IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 5, September 2026
Impact Factor: 8.2

Adsorptive Removal of Pharmaceutical Pollutants from Aquatic Environments Using Sustainable Adsorbent Materials

Sneha Chauhan[1] and Sayali Kamble[2]
Department of Chemistry
Satish Pradhan Dnyanasadhana College, Thane, Maharashtra, India
[1]sanandkamble95@gmail.com

Abstract: *Pharmaceutical pollutants have become significant contaminants in aquatic environments because of their rising use, ongoing release, and incomplete removal by conventional wastewater treatment processes. Among these contaminants, paracetamol (acetaminophen) is one of the most frequently detected analgesics in wastewater and surface water and may pose ecological risks to aquatic organisms even at trace concentrations. Developing simple, cost-effective, and eco-friendly treatment methods is therefore crucial. Adsorption stands out as a promising technique due to its high removal efficiency, operational simplicity, comparatively low energy demand, and minimal generation of harmful by-products. This paper reviews the application of different adsorbent materials for the removal of pharmaceutical pollutants, with particular emphasis on paracetamol. Activated carbon, biochar, zeolites, clays, nanomaterials, and biocomposites have all demonstrated potential for pharmaceutical removal. Activated carbon generally shows high adsorption efficiency owing to its large surface area and porous structure, while modified and waste-derived carbons offer routes to improved sustainability and reduced cost. Agro-industrial residues such as rice husk, wheat straw, bamboo, bagasse, and other biomass can be converted into biochar or activated carbon and used as low-cost biosorbents. Reported studies show that ceramic-derived activated carbon can adsorb paracetamol with maximum sorption capacities of approximately 150-159 mg/g, comparable to or exceeding several conventional carbons. Operating factors such as pH, temperature, contact time, adsorbent dose, and initial pollutant concentration strongly influence adsorption performance. The use of low-cost, waste-derived adsorbents offers a promising strategy for mitigating pharmaceutical pollution in water, although further work is needed on adsorbent regeneration, reusability, selectivity, and the feasibility of large-scale implementation.*

Key Words: Adsorption, wastewater treatment, activated carbon, biochar, biosorbents, low-cost adsorbents, agro-industrial waste, ceramic-derived activated carbon, nanomaterials, biocomposites.

I. INTRODUCTION

The presence of pharmaceutical compounds in natural water bodies has emerged as a global environmental concern over the past two decades. Pharmaceuticals enter aquatic systems mainly through human and veterinary excretion, improper disposal of unused medicines, and effluents discharged from manufacturing units and hospitals. Because most municipal wastewater treatment plants (WWTPs) were originally designed to remove conventional pollutants such as suspended solids, organic matter, and pathogens, they are frequently unable to completely eliminate pharmaceutically active compounds, which are often persistent, polar, and biologically active even at nanogram- to microgram-per-litre concentrations [1], [2].

Copyright to IJARSCT
www.ijarsct.co.in
DOI: 10.48175/IJARSCT-40648

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 6, Issue 5, September 2026 Impact Factor: 8.2

Large-scale monitoring studies confirm this problem. A review of pharmaceutical occurrence and removal across 43 compounds in municipal WWTPs reported that acetaminophen and atenolol showed among the highest average daily mass loads, and that twelve of the monitored pharmaceuticals posed a high potential ecological risk based on risk-quotient assessment [2]. Similarly, a recent multi-plant survey analysing 97 pharmaceuticals in surface water and WWTP influent/effluent found that acetaminophen, caffeine, ibuprofen, and several other analgesics and antibiotics were detected with 100% frequency in both surface water and wastewater samples [3]. Such findings confirm that current treatment infrastructure is insufficient to prevent pharmaceutical discharge into receiving water bodies [4].

