation, but also has the potential to cause hotspots that can damage the structure if not properly regulated[54]. Although conventional heating is slower, more stable temperature and time control makes this process easier to control and reduces the risk of pore damage compared to the microwave method, which is fast but requires optimization of power and high frequency[55].

Activated carbon produced from various biowaste precursors exhibits a wide range of specific surface areas that depend on the type of raw material, carbonization conditions, and activation method used[56]. Scientific literature indicates that surface areas of 700-1500 m^2/g are achievable for activated carbon produced from agricultural biomass, including coffee grounds and coconut shells. This level of performance is on par with, or exceeds, that of traditional activated carbons derived from coal[57]. The distribution of porosity, particularly the ratio between micro and meso pores, is strongly influenced by the activation technique applied to the biowaste precursor[58]. Chemical activation using agents such as KOH or H_3PO_4 generally results in higher microporosity and total pore volume compared to physical activation with CO_2 gas or water vapor, which tends to increase mesopore porosity but with a slightly lower total surface area[59]. Biowaste-based activated carbon exhibits excellent adsorption performance, particularly for contaminants including Pb(II) and Cd(II) ions and organic dyes (e.g., methylene blue). This high efficacy—with removal rates often surpassing 90% in rapid contact times—is fundamentally linked to its microporous structure, which governs the material's overall adsorptive capacity and selectivity[60]. The high adsorption capacity is attributed to a combination of well-developed pore structure and the presence of surface functional groups formed during the activation process[61]. A comparative review of heating methods shows that microwave carbonization of biowaste produces activated carbon with a surface area up to 25% higher and a larger microporous volume compared to conventional thermal carbonization[55]. This improvement contributes to faster adsorption kinetics and higher capacity for organic pollutants, supported by more uniform heating and shorter processing times in the microwave method[62]. However, problems such as hotspot formation need to be addressed with proper power and frequency settings so as not to damage the carbon pore structure.

3. Sustainable approaches for pollutant removal using activated carbons synthesized from biowaste

Biowaste-based activated carbon exhibits high efficiency in the adsorption of numerous aquatic contaminants, such as synthetic dyes, heavy metals, and pharmaceutical compounds. Reflecting this versatility, recent research is often classified according to the specific adsorbate being studied. Each section provides a synopsis of contemporary research, covering the biowaste feedstocks, carbon preparation methods, and key performance metrics (e.g., removal efficiency).

3.1. Dyes

Dyes are compounds used in various industrial sectors, such as the textile, food, rubber, cosmetics, paint, pharmaceutical, paper, and pulp industries[63]. Dyes are usually water-soluble and designed to bond with the surface of the material to produce intense, long-lasting colors[64]. However, dyes can contaminate water because they are toxic, carcinogenic, and mutagenic[65]. Dye waste discharged into surface waters renders the

water unfit for use due to its high toxicity to living organisms[66]. Currently, more than 3,600 textile dyes are manufactured using over 8,000 different chemicals for diverse textile production processes such as dyeing and printing[67]. The use of organic dyes in the textile, cosmetics, food, pharmaceutical, and printing industries makes these sectors major contributors to wastewater pollution[68]. Methylene blue (MB) is a recalcitrant organic dye that is notoriously challenging to degrade. Its persistence is a major concern, as it is associated with adverse health effects involving the eyes, skin, and brain function. For dyes including Methylene Blue, generally occurs at pH > 6[73]. At this range, the activated carbon surface undergoes deprotonation, becoming negatively charged, which drastically enhances the adsorption capacity through strong electrostatic attractions[74]. This is particularly problematic given its extensive industrial use in dyeing processes involving materials such as silk, wool, cotton, and paper[69].

