Low-Cost Biochar Adsorbents for Wastewater Remediation: Case Studies on Ibuprofen, Sulfamethoxazole, and Diclofenac

Eloghosa Nosa-Ihaza [a], Godsent Shepherd-Moses [a], Archana Sharma [b,*]

[a] *Faculty of Pharmacy, Marwadi University, Rajkot-360003, Gujarat, India*

[b] *Department of Agriculture, Marwardi University, Rajkot-360003, Gujarat, India*

Editor's note: Pharmaceuticals like ibuprofen are increasingly found in water sources and are often resistant to traditional treatment. This review by Nosa-Ihaza et al. explores low-cost biochar adsorbents made from biomass, highlighting how production methods affect their effectiveness in removing drugs such as ibuprofen, sulfamethoxazole, and diclofenac. Key factors include the biochar's surface area and properties, as well as conditions like pH and dosage. The review also discusses regeneration methods and the need for standardized testing to establish biochar as a viable wastewater treatment solution.

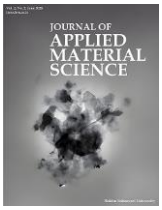
doi: 10.22034/jams.2026.260204

How to cite: E. Nosa-Ihaza et al., *Journal of Applied Material Science*, **2026**, *2*, 260204.

JOURNAL OF
APPLIED
MATERIAL
SCIENCE
jams.hsu.ac.ir

© 2026 *J. Appl. Mater. Sci.* This material is licensed under a Creative Commons Attribution 4.0 International License.

Journal of Applied Material Science **2026**, 2, 260204
How to cite: E. Nosa-Ihaza et al., *Journal of Applied Material Science*, **2026**, 2, 260204.
Journal homepage: **jams.hsu.ac.ir**



Review

Low-Cost Biochar Adsorbents for Wastewater Remediation: Case Studies on Ibuprofen, Sulfamethoxazole, and Diclofenac

Eloghosa Nosa-Ihaza [a], Godsent Shepherd-Moses [a], Archana Sharma [b,*]

[a] *Faculty of Pharmacy, Marwadi University, Rajkot-360003, Gujarat, India*

[b] *Department of Agriculture, Marwardi University, Rajkot-360003, Gujarat, India*

Abstract

Drugs such as ibuprofen, sulfamethoxazole, diclofenac, and pharmaceutical vitamins are increasingly appearing in surface and groundwater, and they are often insoluble in standard wastewater treatment methods. This review discusses low-cost biochar adsorbents, i.e., those produced from agricultural and industrial biomass, and the impact of production methods, physicochemical properties, and surface engineering on determining their efficacy in pharmaceutical remediation. It provides a general overview of the feedstocks (crop residues, forestry wastes, sludges), pyrolysis, and hydrothermal routes, demonstrating how greater pyrolysis temperatures tend to enhance the surface area, porosity, and aromaticity at the expense of polar functional groups responsible for hydrogen bonding. The major adsorption processes include pore filling, van der Waals force, pi interactions, hydrogen bonding, electrostatic interaction, ligand exchange, and surface complexation, associated with the biochar characteristics (surface area, functional groups, mineral content, charge) and the drug characteristics (size, pKa, hydrophobicity). Case studies report large capacity ranges (tens of mg/g to >1000 mg/g for engineered composites), with adsorption typically at pseudo-second-order reaction and Langmuir/Freundlich curves. Practical considerations, including pH, co-contaminants, biochar dosage, and regeneration approach, have significant impacts on removal efficiency. The review reveals regeneration strategies (thermal, chemical, and biological), life-cycle, and other co-benefits, such as carbon sequestration and waste feedstock recycling. Several gaps exist, from inconsistent materials standardizations to pilot-scale validation and LCA information. The standardized testing, scalable production, and built-in treatment systems will play key roles in addressing these issues, transforming biochar from a promising lab adsorbent into a practical and sustainable wastewater technology.

Keywords: Biochar; Wastewater remediation; Ibuprofen; Sulfamethoxazole; Diclofenac.

* Corresponding author.
Email address: archana.sharma@marwadieducation.edu.in (A. Sharma)

Received 4 January 2025
Revised 15 February 2026
Accepted 6 May 2026
Available online 18 May 2026

https://doi.org/10.22034/jams.2026.260204
© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

1. Introduction

One of several contemporary environmental concerns posed by pharmaceuticals is their impact on aquatic life. Chemical compounds, ranging from antibiotics to analgesics, anti-inflammatories, and antidiabetics, significantly degrade the hydrosphere [1, 2]. They flood water systems primarily through industrial effluents, wastewater discharge, and improper disposal. Thus, public health becomes endangered due to their persistence and bioactivity [3]. The concentration of pharmaceuticals in aquatic environments ranges from a few nanograms to several micrograms per liter [4]. Without removal, continuous exposure disrupts ecological processes, such as nutrient cycling and microbial structure. Reproductive and physiological changes in aquatic organisms also pose considerable risks [5-7]. Several studies, sampling thousands of sites across over 100 countries, have found unsafe levels of pharmaceuticals in at least 25% of locations [8]. These prove the limitations of conventional wastewater treatment plants (WWTPs).

Conventional WWTPs arise due to multiple intersecting factors, such as:

- The persistence of pharmaceuticals in effluents treated by traditional biological and physicochemical processes. Sedimentation, filtration, and coagulation are insufficient to eliminate a substantial fraction of the compounds [9, 10].
- The variable efficiencies of conventional treatments depend on the pharmaceutical compound. Some drugs may be degraded and removed at higher rates than others [11].
- The increased tendency to generate by-products or intermediates that may be more toxic or persistent than their parent compounds [12].
- The cost of upscaling conventional plants and techniques into advanced treatment methods is typically discouraging [13].

Therefore, the desperate need for a radical, effective, yet low-cost approach culminates in the discovery of biochar among available options. Biochar is a carbon-rich substance derived from the pyrolysis of natural waste. Aside from its environmentally friendly approach to pollutant removal, biochar supports microbial activity. It enhances the biodegradation of specific contaminants [14-16]. The organic substance is also an efficient adsorbent due to its massive surface area, porosity, and surface functional groups. Such physicochemical properties can also be altered for specificity towards particular pollutants [17]. Biochar is affordable, considering the availability of feedstock and the low energy expended for its preparation. The fact that it originates from renewable resources adds to its sustainability [18-20]. Hence, this review article investigates the potential of biochar for wastewater remediation from pharmaceuticals. Ibuprofen, sulfamethoxazole, and diclofenac are the subjects of concern for several reasons.

These drugs are among the most commonly dispensed pharmaceuticals globally, which can pollute aquatic environments at high concentrations. They are consumed in large amounts, incompletely metabolized in vivo, and are resistant even to traditional methods of wastewater treatment [21-24]. Thus, the medications pose significant ecological and health risks after consumption. Ibuprofen and diclofenac are popular non-steroidal anti-inflammatory drugs (NSAIDs). Diclofenac is among the most widely prescribed NSAIDs globally and is commonly used in clinical practice [25, 26]. Sulfamethoxazole is a widely used antibiotic for treating urinary tract infections, bronchitis, and pneumonia [27]. They reflect the larger issues with pharmaceutical contaminants in the hydrosphere.

2. Pharmaceutical contaminants in wastewater

One of the most common pollutants in wastewater today is pharmaceuticals. They dominate surface water and groundwater, with studies even finding traces in drinking water [28, 29]. These contaminants enter wastewater systems through pharmaceutical industrial effluents and the poor disposal of unused drugs. Human excretion and agricultural runoff containing veterinary drugs also contribute to this misfortune [30]. Among the most persistent drugs in wastewater today are Ibuprofen, Sulfamethoxazole, and Diclofenac.

2.1. Ibuprofen

Ibuprofen (Figure 1) is a non-steroidal anti-inflammatory drug, one of the most well-known in this class. It acts by limiting the hormones that mediate pain and inflammation in humans [31, 32]. Hence, healthcare

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

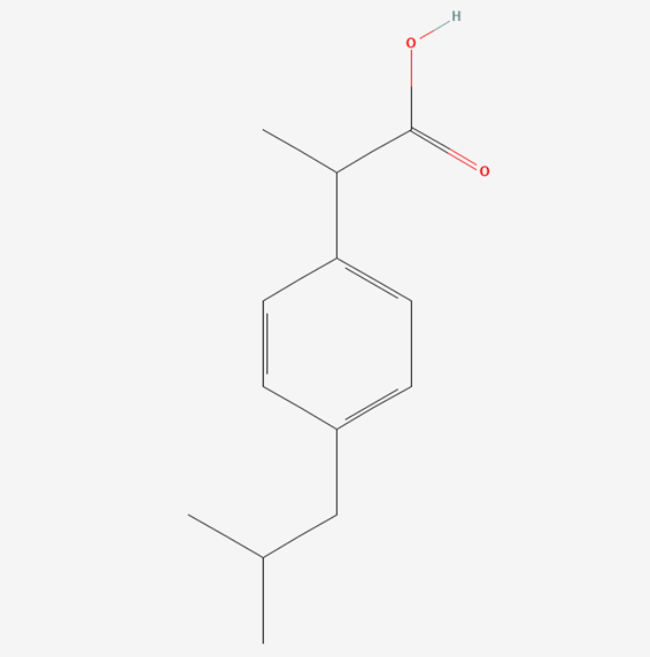


Figure 1. Chemical structure of Ibuprofen.

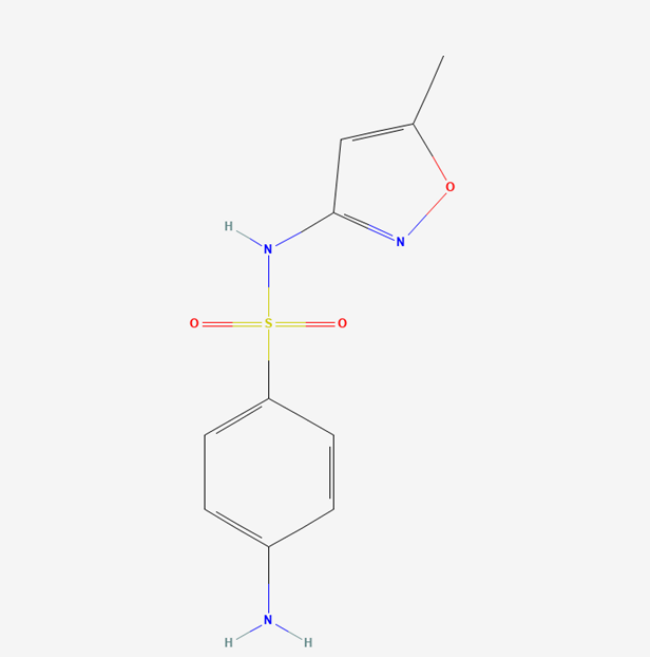


Figure 2. Chemical structure of Sulfamethoxazole.

professionals widely prescribe it for headaches, menstrual cramps, and arthritis, among several sources of pain and inflammation [33]. Like most NSAIDs, ibuprofen is also antipyretic, making it a popular option to reduce fever [34-36].

Unfortunately, the anti-inflammatory drug has also become a serious environmental contaminant due to its widespread use. It persists, especially in aquatic environments, after entering through human and animal excretion, improper disposal, and industrial effluents [37]. Reported levels of ibuprofen range from nanograms per liter in water to hundreds of micrograms per kilogram in soils. At this magnitude, aquatic life is endangered [38]. The NSAID is highly lipophilic and biodegrades slowly, promoting bioaccumulation. It affects the development, health, and fertility of aquatic life by being cytotoxic and genotoxic, causing oxidative stress [39, 40].

Moreover, ibuprofen metabolites are also acutely involved in the water systems by partial degradation. Others are even more toxic to a parent drug, with more environmental concerns [41, 42]. Despite some studies claiming that conventional WWTPs are efficient in degrading ibuprofen, others assert the drug's persistence and incomplete removal. Improved technologies may be necessary for their complete remediation [43-45].

2.2. *Sulfamethoxazole (SMX)*

True to its name, sulfamethoxazole (Figure 2) is a sulfonamide antibiotic that inhibits the synthesis of folic acid in bacteria. It is often used in combination with trimethoprim, forming tablets for oral administration [46, 47]. Clinically, these tablets are first-choice treatments for bronchitis, urinary tract infections, and traveler's diarrhea in humans and animals. However, their extensive use is also the reason behind their high concentration in WWTP effluents, surface waters, and groundwater [48, 49]. Conventional WWTP techniques do not degrade sulfamethoxazole adequately. Therefore, waterbodies, sediments, and aquatic organisms accumulate the antibiotic [50].

In severe cases, SMX concentrations in river water samplings may go up to 10 mg/L. The re-transformation of its metabolites into the parent compound worsens their persistence. Another critical setback of sulfamethoxazole in aquatic environments arises due to its inherent antibiotic nature. Constant sub-therapeutic doses of SMX selectively pressure the bacterial population by encouraging the growth of antibiotic resistance genes (ARGs) even at low concentrations. Such pressure may increase the microbial community's resistance and promote the spread of ARGs in wastewater and natural water bodies [51, 52].