Among the various pharmaceuticals detected in the environment, paracetamol (acetaminophen) is of particular concern because of its status as one of the most widely consumed over-the-counter analgesic and antipyretic drugs worldwide. Its continuous release, moderate water solubility, and resistance to complete biodegradation in conventional activated-sludge systems make it a persistent micropollutant, and chronic exposure has been linked to sub-lethal toxicity in aquatic organisms. Advanced oxidation processes can degrade paracetamol but are energy-intensive, costly, and can generate toxic transformation by-products, limiting their large-scale applicability [5]. Adsorption, in contrast, is widely regarded as a practical, low-cost, and easily scalable alternative that avoids the formation of harmful oxidation products, making it an attractive option for treating pharmaceutical-contaminated water, particularly when the adsorbent is derived from inexpensive or waste-derived precursors [5], [6]. This paper reviews the major classes of adsorbent materials that have been investigated for the removal of pharmaceutical pollutants, with particular focus on paracetamol, and discusses the key operating factors that govern adsorption performance.

II. SOURCES AND OCCURRENCE OF PHARMACEUTICAL POLLUTANTS

Pharmaceuticals reach aquatic environments through several interlinked pathways: excretion of parent drugs and metabolites in human and animal urine and faeces, disposal of expired or unused medication into sewage systems, discharge from pharmaceutical manufacturing and hospital effluents, and agricultural run-off from veterinary drug use [7]. Because a large fraction of an administered dose is often excreted unmetabolised, WWTPs receive a continuous influent load of pharmaceutical residues. Removal efficiency in conventional treatment trains is highly compound-specific; some pharmaceuticals are eliminated to a large extent by biodegradation or sorption onto sludge, while others pass through largely unchanged, resulting in effluent concentrations that can, in some cases, exceed influent concentrations due to deconjugation of metabolites during treatment [4], [8]. This incomplete and inconsistent removal is the principal reason pharmaceuticals are now classified among the priority "contaminants of emerging concern" in water-quality research [2], [8].

III. ADSORPTION AS A WATER TREATMENT TECHNOLOGY

Adsorption is a surface phenomenon in which pollutant molecules accumulate at the interface between a solid adsorbent and the surrounding aqueous solution. Removal typically proceeds through a combination of mechanisms, including physical (van der Waals) interactions, electrostatic attraction between charged pollutant species and oppositely charged adsorbent surfaces, hydrogen bonding, pi-pi stacking between aromatic rings of the adsorbate and graphitic domains of carbonaceous adsorbents, and, in some materials, ion exchange or pore-filling effects [9], [5]. The relative contribution of each mechanism depends on the physicochemical properties of both the adsorbent (surface area, pore-size distribution, surface functional groups, point of zero charge) and the pollutant (molecular size, polarity, and degree of ionisation, which is governed by solution pH relative to the pollutant's pKa) [5].

Compared with advanced oxidation, membrane filtration, and biological treatment, adsorption is generally favoured for pharmaceutical removal because it (i) does not require the addition of oxidising chemicals or generation of potentially toxic transformation products, (ii) can be operated at ambient temperature and pressure with comparatively low energy input, (iii) is mechanically simple and easy to retrofit into existing treatment trains, and (iv) allows the use of inexpensive, waste-derived materials as adsorbents, which directly addresses cost and sustainability concerns associated with commercial activated carbon [5], [6].

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 5, September 2026
Impact Factor: 8.2

IV. ADSORBENT MATERIALS FOR PHARMACEUTICAL POLLUTANT REMOVAL

4.1 Activated Carbon

Activated carbon (AC) remains the most extensively studied adsorbent for pharmaceutical removal owing to its large specific surface area, well-developed micro/mesoporous structure, and tunable surface chemistry. Commercial oxidised activated carbon with a BET surface area of 1284 m2/g and abundant oxygen-containing functional groups has been shown to adsorb acetaminophen effectively across a wide pH range (2-10) and in different real water matrices, including tap water, coastal water, and groundwater [10]. Granular activated carbon has achieved up to 95-99% paracetamol/acetaminophen removal under optimised acidic conditions and moderate contact times in batch studies [11], [12].