Table 1 shows activated carbon derived from various biomasses in adsorbing organic dyes. The adsorption capacity (Qe) shows significant variation, ranging from the lowest value of 17.596 mg/g for rice husk activated carbon (300°C) toward Basic Blue 41 to 600 mg/g for sawdust activated carbon (900°C/H_3PO_4) for Rhodamine B. These observed variations are attributed to the inherent physicochemical properties of each biomass and the specific activation conditions employed (e.g., temperature, chemical activator, and duration). These factors collectively determine the material's final pore volume, surface characteristics, and pore size characteristics[70]. Phosphoric acid (H_3PO_4) activation, particularly at elevated temperatures, typically yields a predominantly mesoporous structure. This morphology enhances the material's active site density, thereby augmenting both electrostatic attractions and van der Waals interactions between the activated carbon surface and dye molecules[71]. Use of H_3PO_4 as an activating agent significantly improves the surface area. While H_3PO_4 activation effectively enhances dye removal, its significant environmental footprint and potential toxicity to human health and ecosystems, such as increasing phosphate levels in water[78]. Furthermore, a proper neutralization process must be implemented to stabilize H_3PO_4 residues before disposal, ensuring that the activation stage does not introduce secondary pollution to the surrounding environment[73].

The different activators produce distinct effects on activated carbon structure and performance. The results indicate that $ZnCl_2$ tends to reduce efficiency due to pore blockage and structural damage, while increasing H_3PO_4 concentration also negatively affects performance because of severe surface blockage. In contrast, KOH is found to enhance pore development and introduce functional groups that improve adsorption capacity[79].

The interaction between pollutants and adsorbents at the physicochemical level plays a crucial role in determining adsorption efficiency. For cationic dyes such as Methylene Blue, Methyl Violet, and Malachite Green, removal is removal is governed by both chemical and physical interactions, primarily through electrostatic attraction between positively charged dye molecules and negatively charged oxygen-containing functional groups (–OH, –COOH) on the activated carbon surface, as well as pore filling and van der Waals forces[80]. In addition to electrostatic interactions, mechanisms such as π–π interactions between the aromatic structures of dyes and the graphitic domains of carbon, along with hydrogen bonding, further enhance adsorption performance[81]. Moreover, the textural properties of the adsorbent, including surface area and pore size distribution, are equally important, as they control the accessibility and diffusion of dye molecules into the pores. For instance, the relatively low adsorption capacity observed in walnut shell powder (19.995 mg/g for Methylene Blue) can be attributed to its limited surface area and unsuitable pore size distribution[73]. The compatibility between dye characteristics (e.g., charge and molecular size) and adsorbent properties has also been demonstrated in various biomass sources, such as sawdust and palm oil residues[72]. Therefore, effective pollutant removal is governed by the synergistic effect of surface chemistry and pore structure, highlighting the importance of optimizing both activation conditions and biomass selection to achieve high adsorption performance.

Table 1. Dyes adsorption on adsorbents derived from biomass.

Biomass Source	Target Polutant	Adsorption Capacity, Qe (mg/g)	Ref
Walnut shell powder (1005°C)	Methylene blue	19.995	[73]
Einkorn husk (500°C/$ZnCl_2$)	Methylene blue	149.86	[74]
Fir bark	Methylene blue	330	[75]
Cotton stem	Rhodamine B	265.96	[76]
Palm bio-waste (600°C/H_3PO_4)	Basic Blue 41	344.83	[77]
Sawdust (900°C/ H_3PO_4)	Rhodamine B	600	[78]
Rice husk (300°C)	Basic Blue41	17.596	[79]
Rice husk (300°C)	Basic Red 09	168.49	[79]
Pineapple leaf (500°C/$ZnCl_2$)	Methyl violet	75.29	[80]
Coconut shell (500°C/$ZnCl_2$)	Methyl violet	52.91	[80]
Cocoa shell (500°C/$ZnCl_2$)	Methyl violet	49.08	[80]
Oil palm leaves (1000°C)	Malachite green	104.16	[81]
Oil palm leaves (1000°C)	Brilliant green	500	[81]
Fennel seeds	Methyl red	216	[82]
Pine sawdust ($ZnCl_2$)	Black	68.5	[83]