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

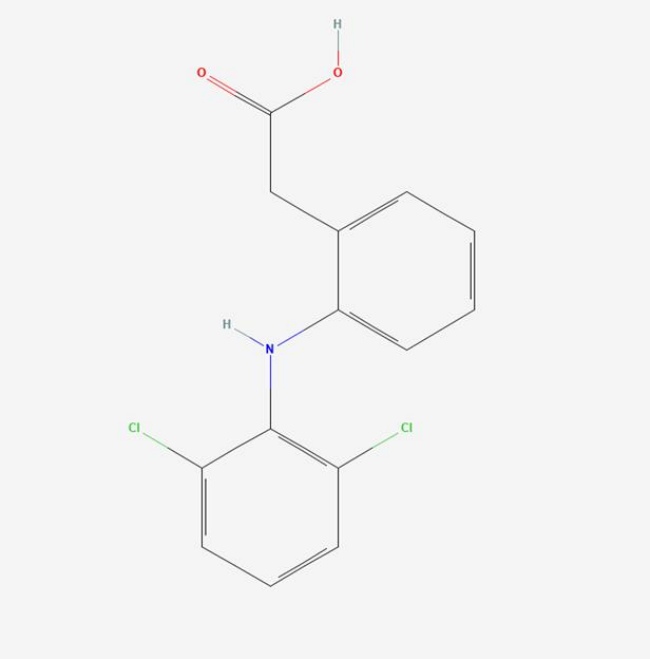


Figure 3. Chemical structure of Diclofenac.

2.3. Diclofenac

Diclofenac (Figure 3), like ibuprofen, is a non-steroidal anti-inflammatory drug (Table 1). It is the most widely prescribed NSAID worldwide, outselling naproxen, indomethacin, and ketorolac in most countries [53]. Owing to its drug class, diclofenac helps to treat mild-to-moderate pain in adults. It relieves inflammation, stiffness, and swelling common in arthritis [26, 54]. Despite the cardiovascular risks, it is still widely used enough to pose serious environmental and ecological threats. It intrudes on the aquatic ecosystem, unchanged or as metabolites, primarily through wastewater, as conventional WWTPs fail to remove a significant portion of the drug [55]. Hence, various studies have uncovered its impact on fish species, including rainbow trout and brown trout. It promotes cellular alterations in the liver, kidney, and gills at low microgram-per-liter concentrations [56, 57]. The rise in status as an emerging contaminant has made diclofenac a globally concerning issue because of its drastic ecological effects. Several regulatory bodies, such as the European Union's Water Framework Directive, have placed it on watch lists [58, 59].

3. Biochar production and characterization for adsorption applications

3.1. Sources of biochar: agricultural and industrial waste biomass

3.1.1. Agricultural waste

The thermal decomposition of organic matter in an oxygen-monitored environment generates a substance known as biochar, a carbon-rich substance. Biochar production offers significant benefits in waste sustainability and soil enhancement. Due to its abundance, renewable nature, and frequent underutilization, agricultural waste is a popular and sustainable source of biochar [63]. Key agricultural waste sources include:

1. **Crop Residues:** These are parts of plants left over after harvesting. They include rice husks, wheat straw, corn stover, sugarcane bagasse, cotton stalks, and other post-harvest plant materials [64-66].
2. **Plant & Forestry Residues:** Includes leaves, stems, and roots left after harvesting. Sawdust, wood chips, bark, and tree leftovers are agricultural or forestry waste [67].
3. **Animal Manure:** Although having different qualities than plant-based sources, wastes such as chicken litter, cattle manure, and other livestock waste can be converted into biochar.

3.1.2. Industrial waste biomass

Industrial processes generate significant amounts of organic waste that the public can utilize to produce biochar. Using this waste supports both economic and

Table 1. Physicochemical properties of pharmaceutical contaminants [60-62]

Property	Ibuprofen	Sulfamethoxazole	Diclofenac
Molecular weight (g/mol)	206.29	253.28	296.1
pKa	4.9–4.85	1.7 / 5.6	4.15
Water solubility (mg/L)	21 mg/L @ 25 °C	~610 mg/L @ 37 °C (~1500 mg/L @ 25 °C)	2.36 mg/L @ 25 °C
Log K_O/W (octanol-water)	~3.5–4.1	~1.37	4.51
Charge at pH ~7 (neutral)	Mostly anionic (pKa < pH)	Zwitterionic/neutral	Mainly anionic (pKa < pH)

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

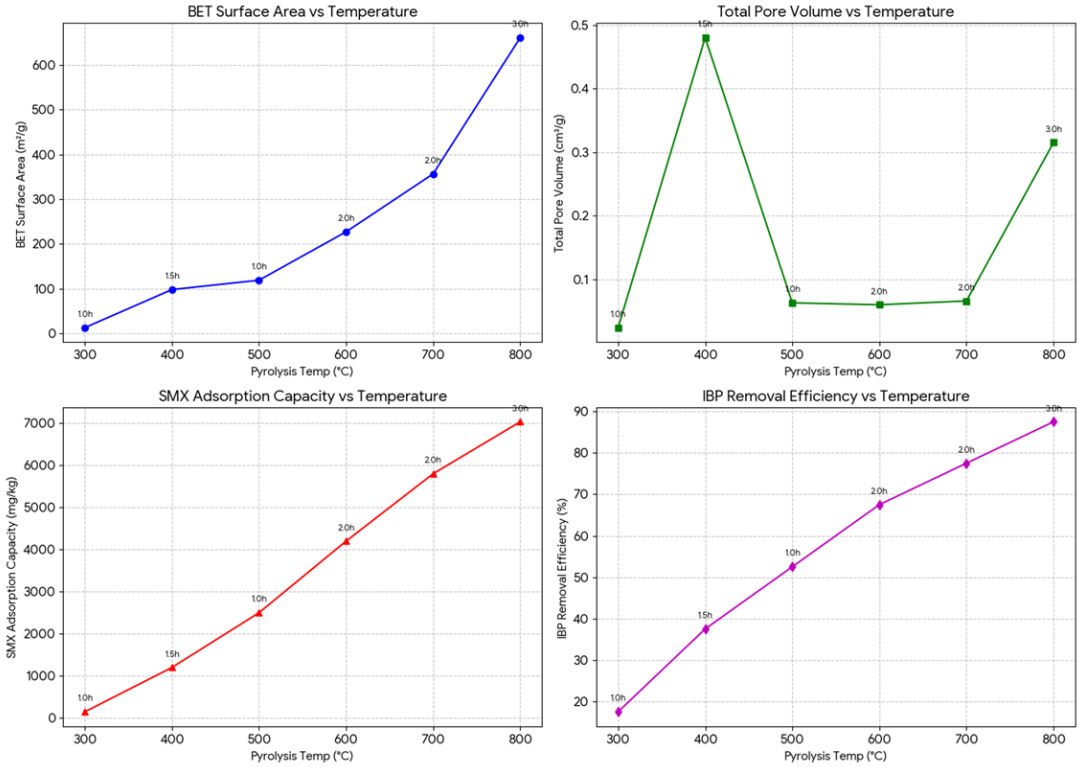


Figure 4. Influence of pyrolysis temperature and residence time on the physical properties and pharmaceutical adsorption performance of the synthesized biochar.

environmental sustainability. The sources of industrial waste include:

1. **Paper Mill Waste:** This refers to the sludge and fiber residues generated during the paper production [68].
2. **Food Processing Waste:** Peels, pulp, shells, and other organic by-products from food and drink industries [69].
3. **Textile Industrial Waste:** Natural fiber residues, such as cotton and jute waste.
4. **Breweries & Distilleries:** Spent grains and other organic by-products.
5. **Municipal Solid Waste:** Food scraps, yard waste, and other materials can be used to make biochar, provided contaminants are controlled.

3.2. Production techniques and pyrolysis conditions

The production of biochar springs from the thermochemical conversion of biomass in an oxygen-limited environment. Some techniques are as follows (Figures 4-6):

1. **Pyrolysis:** This is the thermal breakdown of organic matter at elevated temperatures (usually 300–900°C) without the presence of oxygen. It is categorized as follows:

a. Slow Pyrolysis: Temperatures from 300–600°C and longer residence time (hours to days) at low heating rates of 5–7°C/min will produce the most biochar [70, 71].

b. Fast Pyrolysis: High heating rates (up to 1000°C/s) with temperatures as high as (400–1300°C), and short residence time (seconds) yield 10-25% more bio-oil and less desired product.

c. Microwave and Plasma Pyrolysis: The use of microwave and plasma pyrolysis for quick heating provides high efficiency and improved control, but specialized equipment is necessary.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

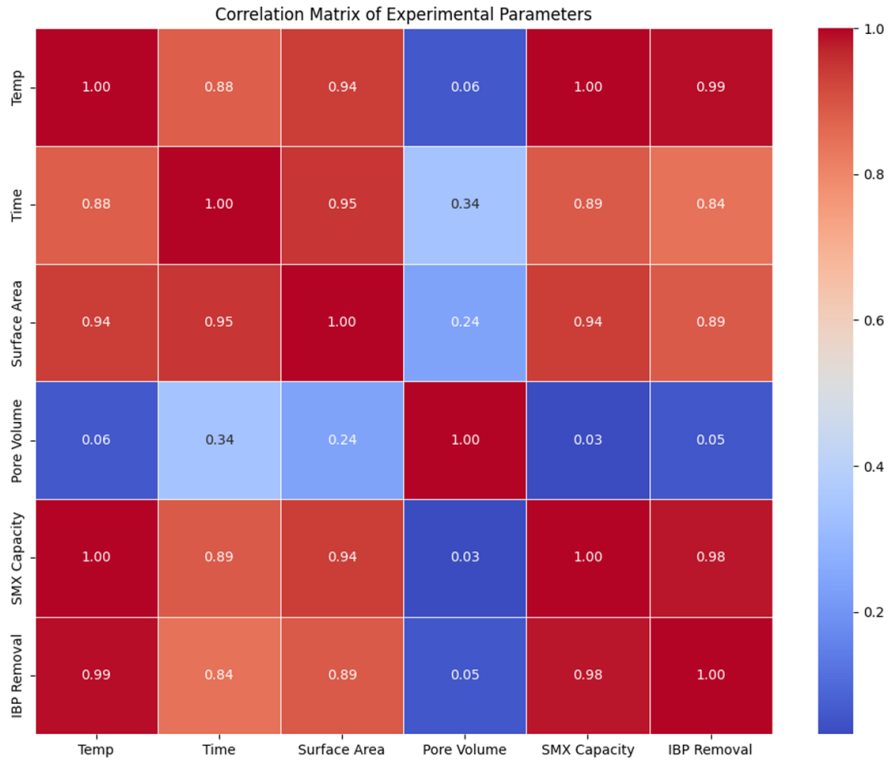


Figure 5. Pearson correlation matrix illustrating the relationships between experimental process parameters and the resulting biochar characteristics.

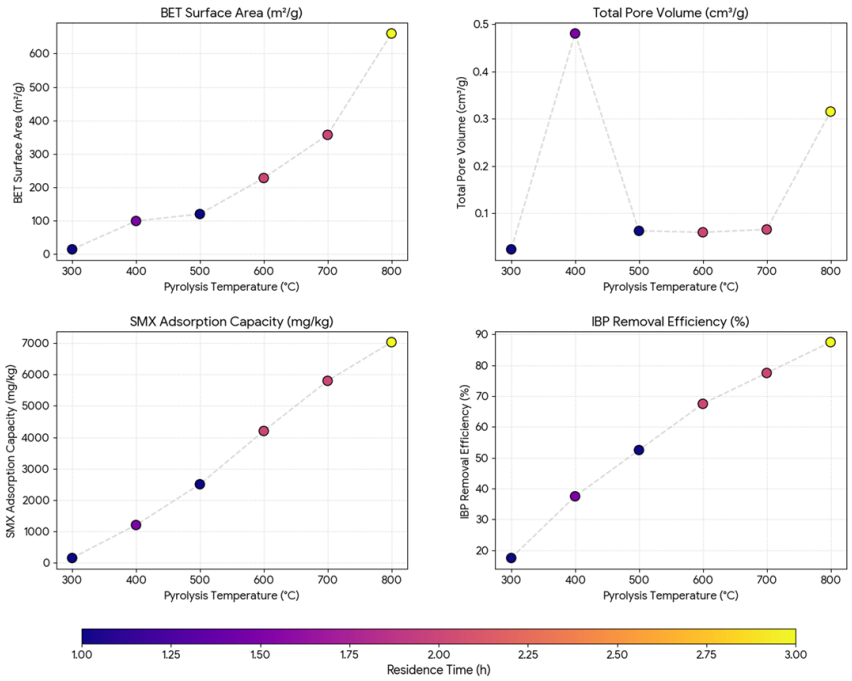


Figure 6. Refined analysis of the synergistic effects of pyrolysis temperature and residence time on biochar quality and pharmaceutical remediation.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

Table 2. Summary of biochar types, feedstock sources, and approximate production yields [63-75]

Biochar category	Feedstock source	Pyrolysis temperature (°C)	Approximate yield (%)	Physicochemical features
Crop Residue BC	Rice Husk	300	37.7 - 55.0	High silica; stable framework
	Rice Husk	500	32.8 - 36.0	Balanced porosity and yield
	Rice Husk	700	35.0 - 35.6	Max micro-surface area
	Wheat Straw	300	48.0	Nutrient-rich; high volatiles
	Wheat Straw	500	31.0 - 33.0	Carbon-rich; moderate stability
	Corn Stover/Stalk	400	31.6 - 36.4	High lignin contribution
	Corn Stover/Stalk	600	24.8	Max aromaticity; high C content
	Sugarcane Bagasse	350	27.0 - 54.3	Variable cellulose breakdown
	Sugarcane Bagasse	700	22.0	Highest carbon stability
Forestry Waste BC	Hardwood	400	~35.0	Strong structural integrity
	Hardwood	700	~25.0	Exceptional surface area; 89.8% C
	Pinewood	500	25.2 - 33.1	Clean carbon profile; low ash
Industrial Waste BC	Paper Mill Sludge	500	40.0	High Ca and mineral content
	Paperboard Sludge	500	~38.1	Spongy, fluffy, porous structure
	Office Paper Waste	800	31.5	High pH (12.47); neutral charge
	Textile (Cotton)	450	~30.0	Rich in basic functional groups
	Mixed Food Waste	650	21.2	Low yield; high carbon ordering
Animal Waste BC	Sewage Sludge	300	75.3	High ash retention; low SSA
	Sewage Sludge	800	49.3	Max mineral concentration
	Poultry Manure	400	~45.0	Nutrient-rich; high N content

2. **Gasification:** Syngas and small amounts of biochar (5-15%) are produced by partial oxidation at higher temperatures (600–1200°C).
3. **Hydrothermal Carbonization (HTC):** This produces 30-90% of biochar by changing wet biomass at 180–260°C under high pressure. It is suitable for wet feedstocks (Table 2).
4. **Torrefaction:** This process involves the production of biochar with higher energy density but moderate yields of around 50-89% through mild pyrolysis at a temperature of 200–300°C.