A notable example of a low-cost yet high-performance carbon is ceramic-derived activated carbon (CeDC), synthesised from a ceramic composite precursor, which achieved a BET surface area of 895 m2/g with a bimodal mesopore/macropore distribution and demonstrated maximum paracetamol sorption capacities of approximately 150-159 mg/g, comparable to or better than a commercial activated carbon tested under identical conditions [13]. Sulphonated and chemically activated carbons derived from sewage sludge have reported maximum adsorption capacities around 145 mg/g for paracetamol, alongside good reusability over repeated regeneration cycles [14]. In contrast, activated carbons derived from simple biomass precursors without further chemical activation, such as Cannabis sativum hemp, show comparatively modest capacities (around 16 mg/g), illustrating that feedstock choice and activation method strongly determine performance [15].

4.2 Biochar

Biochar, produced by pyrolysing biomass under limited-oxygen conditions, is considered a low-cost and sustainable alternative to commercial activated carbon. Its performance depends heavily on feedstock type, pyrolysis temperature, and post-synthesis modification, with engineered/activated biochars able to reach surface areas exceeding 1000 m2/g and removal efficiencies above 90% for a range of organic pollutants [16], [17]. Biochar produced from agricultural and forestry residues has shown strong pharmaceutical-removal capability; reported maximum capacities for different pharmaceutical classes include roughly 88 mg/g for sulfonamides, close to 570 mg/g for ibuprofen, and over 700 mg/g for oxytetracycline hydrochloride on optimised biochars, reflecting the strong influence of feedstock and activation route on uptake [18]. Field-relevant studies using raspberry-cane-derived biochar applied to real municipal WWTP secondary effluent successfully removed nearly all detected pharmaceutical and pesticide residues except a small number of resistant compounds, and performed comparably to commercial powdered activated carbon [19]. Biochar derived from different agro-residues (corn stalk, apple wood, rice husk) has also shown measurable capacity for pharmaceuticals such as propranolol, with adsorption favoured at near-neutral to mildly alkaline pH through electrostatic and cation-exchange interactions [20].

4.3 Zeolites

Zeolites are crystalline, microporous aluminosilicates that remove pollutants primarily through ion exchange, size-selective pore trapping, and surface adsorption. Iron-oxide/zeolite (Fe3O4-ZSM-5) composites have been used to remove acetaminophen from wastewater, with the magnetite phase's capacity increasing from about 25 to 69 mg/g as the initial concentration was raised from 50 to 280 mg/L, and best performance observed near neutral pH [21]. Low-cost synthetic zeolites and zeolite-carbon composites produced from fly ash have achieved over 90% removal of several pharmaceuticals within only two minutes of contact time, demonstrating the potential for very fast-acting, inexpensive zeolite-based sorbents [22]. Natural zeolites such as clinoptilolite, whether left in their native form or modified (e.g., protonated or surfactant-modified), have also been investigated specifically for paracetamol removal owing to their high cation-exchange capacity, thermal stability, and low cost relative to synthetic zeolites or commercial activated carbon [23]. More advanced hybrid zeolite composites, such as ZIF-8/zeolite materials prepared by sonocrystallisation, have reported adsorption capacities around 131 mg/g for other pharmaceutical pollutants (e.g., azithromycin), indicating the promise of metal-organic-framework/zeolite hybrids for this application [24].

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 5, September 2026
Impact Factor: 8.2

4.4 Clays

Natural and modified clay minerals, particularly montmorillonite, offer an inexpensive and widely available adsorbent option. Pristine montmorillonite is hydrophilic and therefore less effective for relatively non-polar pharmaceuticals, but surfactant modification (e.g., with stearyl trimethyl ammonium) markedly improves affinity: modified montmorillonite has achieved removal of 97% for carbamazepine, 95% for ibuprofen, and 63-67% for paracetamol under optimised conditions [25]. Titanium-pillared montmorillonite has similarly been reported effective for the simultaneous adsorptive removal of amoxicillin, imipramine, diclofenac sodium, and paracetamol from water [26]. Acid-treated natural clay has also demonstrated over 80% removal efficiency for both paracetamol and metformin even in complex real water matrices such as tap water, groundwater, and seawater, positioning natural clay as a cost-competitive alternative to more expensive nanomaterial-based sorbents [27].