3.2. Heavy metals

Heavy metal such as Cd^{2+}, Pb^{2+}, Cu^{2+}, Ni^{2+}, and Cr^{6+} represent a big threat to human health and aquatic ecosystems. As common pollutants in industrial and domestic waste, their primary hazard lies in their propensity to bioaccumulate and magnify through the food chain[84]. For some heavy metals such as Ni^{2+}, Cd^{2+} and Pb^{2+} the optimum pH obtained is 5[95]. Biowaste-derived activated carbon has received significant scientific attention as an effective adsorbent for immobilizing toxic heavy metals and anionic species. This interest is driven by its favorable physicochemical characteristics, notably a high surface area, supportive pore structure, and abundant surface functional groups that facilitate adsorption and ion exchange. The removal of these contaminants is critically important as they are toxic and carcinogenic, presenting a severe and often insidious threat to public health and the environment[85].

Activated carbon originated from agricultural residual such as rice husks, coffee grounds, and coconut shells has a strong attachment for heavy metal ions and can achieve removal efficiencies of over 90% under optimal conditions[86]. The main adsorption mechanism involves electrostatic interactions, surface complexation, and ion exchange between metal ions and groups such as carboxyl, hydroxyl, and phenolic on the surface of activated carbon[87]. The phenomenon of competitive ion adsorption is also often encountered, especially in mixed metal systems, so that selectivity and adsorption capacity must be optimized by adjusting parameters such as solution pH, contact time, and adsorbent dosage to achieve maximum efficiency in complex water matrix conditions[88].

The data in **Table 2** shows that different types of biomass have varying adsorption capacities depending on the type of metal and activation conditions. Activated carbon from sawdust can achieve a Pb^{2+} adsorption capacity of 110 mg/g, which is much higher than simple biochar from avocado leaves, bitter orange, and walnuts with a capacity of only 60 mg/g. This shows that the activation process plays an important role in increasing the surface area and active adsorption sites[89]. The activation process with phosphoric acid or sulfuric acid will increase the surface functional groups of activated carbon, the hydroxyl carboxyl groups on the surface of carbon, thereby increasing the adsorption capacity of heavy metals through chemical bonding and ion exchange[90].

Meanwhile, Cd^{2+} ions have adsorption values ranging from 7.13 mg/g (rooibos tea waste) to 45 mg/g (Eupatorium adenophorum and Acer oblongum leaves). This difference is due to variations in the position and functional groups of oxygen (–OH, –COOH) that can bind with Cd^{2+} through ion exchange mechanisms[91]. Adsorption of Cr^{6+} shows very high capacity in pea peels (Pisum sativum) activated with triethylenetetramine, reaching 312.5 mg/g, compared to other adsorbents such as Salvinia molesta (33.33 mg/g) or Typha latifolia (10.3 mg/g). This proves that chemical modification of biomass can enhance electrostatic bonding and complexation with metal ions, resulting in optimal adsorption capacity under specific pH and temperature conditions[92].

Table 2. Heavy Metals adsorption on adsorbents derived from biomass.

Biomass Source	Target Polutant	Adsorption Capacity, Qe (mg/g)	Ref
Loblolly pine chips - Cd^{2+}	Cd^{2+}	16.62	[93]
Eupatorium adenophorum and *Acer oblongum* leaves (acid-activated)	Cd^{2+}	44-45	[94]
Digenia simplex (Calcium chloride pretreatment)	Cd^{2+}	11.16	[95]
Avocado, bitter orange, walnut leaves (biochar)	Pb^{2+}	60	[89]
Sawdust activated carbon (general industrial by-product adsorbent)	Pb^{2+}	110	[96]
bacterial cellulose and *Eichhornia crassipes*	Cr^{6+}	99-123	[97]
Corn stover biochar (700°C)	Cd^{2+}	13.4	[98]
Rooibos tea waste lignocellulosic adsorbent	Cd^{2+}	7.13	[99]
Activated Pisum sativum (pea) peels with triethylenetetramine	Cr^{6+}	312.5	[100]
Salvinia molesta and *Typha latifolia*	Cr^{6+}	33.33 and 10.30	[101]
Hexavalent Chromium	Cr^{6+}	10.6	[102]