Below is the typical pyrolysis temperature for optimal adsorbing properties.

- **Temperature:** Higher pyrolysis temperature (400–900°C) reduces the yield of biochar, but an increase in surface area, porosity, and aromaticity enhances the adsorption capacity of pollutants (Figure 7) [72-74].
- **Heating Rates:** Fast heating rates lead to the production of bio-oil, while slow heating rates favor the production of biochar and more stable compounds.
- **Residence Time:** Higher yields and more developed pore structure often indicate longer residence time at moderate temperatures.
- **Atmosphere:** Minimization of carbon retention and prevention of combustion, the use of an inert or oxygen-deficient atmosphere is required [75].

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

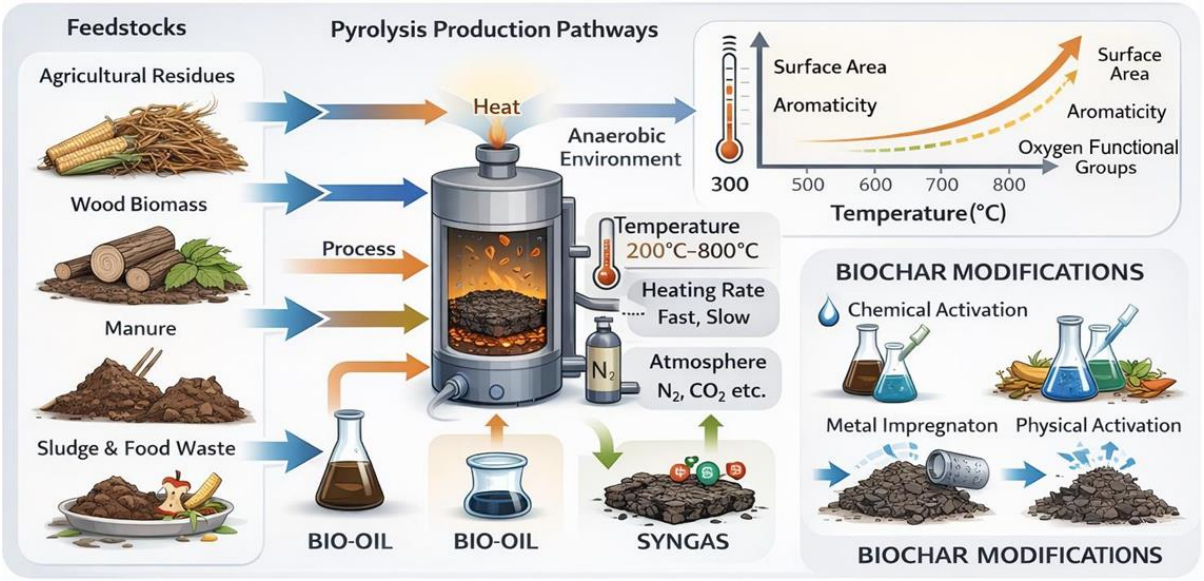


Figure 7. Biochar feedstocks and pyrolysis production pathways.

3.3. Surface properties and adsorption mechanism

The effectiveness of biochar as an adsorbent depends on its surface properties, feedstocks, production technique, and pyrolysis conditions (Figure 8).

Key surface features are:

1. Porous Structure: Biochar has a large specific area due to its micropores, mesopores, and macropores. The network of pores provides a large number of adsorption sites [76, 77].
2. Functional Groups on Surfaces: Oxygen-containing functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and amide groups, are abundantly found on the surface. These groups are essential for chemical interactions.
3. Aromaticity and Graphitic Domains: The biochar's structure is often composed of graphitic layers and aromatic rings, which facilitate π–π interactions with organic pollutants [78].
4. Surface Charge: Surface charge influences electrostatic interactions of ions. These charges are often negative, and modifications can adjust the charge to target specific pollutants.
5. Mineral Content: Inorganic components remove certain metals. These metals can participate in ion exchange and precipitation reactions.

3.4. Cost, availability, and environmental benefits

Depending on the scale, technology, feedstock, and location, the cost of producing biochar varies [79].

- **Small-scale facilities:** $50,000–$200,000 initial investment.
- **Medium-scale facilities:** $200,000–$1 million.
- **Large-scale/industrial:** $1 million–$5 million+.
- **Batch pyrolysis systems:** $50,000–$300,000.
- **Continuous pyrolysis systems:** $300,000–$2 million.

The operating cost ranges roughly around $194-$230, with market prices reaching up to $1000 per tonne [79, 80]. Depending on the technique, the application of biochar on the soil will cost around $5.20-$17.10 per tonne [81]. Organic materials, like agricultural residues (crop straws, husks), forestry waste, animal manure, food-processed by-products, and municipal solid waste, are required to produce biochar. The abundant supplies of biomass from forestry, agriculture, and cities, frequently in the form of residues, ensure the necessary quantity needed for continuous production [82]. Some of the most significant environmental benefits include reduction of landfill and open burning by turning waste into practical products, climate mitigation, improvement of soil and water, and pollution control & adsorption [83-86].

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

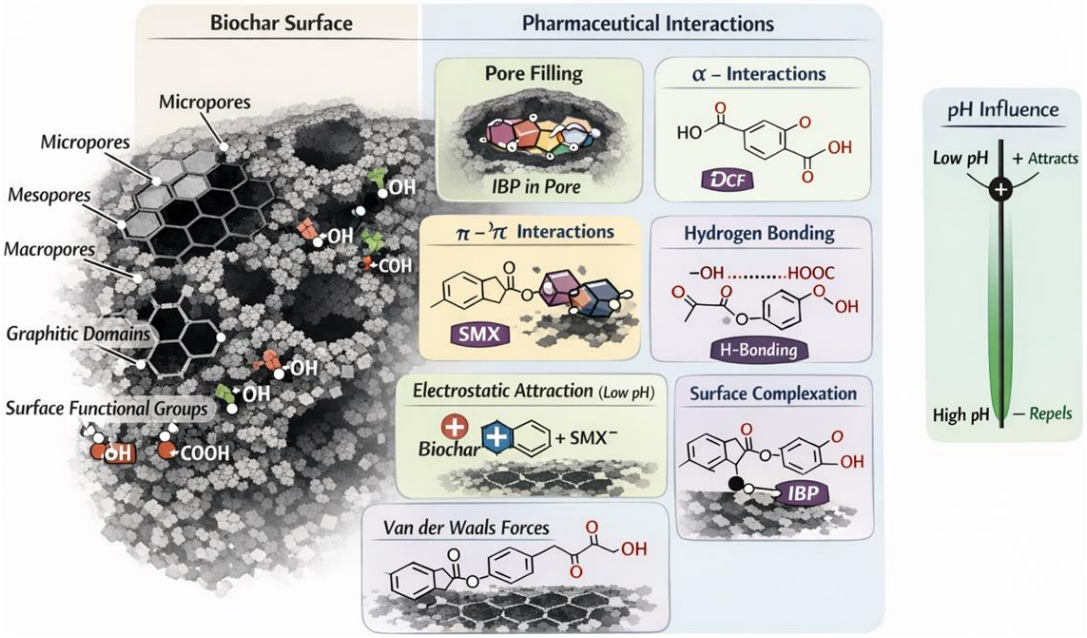


Figure 8. Mechanism of drug–biochar interactions.

4. Adsorption mechanism of pharmaceuticals onto biochar

4.1. Physical adsorption

- Pore Filing: Micropores (<2nm), Mesopores (2-50nm), and Macropores (> 50nm) make up the structure of biochar (Figure 9). These pores allow the diffusion of pharmaceutical molecules, which are then trapped. The size compatibility of the molecules with the pores indicates the efficiency of the process. Higher specific surface area increases the adsorption capacity, raising the number of accessible adsorption sites [87].
- Van der Waals: These are weak, non-covalent interactions that attract molecules to the surface of the biochar. These interactions are essential for the physical adsorption of non-polar or weakly polar pharmaceuticals, as they do not require special bonding or functional interactions [88]. A wide range of medications adhere to van der Waals interaction irrespective of their chemical makeup.

4.2. Chemical adsorption

- Electrostatic Interactions: These occur between charged pharmaceutical molecules and oppositely charged sites on the biochar's surface. The surface charge typically depends on the *pH* and the presence of functional groups, such as carboxyl and hydroxyl. *pH* values below the zero point charge *(pHpzc)* show a positively charged surface, thereby promoting the adsorption of anionic medications. The negatively charged surface (above *pHpzc)* facilitates the adsorption of cationic pharmaceuticals [89]. Depending on their charge state in the solution, electrostatic attraction improves the removal of ionizable medications, particularly antibiotics and NSAIDs.
- Hydrogen Bonding: Hydrogen bonds form when acceptors (such as -COOH & -NO on medications) and donors (like -NH & -OH on biochar) interact. Hydrogen bonding enhances the stability and selectivity of adsorption for pharmaceuticals with polar functional groups [90]. *pH* affects the strength of the hydrogen bonding, thereby influencing the ionization state of the biochar and the pharmaceuticals.
- π–π Interactions: This occurs when there are interactions between the graphite domains present in the aromatic rings of biochar and pharmaceutical molecules. NSAIDS, antibiotics, and organic micropollutants depend on these interactions [91].

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

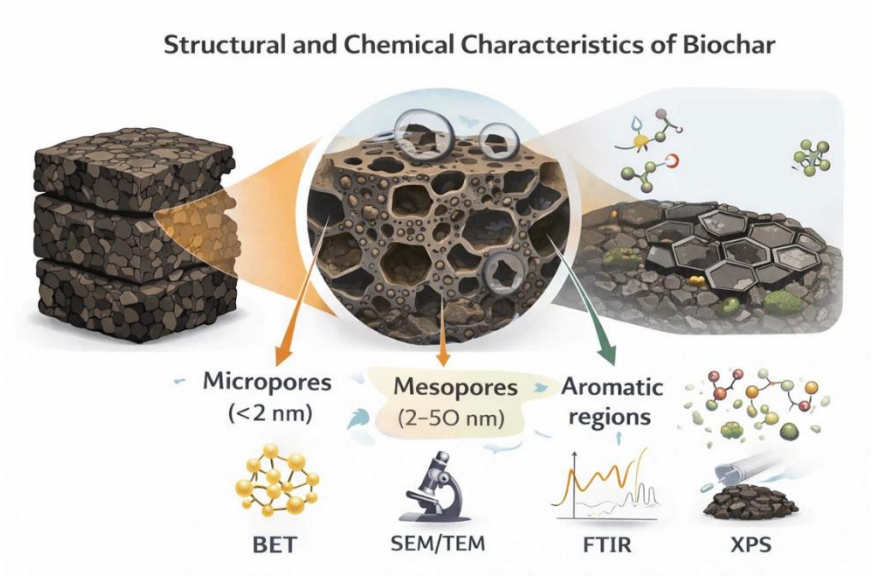


Figure 9. Structural and chemical characteristics of biochar.

- Ligand Exchange: This is the process of changing a surface-bound ligand (-OH or -COOH on the biochar) with a functional group from the pharmaceutical molecule. Typically, the enhancement of adsorption for pharmaceuticals that act as ligands is observed [92].
- Surface Complexation: This refers to the formation of stable, covalent complexes between the pharmaceutics and functional groups or mineral components on the biochar surface. It is a strong, irreversible adsorption mechanism (Table 3).

Table 3. Detailed biochar adsorption mechanisms [76, 92]

S/N	Physical adsorption	Chemical adsorption	Specific interaction	Redox reaction
1.	Pore Filling: Pollutant molecules are physically trapped within the biochar's pores, primarily via van der Waals forces. The efficiency of this mechanism is linked to the surface area and pore volume.	Surface Complexation: Functional groups on the biochar surface form stable complexes with metal ions or polar organic molecules, significantly enhancing adsorption capacity.	Hydrogen Bonding: Surface –OH and –COOH groups can form hydrogen bonds with polar organic contaminants, increasing adsorption stability.	Reduction/Oxidation: Biochar can facilitate redox reactions, such as the reduction of Cr(VI) to Cr(III), further immobilizing or detoxifying specific contaminants.
2.	Hydrophobic Interactions: Non-polar organic molecules are attracted to the hydrophobic regions of biochar, thereby enhancing the adsorption of certain organics.	Ion Exchange: Exchangeable cations or anions on the biochar surface swap places with pollutant ions in solution, which is particularly important for heavy metal removal.	π–π Interactions: Aromatic structures in biochar interact with aromatic rings in organic pollutants, promoting adsorption via π–π electron donor–acceptor mechanisms.	
3.		Electrostatic Attraction: The negatively charged surface attracts positively charged ions (e.g., heavy metals, ammonium), while modifications can enable adsorption of anions.	Surface Precipitation: Certain metals (e.g., Pb^2+) can precipitate with mineral components or functional groups on the biochar surface, leading to their immobilization.	