4.5 Nanomaterials and Biocomposites

Engineered nanomaterials and composite adsorbents combine the high surface area and reactivity of nanoscale materials with the mechanical robustness or magnetic separability of a support matrix. Iron-oxide nanoparticles and mesoporous biocarbon composites have been reported for paracetamol adsorption with the added benefit of magnetic recovery and demonstrated regenerability over multiple cycles [28]. Zeolite-silver and other metal-doped nanocomposites synthesised via green methods have shown promise for broader water-contaminant mitigation, aligning with the wider push toward environmentally friendly nanomaterial synthesis routes [29]. While these hybrid materials frequently exhibit excellent adsorption capacity and additional functionalities (e.g., magnetic separation, antimicrobial action), higher production cost and synthesis complexity remain barriers to their large-scale field deployment compared with simpler carbon-, biochar-, or clay-based adsorbents [24], [28].

4.6 Agro-Industrial Waste-Derived Biosorbents

A major sustainability advantage of adsorption technology lies in the ability to convert low-value or waste agricultural biomass into effective biosorbents, simultaneously addressing waste management and water pollution. Materials such as rice husk, wheat straw, bamboo, bagasse, date pits, coffee waste, and other lignocellulosic residues have all been explored as precursors for activated carbon or biochar [30], [31]. Reported performance varies widely with feedstock and activation conditions: for example, olive-mill-wastewater-derived, tungstate-doped activated carbon achieved very high saturation capacities (over 700 mg/g for diclofenac), while simpler, non-activated biomass carbons (e.g., hemp-derived AC) achieved considerably lower capacities in the range of 16 mg/g for paracetamol [15], [32]. This variability underlines that although agro-waste feedstocks are attractive for cost and sustainability reasons, appropriate activation and surface modification are usually necessary to achieve adsorption capacities competitive with commercial activated carbon.

V. FACTORS AFFECTING ADSORPTION PERFORMANCE

Across the studies reviewed, several operating parameters consistently govern adsorption efficiency for pharmaceutical pollutants:

Solution pH: pH influences both the ionisation state of the pharmaceutical (relative to its pKa) and the surface charge of the adsorbent (relative to its point of zero charge). Acidic conditions have generally favoured paracetamol/acetaminophen adsorption onto activated carbons [11], [12], while clay- and montmorillonite-based systems show pollutant-dependent pH optima [25], [27].

Contact time and kinetics: Most systems reach equilibrium within tens of minutes to a few hours, with the pseudo-second-order kinetic model most frequently providing the best fit, suggesting chemisorption-influenced rate control alongside intraparticle diffusion in carbon-based adsorbents [11], [13], [15].

Adsorbent dose: Increasing adsorbent dose generally increases percentage removal (more available sites) but can reduce the per-gram adsorption capacity due to particle aggregation and site overlap at high doses [11], [21].

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 6, Issue 5, September 2026 Impact Factor: 8.2

Initial pollutant concentration and temperature: Adsorption capacity typically rises with initial concentration up to a saturation point described by Langmuir, Freundlich, or Sips isotherm models, and many systems show endothermic, spontaneous behaviour with capacity increasing at higher temperature [12], [21].

Adsorbent surface chemistry and porosity: High surface area, appropriate pore-size distribution, and the presence of oxygen-containing functional groups consistently correlate with higher pharmaceutical uptake, whether in activated carbon, biochar, zeolite, or clay systems [10], [13], [18].

VI. REGENERATION, REUSABILITY, AND SCALE-UP CHALLENGES

For adsorption to be a practically and economically sustainable water-treatment strategy, spent adsorbents must be regenerable and reusable over multiple cycles without substantial loss of capacity. Some carbon-based adsorbents have demonstrated good regeneration performance, retaining most of their removal efficiency over several reuse cycles with only a small percentage-point decline per cycle [14], [28]. However, several practical barriers to large-scale field deployment remain, including inconsistent adsorption performance under variable real-water conditions (competing ions, natural organic matter, varying pH), the relatively high cost of producing engineered or chemically activated adsorbents at scale, logistical challenges in adsorbent handling, separation, and disposal or regeneration, and the need to integrate adsorption units effectively with existing treatment infrastructure [17], [19]. Addressing these challenges will require continued research into cheaper activation methods, adsorbent selectivity for target pharmaceuticals in complex water matrices, and life-cycle-cost assessment of regeneration versus disposal.