3.3. Pharmaceuticals

Pharmaceutical compounds such as antibiotics, analgesics, and endocrine disruptors are persistent emerging pollutants in water bodies and have significant ecological impacts[103]. The pH optimal for pharmaceutical obtained is 3-5[115]. The adsorption process of pharmaceutical compounds is influenced by hydrophobic interactions, electron donor-acceptor interactions, and hydrogen bonds between pharmaceutical molecules and the carbon surface[104]. Activated carbon from biowaste with a well-developed micro and mesoporous structure provides numerous physical adsorption sites, while surface functional groups support chemical interactions that enhance affinity for specific compounds[105].

Activated carbon from biowaste sources such as coconut shells and agricultural residues can remove pharmaceutical compounds such as ibuprofen, diclofenac, and sulfamethoxazole with a removal rate of over 85% in batch tests[106]. Surface modification of activated carbon with metal oxide impregnation or polymer coating has also been explored to improve selectivity and adsorption regeneration capacity, thereby overcoming the challenge of removing pharmaceutical compounds from complex wastewater[107].

As shown in **Table 3**, activated carbon derived from biomass and agricultural residues has been extensively studied for the adsorption of pharmaceutical pollutants. Activated carbon prepared from alfalfa (*Medicago sativa* L.) and chemically activated using $ZnCl_2$ exhibited a very high adsorption capacity for tetracycline (594.5–1127 mg/g), indicating strong interactions between antibiotic molecules and biomass-derived carbon surfaces[120]. Likewise, cocoa shell–based activated carbon functionalized by plasma treatment and glycine effectively removed ibuprofen, with adsorption capacities ranging from 45 to 120 mg/g, highlighting the role of surface functionalization in enhancing adsorption performance. These results confirm that activated carbon from biowaste sources such as coconut shells and agricultural residues can effectively

remove pharmaceutical compounds such as ibuprofen, diclofenac, and sulfamethoxazole, with adsorption performance strongly dependent on the biomass source, activation method, and surface modification strategy[121].

Table 3. Pharmaceuticals adsorption on adsorbents derived from biomass.

Biomass Source	Target Polutant	Adsorption Capacity, Qe (mg/g)	Ref
Alfalfa Medicago sativa L. (800°C/$ZnCl_2$)	Tetracycline (Antibiotic)	594.5-1127	[120]
Cacao shell functionalized with plasma and glycine	Ibuprofen (IBP)	45 – 120	[121]
Granular Activated Carbon	Diclofenac (DCF)	56,2	[122]
Activated sludge (H_3PO_4)	Sulfamethoxazole (SMX), lincomycin (LIN)	45.6 and 26.6	[123]
Pinus sylvestris bark activated carbon/metaloxides	Tetracycline (antibiotik)	48.2	[124]

4. Advancements in contaminant adsorption utilizing biowaste based activated carbons

4.1. Current Advancements

Recent developments in the use of biomass waste-based activated carbon as an adsorbent have produced significant results in the elimination of a wide range of contaminants from environmental matrices. Activated carbon based on biowaste is increasingly being researched, due to its abundant low manufacturing cost, and contribution to supporting the circular economy concept. Current research is focused on improving adsorption efficiency by surface modification, composite formation and development of multifunctional adsorbents.

The effectiveness of biomass-derived activated carbon in the remediation of heavy metals such as Pb^{2+}, Cd^{2+}, and Cr^{6+} is controlled by various mechanisms. These include ion-exchange reactions, electrostatic forces, and surface complexation, all facilitated by the presence of active functional groups on the adsorbent material[112]. The calcium carbonate present in activated carbon derived from eggshells, for example, enhances the surface affinity, leading to a high adsorption capacity for Pb^{2+}[113]. Other studies have also reported that activated carbon from rice husks is capable of efficiently adsorbing Cr^{6+} ions due to its extensive microporous structure and the presence of abundant active adsorption sites[114]. Adsorption capacity improvements are further enhanced by chemical modification using strong bases or impregnation with metal nanoparticles, which can enrich active sites on the surface of activated carbon[115].