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

4.3. Influence of biochar properties

- **Surface Area Porosity:** A large specific surface area and a well-developed network of micro- and mesopores provide more sites to entrap pharmaceuticals [93]. From observations, higher temperature increases porosity, thereby boosting adsorption [94].
- **Surface Functional Group:** Groups that contain oxygen (-OH, -COOH, -C=O) are essential for hydrogen bonding, ligand exchange, and formation of surface complexes [95, 96]. Polar functional groups enable the removal of polar pharmaceuticals by hydrogen bonding or complexation. Surface oxidation enhances the groups and improves the adsorption of particular drug classes.
- **Surface Charge:** Ionizable drugs at the biochar's zero point show the charge on the surface. These charges determine attraction or repulsion [97, 98]. Chemical modifications and *pH* enhance selective adsorption for anionic and catatonic moieties.
- **Aromaticity and Graphitic Domains:** Strong π–π Interactions with aromatic medications (NSAIDs, antibiotics) are enabled by high aromatic carbon content, favored by higher pyrolysis temperature. This interaction increases the adsorption capacity significantly. Through this mechanism, pharmaceuticals with more aromatic rings or a planar structure interact more effectively [99].
- **Mineral Content:** Biochar's minerals (e.g., Ca, Mg, Fe) are sites for ligand exchange and complexation of drugs with suitable functional groups (-NH2, -COOH) [100]. The feedstock and production processes determine the mineral profile, selectivity, and adsorption strength (Table 4).

4.4. Influence of pharmaceutical properties

- **Molecular Size and Structure:** Due to π–π Interactions with the aromatic domain of biochar, aromatic or planar molecules will adsorb more effectively than larger, more complex molecules, which may experience steric hindrance when entering the biochar's pores. For molecules of the right size, adsorption of antibiotics like ibuprofen has efficient π–π stacking and pore filling [89, 94].
- **Polarity and Functional Group:** Drugs with polar or ionizable functional groups (e.g., -COOH, -OH, -NH2) often interact with the surface functional groups of the biochar through surface complexation, ligand exchange, and hydrogen bonding.
- **Higher Hydrophobicity (logKow):** Hydrophobic pharmaceuticals are more likely to be absorbed by van der Waals forces and hydrophobic partitioning, while hydrophilic pharmaceuticals will interact through electrostatic attraction and hydrogen bonding [99].
- **Charge & Ionization (pKa):** The ionization state of pharmaceuticals and the *pH* of the solution determine whether it is neutral, anionic, or catatonic, which affects how it interacts with the charged surface of biochar [101].

Table 4. A comparative summary of the biochar properties that mostly influence the adsorption of each target pharmaceutical [93-98, 100]

Pharmaceutical	Primary influencing property	Secondary influencing property	Performance insight
Ibuprofen (IBP)	Surface Charge / pH	Porosity (SSA)	Removal is highly restricted by electrostatic repulsion at pH > 5; high SSA biochars still fail if the charge is unfavorable.
Sulfamethoxazole (SMX)	Porosity / SSA	Mineral Content	Efficiency is linked to micropore development; high-temperature or ball-milled biochars show superior capture.
Diclofenac (DCF)	Aromaticity / π-π sites	Surface Charge / pH	Graphitic layers and EDA complexes are essential for binding; pH variations dictate electrostatic attraction vs. repulsion.
General Contaminants	Porosity / SSA	Functional Groups	Surface area determines total capacity; functional groups dictate selectivity and binding kinetics.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

4.5. Influence of solution chemistry

Raising the *pH* can increase the negative charge on both biochar and pharmaceuticals (e.g., SPY and Ibuprofen), thereby changing the potential for hydrogen bonding and electrostatic interactions [89]. Electrostatic repulsion increases at neutral or basic pH levels due to the interactions between anionic particles and negatively charged biochar, but enhanced negative charge-assisted hydrogen bonding can still improve adsorption for certain drugs. While hydrogen bonds are susceptible to *pH*, adsorption processes are typically less affected. Hydrogen bonds are sensitive to *pH*, and adsorption processes are typically less affected. Moreover, the addition of Fe-OH sites to Fe_3O_4 nanoparticle modification changes the adsorption mechanisms from physical to electrostatic and hydrogen bonding interactions. These changes often respond to the ionic composition and *pH* of the solution, which can alter its performance.

5. Case studies on target pharmaceuticals

Despite biochar's relative novelty, several studies have already investigated its potential in water remediation from pharmaceuticals. Basic preparations from readily accessible biomass are effective in eliminating several drugs. However, further physicochemical modifications promote specificity as desired in particular situations. As discussed, ibuprofen, sulfamethoxazole, and diclofenac are of primary concern in this article.

5.1. Ibuprofen

Among the discovered biochars with proven efficiency for ibuprofen removal are Zn-Al composites (Table 5). Studies show that they have high adsorption rates of up to 1032.81 mg/g, with surface diffusion being responsible for the transport [94]. At such a rate, conventional techniques, from activated carbon to zeolite adsorbents, are significantly less efficient. Walnut shell-activated biochar (WSAB) also adsorbs ibuprofen through bonding, pore filling, and hydrophobic donor-acceptor interactions. The sustainable, low-cost option demonstrated an adsorption capacity of 30.08 mg/g in fixed-bed column research [102].

Other popular biochars that are selective for the NSAID include [103-105]:

- Coconut, bamboo, and southern yellow pine biochars
- Peanut shell-derived partially graphitized biochar
- Cross-linked magnetic chitosan/activated biochar (CMCAB)
- Chrysanthemum waste-derived biochar and magnetic biochar

Chrysanthemum waste-derived biochar has a maximum ibuprofen adsorption capacity of 140 mg/g. It reaches equilibrium within an hour following pseudo-second-order kinetics. Sodium hydroxide and phosphoric acid significantly enhance seed-shell biochar. The activated matter adsorbs ibuprofen at a maximum rate of 251.1 mg/g through pore diffusion.

Table 5. Biochar Adsorbents & their Performance Metrics for Ibuprofen Removal [102-105]

Biochar type	Adsorption capacity	Key features & parameters
Zn–Al composite on lychee biochar	1,032.8 mg/g	High SSA (~112 m²/g); effective pore structure; synergistic adsorption + photocatalysis
Chrysanthemum waste biochar (non-magnetic)	167 mg/g	SSA 220 m²/g; equilibrium in ~1 hr; pseudo-second-order kinetics
Chrysanthemum magnetic biochar	140 mg/g	SSA 194 m²/g; magnetic separation; similar kinetics
Peanut shell-derived partially graphitic biochar	450 mg/g	SSA 374 m²/g; rough, heterogeneous surface; supports π–π & H-bond interactions
Pepper-stem biochar	596.6 mg/g	π–π interactions, pore filling, H-bonding; Langmuir q_{max}
Walnut shell-activated biochar (WSAB)	30.1 mg/g (fixed-bed)	Bonding + pore filling + hydrophobic donor-acceptor; sustainable material
Seed-shell biochar (NaOH & H_3PO_4 activated)	251.1 mg/g	Enhanced pore diffusion; chemical activation significantly improved uptake

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

Table 6. Biochar Adsorbents & their Performance Metrics for Sulfamethoxazole Removal [113-117]

Biochar type & modification	Max SMX adsorption capacity	Removal efficiency	Key mechanisms
Sludge biochar (800°C)	7,033 mg/kg	95%	Pore filling, electrostatic associations
Ball-milled hickory/bamboo biochar	100.3 mg/g (lab), 25.7 mg/g (wastewater)	83%	Hydrophobic, π–π stacking, H-bonding
Sugarcane bagasse biochar	105.6–128.8 mg/g	78%	Charge-assisted H-bonding
Rice straw biochar	1,827.8–9,182.7 mg/kg	Unspecified	Hydrophobic partitioning

The adsorption capacity of biochar for ibuprofen is highly dependent on solution pH. Its efficiency is maximum under acidic conditions and decreases as the pH increases [106, 107]. The surface charge of biochar and the ionization state of ibuprofen are responsible for this trend. At low pH (2–4), biochar is positively charged, while ibuprofen maintains its neutral form, which favors hydrophobic interactions and hydrogen bonding. As pH rises above the pKa of ibuprofen (~4.9), the drug becomes negatively charged. It leads to increased electrostatic repulsion from the also negatively charged biochar surface. Hence, the adsorption capacity falls [108].

Moreover, the adsorption of ibuprofen onto biochar is rapid, reaching equilibrium within 60–180 minutes. The initial fast phase is a result of the abundant active sites on the biochar surface. These sites become occupied as diffusion into the internal pores dominates during the slower phase [109]. The chemical adsorption follows pseudo-second-order kinetics [110].

Also, increasing the biochar dosage generally enhances the removal efficiency of ibuprofen because more adsorption sites become available. That said, a further increase in the dosage may not significantly improve the rate after a certain threshold. Beyond this point, aggregation or overlapping at the sites likely reduces the effective surface area.

5.2. Sulfamethoxazole

Sulfamethoxazole-saturated water has also responded to selective treatments with various feedstock biochars (Table 6). Adsorbents produced from rice straw, sugarcane bagasse, municipal sludge, and microalgae show the most promising results [111, 112]. The removal typically involves multiple mechanisms, such as hydrogen bonding and electrostatic attraction. However, detailed studies have also revealed π–π interactions and pore-filling effects between the entities [113, 114]. An investigation into the adsorption of SMX with sludge-derived biochar pyrolyzed at 800°C achieved a maximum capacity of 7,033 mg/kg. Under optimal conditions, the removal efficiency reaches 95% due to the hydrophobic nature, increased surface area, and aromaticity at higher temperatures [115]. Earlier, researchers relied on conventional WWTPs with less than 75% efficiency [116, 117]. Another study involving sugarcane bagasse biochar achieved a removal efficiency of 78% and a maximum adsorption capacity between 105 and 128 mg/g. Hydrogen bonding was the key mechanism behind the spontaneous and exothermic process.

Like diclofenac, solution pH plays a critical role in SMX biochar adsorption. Maximum adsorption occurs under acidic conditions (pH 2–4) due to SMX's neutral nature and the biochar's positive charge. As the solution becomes basic, SMX becomes anionic. Hence, the repulsion with negatively charged biochar surfaces reduces the adsorption efficiency [118]. Also, SMX-filled wastewater may also contain several other contaminants, from microbial pathogens to nutrients. Heavy metals, like cadmium, when present, can enhance SMX adsorption. The enhancement is a result of the synergistic effects between the metal and sulfamethoxazole, as observed with rice straw biochar [119]. Again, increasing the pyrolysis temperature generally improves the adsorption capacity for SMX. It is a result of the enhanced biochar's surface area, porosity, and aromaticity, which promote bonding interactions [120, 121]. However, excessive temperature reduces the polar functional groups that are essential for hydrogen bonding and adsorption. Thus, the pyrolysis temperature must be controlled and optimized to maximize SMX adsorption [122, 123].

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

Table 7. Biochar Adsorbents & their Performance Metrics for Diclofenac Removal [124-127]

Biochar type & modification	Max diclofenac adsorption capacity	Removal efficiency	Key mechanisms
Pig manure biochar (BC-PM)	239.7 µg/g (at 2 g/L)	99.6%	Intraparticle diffusion, hydrophobic, π–π stacking
Pinewood biochar (BC-PW)	107.5 µg/g (at 2 g/L)	98.8% (at 20 g/L)	pH-sensitive, hydrogen bonding
KOH-activated sludge hydrochar	37.23 mg/g	Unspecified	Oxygenated groups, chemisorption
NaOH fique bagasse biochar (FB850-3Na)	Unspecified	Highest among the tested samples	Hydrophobic, π–π stacking
Activated carbon from eucalyptus husk	147.06 mg/g	Unspecified	π–π stacking, electrostatic associations, and hydrogen bonding

5.3. Diclofenac

Current research into the selective remediation of wastewater from diclofenac with biochar has been relatively successful, proving more efficient than conventional WWTPs (Table 7). The process typically relies on hydrophobic interactions, π–π stacking, hydrogen bonding, electrostatic attraction, or pore filling. When two or more processes are involved, the importance of each depends on the biochar's surface chemistry and the solution conditions [124]. For instance, a study involving fique bagasse biochar involved hydrophobic interactions and π–π electron donor-acceptor complexes [125]. The tested sample modified with NaOH at room temperature for 4 hours showed the highest adsorption capacity.

Another, involving activated carbon from eucalyptus husk, recorded a maximum adsorption capacity of 147 mg/g at 25 °C. It demonstrated the pseudo-second-order kinetic nature of the process, involving interactions such as π–π stacking, electrostatic associations, and hydrogen bonding [126]. Furthermore, pig manure biochar was impressively efficient, achieving 99.6% removal of diclofenac at environmentally relevant concentrations [127]. Other investigations report a maximum adsorption capacity for modified biochars ranging from 4.6 mg/g to 150 mg/g, depending on several conditions.

Depending on the type of biochar, solution pH can be a critical factor in diclofenac's adsorption and removal efficiency. For example, pine wood biochar is highly sensitive to pH changes, with acidic conditions favoring maximum efficiency. Alternatively, pig manure biochar is significantly less affected by solution pH due to its rich surface functional groups [128]. Again, increasing the biochar dosage typically enhances the diclofenac removal efficiency, as observed in multiple studies. However, the increased dose decreases the adsorption capacity per unit mass for many reasons. Aggregating biochar particles and the reduction of available active sites are a few such.

6. Comparative analysis

The primary purpose behind exploring biochar for wastewater remediation is the need for a more efficient & affordable technique. Conventional WWTPs have fallen short of desired sustainability goals, culminating in critical environmental concerns. Thus, comparative analyses are necessary to ensure significant improvement & effectiveness.

6.1. Removal efficiency comparison

Efficiency-wise, biochars are proving to be better solutions than conventional WWTPs for removing various pharmaceuticals. Microporous activated charcoal (a conventional treatment method), for example, achieved a 79% removal efficiency for sulfamethoxazole. It was an outperformance of all other charcoals due to its microporous structure [129]. However, several biochars have been considerably more efficient for the antibiotic. One such method, involving biochar as a particulate electrode, achieves complete removal of the drug in mono-component systems. Various comparative studies have also proven this for ibuprofen and diclofenac. Nevertheless, the removal efficiency varies with several conditions and the nature

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

of the wastewater. The pH, presence of other compounds, pyrolysis temperature, and specific type of biochar or activated charcoal used are significant factors. Therefore, optimizing these conditions for every specific application to achieve the best results is essential.

6.2. Adsorption kinetics and isotherms

Several studies on the adsorption of pharmaceuticals consistently report that the adsorption kinetics obey a pseudo-second-order (PSO) model. It is a common phenomenon among ibuprofen, sulfamethoxazole, and diclofenac [90, 130]. It indicates that chemisorption is the rate-limiting step. Therefore, the sharing or exchange of electrons between the biochar and drug molecules is responsible for the valence forces. Researchers witnessing the adsorption of pharmaceuticals by biochars derived from cotton gin waste and guayule bagasse validated this concept. The study showed regression coefficients (R^2), confirming chemisorption as the primary mechanism [131]. Regarding adsorption isotherms, the Langmuir and the Freundlich models describe equilibrium adsorption behavior best [132]. The former suggests monolayer adsorption on a homogeneous biochar surface with limited sites. Conversely, the latter describes adsorption on multilayer or heterogeneous surfaces, highlighting the complex nature of biochar surface chemistry [133].

6.3. Role of biochar properties

The performance of biochar in pharmaceutical remediation depends strongly on its physicochemical properties. They vary with feedstock and pyrolysis

Table 8. The role of biochar properties in ibuprofen, sulfamethoxazole, and diclofenac removal [134-137]

Biochar property	Effects	Examples	Most affected
Porous structure & surface area	A high surface area and well-developed pore structure are more favorable due to their abundant adsorption sites, enhancing removal efficiency.	**Ibuprofen** - Sunflower seed shell biochar (251.1 mg/g) **Sulfamethoxazole** - Sludge biochar (7,033 mg/kg) **Diclofenac** - KOH-activated hydrochar (37.23 mg/g)	Sulfamethoxazole
Surface chemistry & functional groups	Oxygen-containing groups, such as hydroxyl, carboxyl, and carbonyl groups, enable more hydrogen bonding, electrostatic interactions, and π–π electron donor-acceptor mechanisms.	**Ibuprofen** - NaOH-activated coffee grounds biochar **Sulfamethoxazole** - Ball-milled hickory/bamboo biochar **Diclofenac** - Pig manure biochar (99.6% removal)	Diclofenac
Hydrophobicity & aromaticity	Increasing the hydrophobicity and aromaticity typically favors the adsorption of hydrophobic pharmaceuticals via van der Waals forces and π–π interactions.	**Ibuprofen** - Peanut shell graphitized biochar **Sulfamethoxazole** - High-temp sludge biochar (hydrophobicity) **Diclofenac** - NaOH-modified fique bagasse biochar	Ibuprofen
pH & surface charge	Maximum adsorption occurs at acidic pH (2–4), where pharmaceuticals are neutral, and the biochar surfaces are positively charged. The increased adsorption is due to the electrostatic attraction, which reduces as the pH increases.	**Ibuprofen** - Adsorption decreases above pH 4.9 **Sulfamethoxazole** - Optimal at pH 2–4, decreases at higher pH **Diclofenac** - Minimal pH sensitivity	Sulfamethoxazole
Feedstock variability	Different biomass sources produce biochars with unique properties affecting adsorption.	**Ibuprofen** - Coconut, bamboo, southern yellow pine biochar **Sulfamethoxazole** - Rice straw biochar with Cd **Diclofenac** - Pig manure biochar vs. pine wood biochar	Diclofenac

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

conditions, among several conditions. Below is a comparative summary of these effects on ibuprofen, sulfamethoxazole, and diclofenac (Table 8).

6.4. Knowledge gaps and limitations in current studies

Despite the promise biochar adsorbents hold for wastewater remediation, comparative analysis reveals several knowledge gaps and limitations in current studies. These gaps underscore the need for further research to ensure biochar is effective in real-world applications. One such gap is in the deeper understanding of the adsorption mechanisms at play, such as π-π stacking, hydrogen bonding, and pore filling. It is crucial for optimizing biochar's performance in removing specific pharmaceuticals, such as ibuprofen, SMX, or diclofenac [138]. Moreover, current studies focus on laboratory-scale experiments, which are significantly behind those for large-scale wastewater treatment. Reliable parameters for upscaling are necessary to transition from experimental to practical applications [139-141]. Besides, the effectiveness of biochar varies across different pharmaceutical compounds. There is limited research on its performance in adsorbing a broader range of pharmaceuticals beyond commonly studied compounds, such as ibuprofen. Biochar may also be considered environmentally friendly from a superficial stance. However, extensive life cycle assessments are necessary to confirm sustainability and long-term environmental impact in wastewater treatments. Future biochar studies can also aim for increased consistency in biochar properties to avoid differences in feedstock and production methods, which yield inconsistent results. The application of biochar, especially in real-world wastewater remediation, will reach new heights if future research can address these knowledge gaps and limitations.

7. Regeneration and reusability of biochar adsorbents

7.1. Importance of regeneration

Recycled and regenerated biochar use has a great benefit as it is cost-effective due to the selection of new adsorbents and consequently reduces the costs of operation and maintenance. Moreover, good regeneration also leads to the minimization of waste as well as environmental sustainability because of the minimal waste build-up. The process additionally leads to the conservation of resources since energy and feedstocks are normally needed to produce new biochar, but through this process, a variety of adsorption-desorption cycles are facilitated. Besides these resource savings, the regeneration done regularly ensures the consistency in performance because, due to the adsorption capacity of the biochar, the efficiency reduces with time as a saturation of contaminants usually occurs; therefore, the high efficiency of the biochar resource ensures the further successful elimination of medications and other pollutants. Finally, the preference for regeneration over single-use adsorbents reduces the environmental impact in general on the ecosystem, as regeneration contributes to the sustainable use of the circle.

7.2. Regeneration methods

- **Thermal Regeneration:** This process involves heating used biochar at high temperatures (400–800 °C) in an inert or oxygen-limited environment to break down adsorbed pollutants. The method effectively removes organic contaminants, like dyes and medications. Key points for this process are [142, 143]:

1. By breaking down adsorbed materials, the adsorption capacity returns.
2. Suitable for strong, heat-resistant biochars.
3. Heating at such high temperatures may cause partial loss of surface area, pore structure, or even functional groups, resulting in a decrease in adsorption capacity.
4. High energy cost and possible loss of carbon mass reduced sustainability after repeated cycles. Example: pine biochar that is regenerated thermally at 600 °C shows a 3.5-fold adsorption capacity for sulfamethoxazole compared to an exhausted biochar. After a second regeneration cycle, the adsorption capacity increased, but mass loss was seen.

- **Chemical Regeneration:** This process utilizes chemical agents, including acids, bases, oxidants, and solvents, to remove pollutants from the surface of the biochar. It works for ionizable biochar that removes materials such as metals, dyes, and certain organics [144]. Compared to thermal regeneration, chemical regeneration preserves pore structure

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

more, but can also cause a gradual decline due to incomplete desorption or fouling [145].

- **Biological Regeneration:** This process utilizes microorganisms to degrade materials within the biochar. More applicable to biodegradable organic pollutants, but have been employed less than thermal or chemical methods. This process prevents high-energy output and high-risk chemicals. Microbial activity will also degrade the contaminants over time. For example, using bio-sulfide precipitation regenerated a copper-loaded biochar. This regenerated biochar demonstrated that bacterial processes can work to remove metals and re-use biochar [146].

7.3. Adsorption performance after re-use

The ability to maintain adsorption capacity over multiple use cycles determines both the cost-effectiveness and environmental impact of biochar as an adsorbent (Figure 10). Studies show that regenerated biochar retains a high proportion of its initial adsorption capacity after several cycles, though a gradual decline is noticeable. For heavy metals such as Pb(II), removal efficiencies often start above 90%, and decrease only modestly: after five adsorption/desorption cycles, Pb(II) removal may decrease from approximately ~83-95% to around 76-85%, depending on specific biochar and regeneration method. For organic contaminants such as dyes (e.g., p-nitrophenol), KOH-activated biochar retained nearly 90% of its initial adsorption capacity even after five regeneration cycles. The slight drop is due to pore blockage and deactivation of surface functional groups.

7.4. Fate of adsorbed pharmaceuticals

1. **Desorption & Leaching:** The regeneration process causes desorption of adsorbed pharmaceuticals, which become part of the washing solution. If users don't treat or manage the regenerant properly, the desorption can pose risks of secondary contamination to the environment. Studies reveal concentrations that exceeded measurable limits and were evident in the regenerant wash solutions, having adsorbed drugs [147].
2. **Degradation:** Regeneration methods from thermal treatment to Advanced Oxidation Process can also chemically transform pharmaceuticals on the surface of the biochar (and not just for desorption).

Figure 10. Regeneration, reuse, and environmental sustainability of biochar adsorbents.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

For example, with a persulfate-activated system in red mud-biochar, pharmaceuticals including arbidol, chloroquine, and acyclovir were not only desorbed but also degraded into smaller and less toxic transformation products via radical attack. In some cases, there is complete mineralization to CO_2 and H_2O [148].

3. **Irreversible Binding:** Some pharmaceuticals undergo irreversible adsorption or covalent transformation on the biochar's surface, thereby avoiding desorption and causing persistence even after multiple regeneration cycles [149].

8. Cost effectiveness and environmental implications

8.1. Economic Analysis (Raw Materials, Production & Operating Cost)

- **Raw Materials:** The profit margin for biochar is favorable compared to alternatives, such as activated carbon, primarily due to lower raw material and capital costs [150]. Revenue increases due to additional benefits, including cost savings on fertilizers in agricultural applications and soil health development [151]. However, there is high variability in price due to the early stage of global biochar markets.
- **Environmental Implications:** Using waste biomass from agriculture and forestry avoids disposed emissions and enhances the trapping of atmospheric carbon to reduce the concentration of CO_2 in the atmosphere, thereby preventing climate change. Environmental benefits increase when feedstocks are locally sourced (lowering transportation emissions) and would otherwise be disposed of (e.g., open burning), thus minimizing the carbon footprint of both raw material acquisition and the overall process.
- **Production Cost:** Biochar production, particularly from waste biomass, is inherently cost-effective. Production costs are generally lower than those of activated carbon for several production systems, while various indicators demonstrate that biochar production industries are usually profitable. Environmentally, biochar is a significant contributor to carbon sequestration and sustainable waste management. Nevertheless, costs and benefits fluctuate with technology, scale, feedstock source, and local terrain conditions. In general, specific economic and environmental evaluations must identify projects for that location [152, 153].
- **Operating Costs:** Operating costs govern the cost-effectiveness of biochar production. Raw material acquisition, energy usage, labor, maintenance, and logistics are the major contributors, all of which can be optimized to reduce financial input and carbon footprint. Effective management of these costs, particularly through local feedstock sourcing and energy-conserving technologies, supports financial viability and positive environmental outcomes [154, 155].

8.2. Life-cycle assessment (resource use & GHG emission)

- **Resource Use:** The inputs in biochar production include biomass feedstock, energy inputs for processing and pyrolysis, transportation fuels, and various contributory inputs in much smaller quantities. Cost and environmental impacts can be lower based on the selected feedstocks (ideally agricultural or forestry residues), the energy efficiency of the pyrolysis process (especially with energy recovery), and whether the biomass is purchased locally. Ultimately, all of these factors are critical to ensure that biochar production and use are cost-effective and environmentally sustainable, viewed from a life cycle perspective [156, 157].
- **GHG Emissions:** Studies show that biochar's production, combined with soil application, can reduce net greenhouse emissions. It is mainly due to efficient long-term carbon storage and offsets from bioenergy co-products [158]. Waste biomass feedstock systems offer the most favorable climate-related emissions benefits, while feedstock cartage and land-use change impacts can further influence life-cycle assessments [159]. Incorporating greenhouse gas (GHG) reduction benefits into the economic analysis of biochar projects—particularly by applying carbon pricing—can enhance both the cost-effectiveness and overall appeal of biochar production [160].