In addition to heavy metals, synthetic dyes are also a major concern due to their massive usage at the textile and leather industries and their resistance to natural degradation[116]. Activated carbon from coffee husks, banana peels, and tea leaves has been reported to be capable of adsorbing dyes such as MB and MV with high capacity through interaction, hydrogen bonding, and pore filling[117]. Surface modification using positively charged polymers has been shown to increase adsorption effectiveness against anionic dyes such as Congo red and Reactive Black 5, demonstrating the flexibility of biowaste-based activated carbon in targeting various types of dyes with different chemical properties[76].

Other organic pollutants such as phenol, bisphenol A, antibiotics, and pesticides have also been highly adsorbed using activated carbon from biowaste[118]. The adsorption mechanism generally involves hydrophobic interactions and stacking. For example, activated carbon from palm oil waste shows high capacity in removing phenol, while activated carbon from rice husks modified with Fe_3O_4 shows increased capacity against tetracycline antibiotics[119]. These findings indicate that biowaste can be utilized not only for the removal of conventional pollutants, but also emerging pollutants that are increasingly becoming a global concern.

In addition to pollutants in the liquid phase, activated carbon from biomass also shows promising performance in gas absorption. CO_2 adsorption on biowaste activated carbon occurs mainly through physisorption in micropores, but capacity can be increased through impregnation with bases or amine modification to enable chemisorption[120]. For example, activated carbon from coffee grounds modified with polyethyleneimine (PEI) showed a significant increase in CO_2 capture due to chemical interactions between the amine groups and gas molecules[121]. This innovation opens up great opportunities for the use of biowaste activated carbon in greenhouse gas emission mitigation technology.

Fundamentally, the performance of adsorption as biowaste into activated carbon is a function of its physicochemical properties, namely its specific surface area of a material per gram, pore architecture, and surface functional groups[56]. The adsorption process is also profoundly affected by environmental and operational factors, namely pH, temperature, adsorbent dosage, and contact time[122]. Recent research emphasizes that the combination of pore structure engineering and surface functionalization is a key strategy in optimizing adsorbent performance.

Comparison with commercial activated carbon shows that in many cases, biowaste-based activated carbon has competitive adsorption capacity, even superior to some organic pollutants and dyes[123]. Its industrial feasibility has been demonstrated through pilot-scale implementation using an integrated PAC-based filtration system, enabling effective decolorization of sugar beet extract without significant sucrose loss[136]. Furthermore, the use of abundant and low-cost agro-industrial residues, such as palm oil waste, enhances its economic feasibility, with production costs ranging from USD 0.5–2/kg, lower than commercial activated carbon (USD 2–5/kg)[137]. These findings highlight its strong potential for sustainable large-scale industrial applications.

4.2. Future perspectives

The application of biomass waste that is turning into activated carbon in wastewater remediation is a compelling future solution due to its sustainable and environmentally friendly profile. It leverages abundant, often-overlooked resources, including rice husks, fruit peels, and agricultural/food waste. These materials can be processed via carbonization and activation to yield adsorbents possessing high porosity and large specific surface areas. These material attributes are directly responsible for their high efficacy in removing various micropollutants, such as synthetic dyes, heavy metals, and hazardous organics[124].

The industrial application of biomass-derived activated carbon faces a significant hurdle in the variability of its precursors. The disparate chemical compositions and physical structures of different biomass sources can lead to inconsistent product quality and performance. Consequently, achieving a stable material requires a process-specific optimization of conditions, including carbonization temperature, activator type, and duration, tailored to the specific feedstock[125].