8.3. Comparison with other treatment methods and co-benefits (carbon sequestration)

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

Biochar typically comes with a greater initial cost than raw organic amendments; however, it offers more lasting environmental benefits, including long-lasting carbon sequestration, greater soil physical and chemical properties, and more effective contaminant immobilization. Biochar can be an environmentally more sustainable and, often, cost-competitive alternative to conventional chemical treatments, especially when utilizing waste biomass feedstocks [161]. Benefit-wise, co-produced bioenergy (syngas, bio-oil) reduces the use of fossil fuels and enhances climate benefits above and beyond carbon sequestration alone due to total emission avoidance of 1.5 times greater than carbon removal via biochar carbon alone. Biochar also mitigates emissions of potent greenhouse gases (methane & nitrous oxide) from soils. It also offers another significant GHG mitigation mechanism [162]. It enhances soil physical properties (e.g., porosity, water holding capacity, and bulk density), which leads to an enhancement in root growth and water/nutrient retention. It increases soil pH, soil organic carbon content, and nutrient retention, enhancing crop yields and reducing fertilizer needs. They benefit the users (financially) and the environment.

9. Future perspective and research direction

9.1. Opportunities for scale-up and novel modification techniques

Biochar production technologies that can be scaled include slow, medium, fast, and flash pyrolysis, gasification, and hydrothermal carbonization. Slow pyrolysis produces a maximum amount of biochar (approximately 35%), providing the most flexibility in terms of feedstock particle size. It can be very advantageous for scaling. Fast and flash pyrolysis technologies are biased towards the production of bio-oil and gas, which detracts from the potential yield of biochar. However, they can allow valorizing biochar as a co-product. Also, recent developments in research and upscaling methods suggest a transition from batch to non-stop pyrolysis systems (e.g., rotary kilns, screw pyrolyzers, continuous rollaway bed kilns). Continuous pyrolysis systems will improve energy efficiency, provide stable temperature control, and support increased throughput, which are essential for developing an industrial biochar industry [163].

By adding additional waste stream materials (e.g., sewage sludge or plastic waste) in co-pyrolysis alongside biochar production, the surface chemistry and pore architectures become altered, and allow for tailored adsorbents for ranking pollutants [164]. Laser and plasma-assisted functionalization are also advanced types of surface modification that can create a wider variety of etched and doped reactive sites with specific electronic characteristics. Still in the experimental stage, these methods can successfully advance the stated functions [165, 166].

9.2. Integration with other technologies and standardization of testing methods

The future of biochar research and scaling is contingent upon integrated systems such as CHAB, biorefineries, precision agriculture, and co-application with various soil amendments, thus creating technology synergies to increase efficiency, profitability, and sustainability. Additionally, integrated systems will be one of the primary methods of waste management, energy recovery, and climate targets, rapidly propelling biochar from a technology still in experimentation into an essential practice for sustainable environmental management [167, 168].

Standardizing testing protocols for biochar improves quality, safety, comparability, and market confidence in the industry. Standardizing testing protocol will allow for innovation, provide a basis for regulations, and support biochar products for global trade. The EBC and IBI Standards and WBC are an increasingly important pathway for new global protocols and certifications [169].

9.2.1. Testing categories

IBI and EBC standards group laboratory testing in the following ways [169]:

- **Basic Properties:** Carbon content, pH, water/ash content, bulk density, and particle size.
- **Toxicant Assessment:** Heavy metals, polycyclic aromatic hydrocarbons (PAHs), dioxins, and possibly other contaminants.
- **Advanced/Supplementary Properties:** Surface area, porosity, identification of functional groups, volatile matter, and C-stability - recommended for higher quality products or particular uses.

9.4.2. Popular methods of evaluation and evaluation methods

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

- **pH Assessment:** Should evaluate for agricultural suitability and soil/buffer interaction.
- **BET Surface Area Assessment:** Consideration is significant for pollutant sorption and soil activity.
- **Elemental Assessment (C, N, H, O):** Significance is for determining potential for sequestration and stability.
- **Heavy Metal Assessment (ICP/MS, or AAS):** For environmental and food contaminant safety compliance.
- **Functional Group Assessment:** FTIR and Boehm titration for functionality and reactive area.

10. Conclusions

Pharmaceuticals, from ibuprofen to sulfamethoxazole and diclofenac, have become one of the most widespread contaminants in water systems. They flood aquatic environments via industrial effluents and improper disposal, among other sources. Unfortunately, conventional WWTPs have proven insufficient to surmount the challenge of their complete remediation. Upscaling these techniques is expensive, and pharmaceuticals persist in wastewater even after treatments. Thus, biochar has emerged as one of the most promising solutions in recent studies. The organic product can remove specific pharmaceuticals at the highest efficiency at a low cost while ensuring sustainability. Researchers develop biochar from industrial and agricultural waste through various techniques involving pyrolysis at varying temperatures. Depending on the source, each preparation has unique physicochemical properties that allow selective adsorption of any desired drug.

The adsorption mechanisms include π-π stacking, Van der Waals forces, hydrogen bonding, electrostatic associations, and pore filling, etc. The properties of each drug and solution chemistry also play a role in the removal efficiency and adsorption of targeted compounds. Therefore, several optimizations are necessary to maximize the performance of biochar. Although biochar adsorption is poised to become the breakthrough technique for wastewater treatment, further research can enhance its increased acceptability much faster. Currently, many biochar studies are strictly laboratory-scale in size and operation. A deeper understanding of the adsorption mechanisms is still lacking, and there are no standardized protocols regarding experimentation and evaluation to ensure consistent results. Thus, this review article calls for more laboratory investigations, opportunities to scale up every application, and possible integration with other treatment methods. The ripple effects of greener, pharmaceutical-waste-free aquatic environments are a healthier future for water life and a safer, more sustainable world for humans.

Conflict of Interest

The authors declare no conflict of interest.

References

1. M. Hejna, D. Kapuścińska, and A. Aksmann. Pharmaceuticals in the Aquatic Environment: A Review on Eco-Toxicology and the Remediation Potential of Algae. *International Journal of Environmental Research and Public Health*, **2022**, *19*, 7717.
2. M. Ortúzar, et al. Pharmaceutical Pollution in Aquatic Environments: A Concise Review of Environmental Impacts and Bioremediation Systems. *Frontiers in Microbiology*, **2022**, *13*, 869332.
3. N.P. Ngqwala and P. Muchesa. Occurrence of pharmaceuticals in aquatic environments: A review and potential impacts in South Africa. *South African Journal of Science*, **2020**, *116*, 5730.
4. J.V. Eapen, et al. A review of the effects of pharmaceutical pollutants on humans and aquatic ecosystem. *Exploration of Drug Science*, **2024**, *2*, 484.
5. H. Aib, M.S. Parvez, and H.M. Czédli. Pharmaceuticals and Microplastics in Aquatic Environments: A Comprehensive Review of Pathways and Distribution, Toxicological and Ecological Effects. *International Journal of Environmental Research and Public Health*, **2025**, *22*, 799.
6. E. Fabbri and S. Franzellitti. Human pharmaceuticals in the marine environment: Focus on exposure and biological effects in animal species. *Environmental Toxicology and Chemistry*, **2015**, *35*, 799.
7. J.P. Sumpter, A.C. Johnson, and Tamsin J. Runnalls. Pharmaceuticals in the Aquatic Environment: No Answers Yet to the Major Questions. *Environmental Toxicology and Chemistry*, **2022**, *43*, 589.
8. J.L. Wilkinson, et al. Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences*, **2022**, *119*, e2113947119.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

9. M.A. Hossen, G.S. Sattar, and M.G. Mostafa. Factors affecting the performance of a pharmaceutical wastewater treatment plant: Characterization of effluent and environmental risk. *Heliyon*, **2024**, *10*, e29165.

10. E.S. Massima Mouele, et al. Removal of Pharmaceutical Residues from Water and Wastewater Using Dielectric Barrier Discharge Methods—A Review. *International Journal of Environmental Research and Public Health*, **2021**, *18*, 1683.

11. P. Alfonso-Muniozguren, et al. A review on pharmaceuticals removal from waters by single and combined biological, membrane filtration and ultrasound systems. *Ultrasonics Sonochemistry*, **2021**, *76*, 105656.

12. K. Kodom, F. Attiogbe, and F.A. Kuranchie. Assessment of removal efficiency of pharmaceutical products from wastewater in sewage treatment plants: A case of the sewerage systems Ghana limited, Accra. *Heliyon*, **2021**, *7*, e08385.

13. S. Jha, et al. Biochar as Sustainable Alternative and Green Adsorbent for the Remediation of Noxious Pollutants: A Comprehensive Review. *Toxics*, **2023**, *11*, 117.

14. B.K. Biswal and R. Balasubramanian. Use of biochar as a low-cost adsorbent for removal of heavy metals from water and wastewater: A review. *Journal of Environmental Chemical Engineering*, **2023**, *11*, 110986.

15. M. Dong, et al. Biochar for the Removal of Emerging Pollutants from Aquatic Systems: A Review. *International Journal of Environmental Research and Public Health*, **2023**, *20*, 1679.

16. M. Qiu, et al. Biochar for the removal of contaminants from soil and water: a review. *Biochar*, **2022**, *4*, 19.

17. F. Amalina, et al. Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review. *Journal of Hazardous Materials Advances*, **2022**, *7*, 100134.

18. R. Tareq, N. Akter, and M.S. Azam, *Biochars and Biochar Composites*, in *Biochar from Biomass and Waste*. **2019**, Elsevier. p. 169.

19. D. Laishram, et al. Advancements in Biochar as a Sustainable Adsorbent for Water Pollution Mitigation. *Advanced Science*, **2025**, *12*, 2410383.

20. Y. Chun, et al. Recent advancements in biochar production according to feedstock classification, pyrolysis conditions, and applications: A review. *BioResources*, **2021**, *16*, 6512.

21. J. Jan-Roblero and J.A. Cruz-Maya. Ibuprofen: Toxicology and Biodegradation of an Emerging Contaminant. *Molecules*, **2023**, *28*, 2097.

22. C.F. Granatto, et al. Methanogenic potential of diclofenac and ibuprofen in sanitary sewage using metabolic cosubstrates. *Science of The Total Environment*, **2020**, *742*, 140530.

23. P. Verlicchi, M. Al Aukidy, and E. Zambello. Occurrence of pharmaceutical compounds in urban wastewater: Removal, mass load and environmental risk after a secondary treatment—A review. *Science of The Total Environment*, **2012**, *429*, 123.

24. B. Petrie, R. Barden, and B. Kasprzyk-Hordern. A review on emerging contaminants in wastewaters and the environment: Current knowledge, understudied areas and recommendations for future monitoring. *Water Research*, **2015**, *72*, 3.

25. S. Harirforoosh, W. Asghar, and F. Jamali. Adverse Effects of Nonsteroidal Antiinflammatory Drugs: An Update of Gastrointestinal, Cardiovascular and Renal Complications. *Journal of Pharmacy & Pharmaceutical Sciences*, **2014**, *16*, 821.

26. Brune and P. Patrignani. New insights into the use of currently available non-steroidal anti-inflammatory drugs. *Journal of Pain Research*, **2015**, *8*, 105.

27. P.A. Masters, et al. Trimethoprim-Sulfamethoxazole Revisited. *Archives of Internal Medicine*, **2003**, *163*, 402.

28. D.J. Lapworth, et al. Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. *Environmental Pollution*, **2012**, *163*, 287.

29. T. aus der Beek, et al. Pharmaceuticals in the environment—Global occurrences and perspectives. *Environmental Toxicology and Chemistry*, **2015**, *35*, 823.

30. K. Samal, S. Mahapatra, and M. Hibzur Ali. Pharmaceutical wastewater as Emerging Contaminants (EC): Treatment technologies, impact on environment and human health. *Energy Nexus*, **2022**, *6*, 100076.

31. R. Bushra and N. Aslam. An Overview of Clinical Pharmacology of Ibuprofen. *Oman Medical Journal*, **2010**, *25*, 155.

32. K.D. Rainsford. Ibuprofen: pharmacology, efficacy and safety. *Inflammopharmacology*, **2009**, *17*, 275.

33. N. Cooney, C. Pollack, and P. Butkerait. Adverse drug reactions and drug–drug interactions with over-the-counter NSAIDs. *Therapeutics and Clinical Risk Management*, **2015**, *11*, 1061.

34. R.J. Flower. The development of COX2 inhibitors. *Nature Reviews Drug Discovery*, **2003**, *2*, 179.

35. L.L. Mazaleuskaya, et al. PharmGKB summary. *Pharmacogenetics and Genomics*, **2015**, *25*, 96.

36. K.D. Rainsford, *Ibuprofen*. **1999**: CRC Press.

37. Y. Trianda, S. Adityosulindro, and S.S. Moersidik. Ibuprofen as an Emerging Contaminant of Concern: Occurrence in Southeast Asia Water Environment. *E3S Web of Conferences*, **2024**, *530*, 02007.

38. J. Blasco and C. Trombini. Ibuprofen and diclofenac in the marine environment - a critical review of their occurrence and

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

potential risk for invertebrate species. *Water Emerging Contaminants & Nanoplastics*, **2023**, *2*, 14.

39. L. Grădinariu, et al. Oxidative Stress Biomarkers in Fish Exposed to Environmental Concentrations of Pharmaceutical Pollutants: A Review. *Biology*, **2025**, *14*, 472.

40. H. Islas-Flores, et al. Effect of ibuprofen exposure on blood, gill, liver, and brain on common carp (Cyprinus carpio) using oxidative stress biomarkers. *Environmental Science and Pollution Research*, **2014**, *21*, 5157.

41. L. Ferrando-Climent, et al. Comprehensive study of ibuprofen and its metabolites in activated sludge batch experiments and aquatic environment. *Science of The Total Environment*, **2012**, *438*, 404.

42. M.D. Celiz, J. Tso, and D.S. Aga. Pharmaceutical metabolites in the environment: Analytical challenges and ecological risks. *Environmental Toxicology and Chemistry*, **2009**, *28*, 2473.

43. C. Miège, et al. Fate of pharmaceuticals and personal care products in wastewater treatment plants – Conception of a database and first results. *Environmental Pollution*, **2009**, *157*, 1721.

44. K. Kümmerer. Pharmaceuticals in the Environment. *Annual Review of Environment and Resources*, **2010**, *35*, 57.

45. S. Aydin, et al. Effective removal of selected pharmaceuticals from sewerage treatment plant effluent using natural clay (Na-montmorillonite). *Applied Water Science*, **2023**, *13*, 129.

46. J.D. Smilack. Trimethoprim-Sulfamethoxazole. *Mayo Clinic Proceedings*, **1999**, *74*, 730.

47. G.M. Eliopoulos and P. Huovinen. Resistance to Trimethoprim-Sulfamethoxazole. *Clinical Infectious Diseases*, **2001**, *32*, 1608.

48. W. Duan, et al. Occurrence and ecotoxicity of sulfonamides in the aquatic environment: A review. *Science of The Total Environment*, **2022**, *820*, 153178.

49. I. Pala-Ozkok, et al. Impact of acute and chronic exposure to sulfamethoxazole on the kinetics and microbial structure of an activated sludge community. *Frontiers in Antibiotics*, **2024**, *3*, 1335654.

50. Y. Yang, et al. Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review. *Science of The Total Environment*, **2017**, *596-597*, 303.

51. M.C. La Rosa, et al. The Impact of Wastewater on Antimicrobial Resistance: A Scoping Review of Transmission Pathways and Contributing Factors. *Antibiotics*, **2025**, *14*, 131.

52. S. Zhang, et al. Constructed Wetland Revealed Efficient Sulfamethoxazole Removal but Enhanced the Spread of Antibiotic Resistance Genes. *Molecules*, **2020**, *25*, 834.

53. T.J. Gan. Diclofenac: an update on its mechanism of action and safety profile. *Current Medical Research and Opinion*, **2010**, *26*, 1715.

54. M. Schmidt, H.T. Sørensen, and L. Pedersen. Diclofenac use and cardiovascular risks: series of nationwide cohort studies. *BMJ*, **2018**, *362*, k3426.

55. C. Duarte, T. Di Lorenzo, and A.S.P.S. Reboleira. Environmental risk of diclofenac in European groundwaters and implications for environmental quality standards. *Scientific Reports*, **2024**, *14*, 20689.

56. Q. Fu, et al. Biotransformation Changes Bioaccumulation and Toxicity of Diclofenac in Aquatic Organisms. *Environmental Science & Technology*, **2020**, *54*, 4400.

57. S. Joachim, et al. Effects of diclofenac on sentinel species and aquatic communities in semi-natural conditions. *Ecotoxicology and Environmental Safety*, **2021**, *211*, 111812.

58. E.J. Tiedeken, et al. Monitoring, sources, receptors, and control measures for three European Union watch list substances of emerging concern in receiving waters – A 20 year systematic review. *Science of The Total Environment*, **2017**, *574*, 1140.

59. W. Brack, et al. Towards the review of the European Union Water Framework Directive: Recommendations for more efficient assessment and management of chemical contamination in European surface water resources. *Science of The Total Environment*, **2017**, *576*, 720.

60. M. Hernando, et al. Environmental risk assessment of pharmaceutical residues in wastewater effluents, surface waters and sediments. *Talanta*, **2006**, *69*, 334.

61. F. De Mastro, et al. Influence of chemical and mineralogical soil properties on the adsorption of sulfamethoxazole and diclofenac in Mediterranean soils. *Chemical and Biological Technologies in Agriculture*, **2022**, *9*, 34.

62. S. Mompelat, B. Le Bot, and O. Thomas. Occurrence and fate of pharmaceutical products and by-products, from resource to drinking water. *Environment International*, **2009**, *35*, 803.

63. M. Tripathi, J.N. Sahu, and P. Ganesan. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews*, **2016**, *55*, 467.

64. M.R. Patel and N.L. Panwar. Biochar from agricultural crop residues: Environmental, production, and life cycle assessment overview. *Resources, Conservation & Recycling Advances*, **2023**, *19*, 200173.

65. P. Rex, et al. Agricultural Biomass Waste to Biochar: A Review on Biochar Applications Using Machine Learning Approach and Circular Economy. *ChemEngineering*, **2023**, *7*, 50.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

66. W.-J. Liu, H. Jiang, and H.-Q. Yu. Development of Biochar-Based Functional Materials: Toward a Sustainable Platform Carbon Material. *Chemical Reviews*, **2015**, *115*, 12251.

67. J.J. Manyà. Pyrolysis for Biochar Purposes: A Review to Establish Current Knowledge Gaps and Research Needs. *Environmental Science & Technology*, **2012**, *46*, 7939.

68. E.N. Coker, et al. An Assessment of the Conversion of Biomass and Industrial Waste Products to Activated Carbon. *Energies*, **2023**, *16*, 1606.

69. K. Nadarajah, T. Asharp, and Y. Jeganathan. Biochar from waste biomass, its fundamentals, engineering aspects, and potential applications: an overview. *Water Science & Technology*, **2024**, *89*, 1211.

70. N.A. Qambrani, et al. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. *Renewable and Sustainable Energy Reviews*, **2017**, *79*, 255.

71. S.E. Ibitoye, et al. An overview of biochar production techniques and application in iron and steel industries. *Bioresources and Bioprocessing*, **2024**, *11*, 65.

72. K. Weber and P. Quicker. Properties of biochar. *Fuel*, **2018**, *217*, 240.

73. E.D. Visser, N.S. Seroka, and L. Khotseng. Recent Advances in Biochar: Synthesis Techniques, Properties, Applications, and Hydrogen Production. *Processes*, **2024**, *12*, 1111.

74. E.-S. Khater, et al. Biochar production under different pyrolysis temperatures with different types of agricultural wastes. *Scientific Reports*, **2024**, *14*, 2625.

75. S.-X. Zhao, N. Ta, and X.-D. Wang. Effect of Temperature on the Structural and Physicochemical Properties of Biochar with Apple Tree Branches as Feedstock Material. *Energies*, **2017**, *10*, 1293.

76. X. Dong, et al. Mechanisms of adsorption and functionalization of biochar for pesticides: A review. *Ecotoxicology and Environmental Safety*, **2024**, *272*, 116019.

77. L. Cui, et al. Changes in surface characteristics and adsorption properties of 2,4,6-trichlorophenol following Fenton-like aging of biochar. *Scientific Reports*, **2021**, *11*, 4293.

78. P. Zhang, et al. Functional Biochar and Its Balanced Design. *ACS Environmental Au*, **2021**, *2*, 115.

79. K.G. Roberts, et al. Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environmental Science & Technology*, **2009**, *44*, 827.

80. J. Lehmann, J. Gaunt, and M. Rondon. Bio-char Sequestration in Terrestrial Ecosystems – A Review. *Mitigation and Adaptation Strategies for Global Change*, **2006**, *11*, 403.

81. L. Campion, et al. The costs and benefits of biochar production and use: A systematic review. *Journal of Cleaner Production*, **2023**, *408*, 137138.

82. T. Kan, V. Strezov, and T.J. Evans. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renewable and Sustainable Energy Reviews*, **2016**, *57*, 1126.

83. B.A. Oni, O. Oziegbe, and O.O. Olawole. Significance of biochar application to the environment and economy. *Annals of Agricultural Sciences*, **2019**, *64*, 222.

84. J. Lehmann, et al. Biochar effects on soil biota – A review. *Soil Biology and Biochemistry*, **2011**, *43*, 1812.

85. A.M. Freitas, V.D. Nair, and W.G. Harris. Biochar as Influenced by Feedstock Variability: Implications and Opportunities for Phosphorus Management. *Frontiers in Sustainable Food Systems*, **2020**, *4*, 510982.

86. A.V. Karre and T. Cai. Review of innovative uses of biochar in environmental applications for nitrobenzene removal in aqueous and soil phases. *Frontiers in Chemical Engineering*, **2023**, *5*, 1186878.

87. H.N. Tran, et al. Innovative spherical biochar for pharmaceutical removal from water: Insight into adsorption mechanism. *Journal of Hazardous Materials*, **2020**, *394*, 122255.

88. G. Murtaza, et al. A review of mechanism and adsorption capacities of biochar-based engineered composites for removing aquatic pollutants from contaminated water. *Frontiers in Environmental Science*, **2022**, *10*, 1035865.

89. C.F. Varela, L.C. Moreno-Aldana, and Y.Y. Agámez-Pertuz. Adsorption of pharmaceutical pollutants on ZnCl2-activated biochar from corn cob: Efficiency, selectivity and mechanism. *Journal of Bioresources and Bioproducts*, **2024**, *9*, 58.

90. M.C. Ndoun, et al. Adsorption of pharmaceuticals from aqueous solutions using biochar derived from cotton gin waste and guayule bagasse. *Biochar*, **2020**, *3*, 89.

91. Y. Fan, et al. Improvement of the specific surface area of biochar by calcium-precipitated nanoparticles synthesized by microbial induction as a template skeleton: Removal mechanism of tetracycline in water. *Journal of Environmental Management*, **2023**, *348*, 119279.

92. A.B. Duwiejuah, et al. Review of Biochar Properties and Remediation of Metal Pollution of Water and Soil. *Journal of Health and Pollution*, **2020**, *10*, 200902.

93. K.H. Hama Aziz, et al. Biochar as green adsorbents for pharmaceutical pollution in aquatic environments: A review. *Desalination*, **2024**, *583*, 117725.

94. D. Zhan, A. Ye, and T. Hou. Research progress on biochar-based material adsorption and removal of ibuprofen. *Frontiers in Environmental Science*, **2023**, *11*, 1327000.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

95. S. Nand, et al. Biochar for mitigating pharmaceutical pollution in wastewater: A sustainable solution. *Science of The Total Environment*, **2025**, *966*, 178743.

96. M. Ahmad, et al. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere*, **2014**, *99*, 19.

97. A. Solanki and T.H. Boyer. Pharmaceutical removal in synthetic human urine using biochar. *Environmental Science: Water Research & Technology*, **2017**, *3*, 553.

98. Y. Zheng, et al. Characterization and Adsorption Capacity of Modified Biochar for Sulfamethylimidine and Methylene Blue in Water. *ACS Omega*, **2023**, *8*, 29966.

99. S. Chauhan, et al. Biochar-mediated removal of pharmaceutical compounds from aqueous matrices via adsorption. *Waste Disposal & Sustainable Energy*, **2022**, *5*, 37.

100. X.-f. Tan, et al. Biochar as potential sustainable precursors for activated carbon production: Multiple applications in environmental protection and energy storage. *Bioresource Technology*, **2017**, *227*, 359.

101. Z. Kang, et al. A Review on Application of Biochar in the Removal of Pharmaceutical Pollutants through Adsorption and Persulfate-Based AOPs. *Sustainability*, **2022**, *14*, 10128.

102. M. Patel, et al. Aqueous ibuprofen sorption by using activated walnut shell biochar: process optimization and cost estimation. *Environmental Science: Advances*, **2022**, *1*, 530.

103. Y. Ngernyen, et al. Adsorption of the non-steroidal anti-inflammatory drug (ibuprofen) onto biochar and magnetic biochar prepared from chrysanthemum waste of the beverage industry. *RSC Advances*, **2023**, *13*, 14712.

104. X. Yang, et al. Sorptive removal of ibuprofen from water by natural porous biochar derived from recyclable plane tree leaf waste. *Journal of Water Process Engineering*, **2022**, *46*, 102627.

105. N. Gao, et al. Chitosan-modified biochar: Preparation, modifications, mechanisms and applications. *International Journal of Biological Macromolecules*, **2022**, *209*, 31.

106. C. Jung, et al. Adsorption of selected endocrine disrupting compounds and pharmaceuticals on activated biochars. *Journal of Hazardous Materials*, **2013**, *263*, 702.

107. S. Mondal, et al. Biosorptive uptake of ibuprofen by steam activated biochar derived from mung bean husk: Equilibrium, kinetics, thermodynamics, modeling and eco-toxicological studies. *Journal of Environmental Management*, **2016**, *182*, 581.

108. M.R. Islam, et al. Adsorption of Ibuprofen from Water Using Banana Peel Biochar: Experimental Investigation and Machine Learning Algorithms. *Water*, **2024**, *16*, 3469.

109. T. Ai, et al. Methanol-modified ultra-fine magnetic orange peel powder biochar as an effective adsorbent for removal of ibuprofen and sulfamethoxazole from water. *Adsorption Science & Technology*, **2020**, *38*, 304.

110. Y.S. Ho and G. McKay. Pseudo-second order model for sorption processes. *Process Biochemistry*, **1999**, *34*, 451.

111. J. Huang, et al. Ball milled biochar effectively removes sulfamethoxazole and sulfapyridine antibiotics from water and wastewater. *Environmental Pollution*, **2020**, *258*, 113809.