In addition, production costs and energy efficiency in the manufacture of biomass-based activated carbon remain considerable challenges, so more energy-efficient and environmentally friendly technologies are needed to make this process more competitive compared to commercial activated carbon[126]. Commercial activated carbon derived from conventional sources such as coal or coconut shells is typically priced at around USD 3.30/kg, whereas biowaste-derived activated carbon can be produced at a comparable or lower cost, generally ranging from approximately USD 1.44 to 3.24/kg depending on the feedstock and activation method[140]. This cost difference highlights a significant economic advantage, particularly in terms of reduced raw material expenses and lower initial production costs. Moreover, the use of abundant biowaste not only minimizes feedstock costs but also reduces waste management expenditures, further strengthening its economic feasibility. However, a more comprehensive comparison should consider the life cycle cost (LCC), including production, operation, regeneration, and disposal costs. In this context, biowaste-based activated carbon offers additional long-term economic advantages through its potential for regeneration

and sustainable reuse[141]. Therefore, integrated LCC and techno-economic analyses are essential to quantitatively demonstrate its overall economic superiority and industrial applicability compared to commercial activated carbon[142].

A major difficulty arises when scaling up the application of biomass-derived activated carbonfrom laboratory experiments to real-world wastewater treatment systems. Most existing studies have been conducted under controlled laboratory conditions, which do not accurately reflect the complexity of industrial wastewater, where diverse contaminants often coexist and interact in ways that can diminish adsorption efficiency. Consequently, additional studies are required to evaluate the performance of biomass-based activated carbon in realistic operational environments and to develop effective regeneration strategies that allow for repeated use without substantial loss of adsorption capacity.

A critical technical challenge for the future is maintaining the long-term stability of biowaste-derived activated carbon throughout multiple treatment cycles. Recent studies on electrochemical regeneration have demonstrated that while activated carbon can be effectively recycled up to six times, there is a progressive decline in performance. For example, the adsorption efficiency was found to decrease from an initial 98.78% in the first cycle to 68.55% by the sixth cycle[143]. This reduced effectiveness highlights a key disadvantage of current regeneration methods, likely due to structural damage or incomplete adsorbate removal. Therefore, more robust protocols are needed to maintain adsorbent integrity and ensure economic viability in wastewater treatment.

In the long term, future research should focus on integrating activated carbon derived from biomass waste with complementary treatment approaches, such as membrane filtration, photocatalytic degradation, and bioremediation systems, to enhance the overall efficiency and sustainability of wastewater treatment processes. Moreover, valorizing biomass waste for activated carbon production embodies the core principles of the circular economy, as it not only diverts waste from environmental disposal but also transforms it into high-value functional materials that support resource recovery and sustainable environmental management[127]. Thus, despite various technical and economic obstacles that still need to be overcome, biomass waste-based activated carbon remains promising as an innovative solution for sustainable wastewater remediation.

5. Conclusion

Effective wastewater treatment is essential to maintaining the continuous supply of clean water resources. Activated carbon produced from biomass has attracted considerable interest as an environmentally sustainable and economically viable substitute for traditional commercial activated carbon, primarily due to its inexpensive raw materials and strong adsorption performance. Recent research has demonstrated its high efficiency in removing synthetic dyes and heavy metals from contaminated water. However, additional studies are necessary to evaluate its performance in treating more complex pollutants such as pharmaceuticals and personal care products (PPCPs), pesticides, phenols, palm oil mill effluent (POME), and landfill leachate.

A critical challenge lies in bridging the gap between laboratory-scale research and practical industrial implementation. In real wastewater systems, adsorption performance is often reduced due to competitive adsorption among multiple coexisting contaminants, which differs significantly from ideal laboratory conditions. In addition, adsorbent regeneration remains a major limitation, as repeated cycles can lead to decreased adsorption capacity caused by pore blockage, loss of active sites, and structural degradation. The potential for secondary pollution also needs to be considered, as regeneration processes particularly chemical and thermal methods may generate harmful by-products or secondary waste streams. Overall, while the conversion of biowaste into activated carbon supports circular economy principles and offers a promising approach for sustainable wastewater treatment, addressing these practical challenges is essential for its large-scale application.

Author contributions

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Conflict of interest

The authors declare no conflict of interest.

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