112. F. Reguyal, A.K. Sarmah, and W. Gao. Synthesis of magnetic biochar from pine sawdust via oxidative hydrolysis of FeCl2 for the removal sulfamethoxazole from aqueous solution. *Journal of Hazardous Materials*, **2017**, *321*, 868.

113. Y. Li, et al. High performance removal of sulfamethoxazole using large specific area of biochar derived from corncob xylose residue. *Biochar*, **2022**, *4*, 11.

114. Y. Niu, et al. Highly effective removal of sulfamethoxazole by Na₂CO₃-modified biochar derived from sorghum straw and sewage sludge. *Environmental Science: Water Research & Technology*, **2023**, *9*, 2355.

115. X. Qiu, et al. Physicochemical and adsorptive properties of biochar derived from municipal sludge: sulfamethoxazole adsorption and underlying mechanism. *Frontiers in Environmental Science*, **2023**, *11*, 1275087.

116. M. Bizi. Sulfamethoxazole Removal from Drinking Water by Activated Carbon: Kinetics and Diffusion Process. *Molecules*, **2020**, *25*, 4656.

117. N. Inarmal and B. Moodley. Removal efficiencies and environmental risk assessment of selected pharmaceuticals and metabolites at a wastewater treatment plant in Pietermaritzburg, South Africa. *Environmental Monitoring and Assessment*, **2024**, *197*, 102.

118. M. Xie, et al. Adsorption of sulfonamides to demineralized pine wood biochars prepared under different thermochemical conditions. *Environmental Pollution*, **2014**, *186*, 187.

119. X. Tan, et al. Adsorption of sulfamethoxazole via biochar: The key role of characteristic components derived from different growth stage of microalgae. *Environmental Research*, **2022**, *210*, 112965.

120. D. Mohan, et al. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – A critical review. *Bioresource Technology*, **2014**, *160*, 191.

121. Y. Deng, et al. Enhanced adsorption performance of sulfamethoxazole and tetracycline in aqueous solutions by MgFe2O4-magnetic biochar. *Water Science and Technology*, **2022**, *86*, 568.

122. M.P. Schmidt, et al. Optimizing date palm leaf and pistachio shell biochar properties for antibiotic adsorption by varying

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

pyrolysis temperature. *Bioresource Technology Reports*, **2023**, *21*, 101325.

123. Y.M. Correa-Navarro, L. Giraldo, and J.C. Moreno-Piraján. Biochar from Fique Bagasse for Remotion of Caffeine and Diclofenac from Aqueous Solution. *Molecules*, **2020**, *25*, 1849.

124. Y.M. Correa-Navarro, J.C. Moreno-Piraján, and L. Giraldo. Competitive Adsorption of Caffeine and Diclofenac Sodium onto Biochars Derived from Fique Bagasse: An Immersion Calorimetry Study. *ACS Omega*, **2022**, *8*, 1967.

125. B. Kocabıyık, O. Üner, and Ü. Geçgel. Diclofenac sodium adsorption in aqueous media by activated carbon obtained from einkorn (Triticum monococcum L.) husk. *Adsorption*, **2024**, *30*, 1033.

126. L. Lonappan, et al. An insight into the adsorption of diclofenac on different biochars: Mechanisms, surface chemistry, and thermodynamics. *Bioresource Technology*, **2018**, *249*, 386.

127. I.A. Lawal, et al. Theoretical and experimental adsorption studies of phenol and crystal violet dye on carbon nanotube functionalized with deep eutectic solvent. *Journal of Molecular Liquids*, **2019**, *288*, 110895.

128. J.L. Sotelo, et al. Removal of caffeine and diclofenac on activated carbon in fixed bed column. *Chemical Engineering Research and Design*, **2012**, *90*, 967.

129. V.T. Nguyen, et al. Fabrication of Partially Graphitic Biochar for the Removal of Diclofenac and Ibuprofen from Aqueous Solution: Laboratory Conditions and Real Sample Applications. *Environmental Engineering Science*, **2021**, *38*, 974.

130. H. Qiu, et al. Critical review in adsorption kinetic models. *Journal of Zhejiang University-SCIENCE A*, **2009**, *10*, 716.

131. A.I. Osman, et al. Advanced adsorbents for ibuprofen removal from aquatic environments: a review. *Environmental Chemistry Letters*, **2023**, *22*, 373.

132. K.Y. Foo and B.H. Hameed. Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, **2010**, *156*, 2.

133. A.S. Mestre, et al. Activated carbons from sisal waste by chemical activation with K2CO3: Kinetics of paracetamol and ibuprofen removal from aqueous solution. *Bioresource Technology*, **2011**, *102*, 8253.

134. M.E. Peñafiel and D. Flores. Competitive Adsorption of Drugs from a Multi-Component Mixture on Sugarcane Bagasse. *Water*, **2023**, *15*, 2127.

135. M. Thommes, et al. Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure and Applied Chemistry*, **2015**, *87*, 1051.

136. L. Lonappan, et al. Diclofenac and its transformation products: Environmental occurrence and toxicity - A review. *Environment International*, **2016**, *96*, 127.

137. A. Michelon, et al. Agro-industrial residues as biosorbents for the removal of anti-inflammatories from aqueous matrices: An overview. *Environmental Advances*, **2022**, *9*, 100261.

138. J. Fang, et al. Realistic and field scale applications of biochar for water remediation: A literature review. *Journal of Environmental Management*, **2025**, *385*, 125524.

139. S. Wu and H. Wu. Incorporating Biochar into Wastewater Eco-treatment Systems: Popularity, Reality, and Complexity. *Environmental Science & Technology*, **2019**, *53*, 3345.

140. T. Alsawy, et al. A comprehensive review on the chemical regeneration of biochar adsorbent for sustainable wastewater treatment. *npj Clean Water*, **2022**, *5*.

141. D. Woolf, et al. Sustainable biochar to mitigate global climate change. *Nature Communications*, **2010**, *1*, 56.

142. C. Gallego-Ramírez, E. Chica, and A. Rubio-Clemente. Coupling of Advanced Oxidation Technologies and Biochar for the Removal of Dyes in Water. *Water*, **2022**, *14*, 2531.

143. T. Alsawy, et al. A comprehensive review on the chemical regeneration of biochar adsorbent for sustainable wastewater treatment. *npj Clean Water*, **2022**, *5*, 29.

144. Y. Dai, et al. The adsorption, regeneration and engineering applications of biochar for removal organic pollutants: A review. *Chemosphere*, **2019**, *223*, 12.

145. B. Bhattacharjee and M. Ahmaruzzaman. Photocatalytic degradation of pharmaceuticals: Insights into biochar modification and degradation mechanism. *Next Materials*, **2024**, *5*, 100238.

146. Z. Guo, et al. Effective degradation of COVID-19 related drugs by biochar-supported red mud catalyst activated persulfate process: Mechanism and pathway. *Journal of Cleaner Production*, **2022**, *340*, 130753.

147. C. Gallego-Ramírez, E. Chica, and A. Rubio-Clemente. Combination of Biochar and Advanced Oxidation Processes for the Sustainable Elimination of Pharmaceuticals in Water. *Sustainability*, **2024**, *16*, 10761.

148. J. Shaheen, Y.H. Fseha, and B. Sizirici. Performance, life cycle assessment, and economic comparison between date palm waste biochar and activated carbon derived from woody biomass. *Heliyon*, **2022**, *8*, e12388.

149. J.J. Pignatello, S. Kwon, and Y. Lu. Effect of Natural Organic Substances on the Surface and Adsorptive Properties of Environmental Black Carbon (Char): Attenuation of Surface Activity by Humic and Fulvic Acids. *Environmental Science & Technology*, **2006**, *40*, 7757.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

150. E.S. Azzi, E. Karltun, and C. Sundberg. Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm. *Environmental Science & Technology*, **2019**, *53*, 8466.

151. K. Pandian, et al. Biochar – a sustainable soil conditioner for improving soil health, crop production and environment under changing climate: a review. *Frontiers in Soil Science*, **2024**, *4*, 1376159.

152. J.L. Gaunt and J. Lehmann. Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis Bioenergy Production. *Environmental Science & Technology*, **2008**, *42*, 4152.

153. D. Gamaralalage, et al. Biowaste to biochar: a techno-economic and life cycle assessment of biochar production from food-waste digestate and its agricultural field application. *Biochar*, **2025**, *7*, 50.

154. R. Ibarrola, S. Shackley, and J. Hammond. Pyrolysis biochar systems for recovering biodegradable materials: A life cycle carbon assessment. *Waste Management*, **2012**, *32*, 859.

155. S.M. Desjardins, M.T. Ter-Mikaelian, and J. Chen. Cradle-to-gate life cycle analysis of slow pyrolysis biochar from forest harvest residues in Ontario, Canada. *Biochar*, **2024**, *6*, 58.

156. Y. He, et al. Effects of biochar application on soil greenhouse gas fluxes: a meta-analysis. *GCB Bioenergy*, **2016**, *9*, 743.

157. F. Xia, et al. Life cycle assessment of greenhouse gas emissions for various feedstocks-based biochars as soil amendment. *Science of The Total Environment*, **2024**, *911*, 168734.

158. M. Elias, et al. Market analysis of coupled biochar and carbon credit production from wildfire fuel reduction projects in the western <scp>USA</scp>. *Biofuels, Bioproducts and Biorefining*, **2024**, *18*, 1226.

159. P. Sharma, et al. Effectiveness of biochar and compost on improving soil hydro-physical properties, crop yield and monetary returns in inceptisol subtropics. *Saudi Journal of Biological Sciences*, **2021**, *28*, 7539.

160. A. Tisserant and F. Cherubini. Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation. *Land*, **2019**, *8*, 179.

161. J.Y. Seo, et al. Production of biochar from crop residues and its application for biofuel production processes – An overview. *Bioresource Technology*, **2022**, *361*, 127740.

162. M.J. Ahmed and B.H. Hameed. Insight into the co-pyrolysis of different blended feedstocks to biochar for the adsorption of organic and inorganic pollutants: A review. *Journal of Cleaner Production*, **2020**, *265*, 121762.

163. K. Wang, et al. Enhanced Capacitance and Desalination Performance with Plasma-Activated Biochar Electrodes. *Energy Technology*, **2023**, *11*, 2300043.

164. M.Z. Yameen, et al. Harnessing the power of functionalized biochar: progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability. *Biochar*, **2024**, *6*, 25.

165. G. Agegnehu, A.K. Srivastava, and M.I. Bird. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology*, **2017**, *119*, 156.

166. J. Lehmann, et al. Biochar in climate change mitigation. *Nature Geoscience*, **2021**, *14*, 883.

167. J. Wang and S. Wang. Preparation, modification and environmental application of biochar: A review. *Journal of Cleaner Production*, **2019**, *227*, 1002.

168. T. Xie, et al. Characteristics and Applications of Biochar for Environmental Remediation: A Review. *Critical Reviews in Environmental Science and Technology*, **2015**, *45*, 939.

169. R. Breen, et al. A Collaborative Cocurricular Undergraduate Research Experience on Sustainable Materials: Analysis of Biochar Using the Boehm Titration and Spectroscopic Techniques. *Journal of Chemical Education*, **2025**, *102*, 1323.

© 2026 Authors. The authors retain the copyright and full publishing rights. This article is licensed under a Creative Commons Attribution 4.0 BY International License.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.

Author Biography

Eloghosa Nosa-Ihaza is an undergraduate researcher in pharmaceutical sciences at Marwadi University with a keen interest in environmental remediation and public health. He combines expertise in analytical chemistry, medicinal chemistry, and biotechnology with a commitment to addressing environmental and health challenges through sustainable pharmaceutical innovation. His current research focuses on low-cost biochar adsorbents for the removal of pharmaceutical pollutants from wastewater, computational drug discovery, and genomic data science. Eloghosa has published multiple peer-reviewed preprints and presented at international conferences, including a first-place oral presentation on computational drug discovery. His professional experience includes pharmaceutical industry analytics (HPLC, spectrophotometry) and machine learning applications in genomic analysis.

Godsent Shepherd-Moses is currently a Pharmacy Student studying at Marwadi University. His research interests include Translational Nanomedicine & Targeted Drug Delivery, Pharmacogenomics & Precision Therapeutics, and Regenerative Pharmacology & Bio-integrative Implants. He has worked on projects like Biochar use as Adsorbents for Wastewater Remediation, and is currently focused on Green Chemistry Innovative Techniques. His interests and Projects are quite vast because he believes that every aspect of health is intertwined with each other, and a general knowledge in all aspects makes you a well-grounded scientist.

Archana Sharma is an accomplished Associate Professor in the Department of Agriculture at Marwadi University, Rajkot, with over 24 years of academic and research experience. A Ph.D. graduate from Mohanlal Sukhadia University, she has established herself as a distinguished environmental scientist specializing in phytoremediation, solid waste management, environmental impact assessment, and wastewater treatment. Recognized as a National Eligibility Test qualifier and an internationally certified engineering educator, Dr. Sharma has made significant contributions to environmental research, particularly in municipal solid waste management. Her scholarly work includes guiding two Ph.D. scholars, conducting environmental audits since 2013, and serving as an environmental chemist in the NABL Audit team at Marwadi University. She has been honored with the "Best Scientist Award" and has published extensively, with her research providing critical insights into sustainable environmental practices and waste management strategies in Rajkot and beyond.

© 2026 Authors. The authors retain copyright and full publishing rights under a CC BY 4.0 International License.