VII. CONCLUSION AND FUTURE PERSPECTIVES

Pharmaceutical pollutants, and paracetamol in particular, are persistent and increasingly well-documented contaminants of aquatic environments that are not fully eliminated by conventional wastewater treatment. Adsorption offers a practical, energy-efficient, and by-product-free alternative for their removal, and a wide range of materials, including activated carbon, biochar, zeolites, clays, nanomaterials, and biocomposites, have demonstrated meaningful removal capacity in laboratory and, in some cases, real-effluent studies. Among these, waste- and agro-residue-derived adsorbents are particularly attractive because they convert low-value biomass into functional materials while lowering treatment cost, directly supporting circular-economy and sustainability goals in water treatment. Adsorption performance is governed by an interplay of solution pH, contact time, adsorbent dose, pollutant concentration, temperature, and adsorbent surface chemistry, and optimisation of these factors is essential for translating laboratory-scale results into field-relevant performance. Future research should prioritise the development of low-cost, highly selective, and easily regenerable adsorbents; performance validation using real, multi-component wastewater rather than single-pollutant model solutions; and techno-economic and life-cycle assessments to establish the feasibility of large-scale implementation of adsorption-based technologies for pharmaceutical pollutant removal from water.

ACKNOWLEDGEMENT

The authors thank the Department of Chemistry, Satish Pradhan Dnyanasadhana College, Thane, for providing the resources and support necessary to carry out this review work.

REFERENCES

[1] Occurrence, transformation, bioaccumulation, risk and analysis of pharmaceutical and personal care products from wastewater: a review. Environmental Chemistry Letters, 2022.

[2] Occurrence and removal of pharmaceuticals in wastewater treatment plants: a global review (2010-2020). Journal of Environmental Management, 2021.

[3] Occurrence of 97 pharmaceuticals in wastewater and receiving waters: analytical validation and treatment influence. PMC12193875, 2024.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 6, Issue 5, September 2026 Impact Factor: 8.2

[4] Pharmaceutical pollutants in wastewater treatment plants: a global review of occurrence, treatment efficiency, and implications for receiving water bodies. Science of the Total Environment, 2026.
[5] Adsorptive removal of paracetamol from aqueous media: a review of adsorbent materials, adsorption mechanisms, advancements, and future perspectives. Journal of Molecular Liquids, 2024.
[6] Zubair, M. et al. Biochar for Adsorptive Removal of Pharmaceuticals from Environmental Water. In: Handbook of Environmental Engineering, vol. 27, Springer, 2024.
[7] Removal efficiency of pharmaceuticals during the wastewater treatment process: emission and environmental risk assessment. PLOS ONE, 2025.
[8] Occurrence and removal of pharmaceuticals in wastewater treatment plants at the Spanish Mediterranean area of Valencia. Chemosphere, 2012.
[9] Biochar as green adsorbents for pharmaceutical pollution in aquatic environments: a review. Desalination, 2024.
[10] Adsorption process and mechanism of acetaminophen onto commercial activated carbon. Journal of Environmental Chemical Engineering, 2020.
[11] Kinetic, equilibrium and thermodynamic studies of the adsorption of paracetamol in activated carbon in batch model and fixed-bed column. Applied Water Science, 2021.
[12] Wisniewska, M. et al. Removal of Acetaminophen from Aqueous Solutions in an Adsorption Process. Materials, 2024, 17(3), 431.
[13] Bursztyn Fuentes, A.L., Benito, D.E., Montes, M.L., Scian, A.N., Lombardi, M.B. Paracetamol and Ibuprofen Removal from Aqueous Phase Using a Ceramic-Derived Activated Carbon. Arabian Journal for Science and Engineering, 2023, 48(1), 525-537.
[14] Removal of acetaminophen from the contaminated water using adsorption onto carbon activated with NH4Cl. Journal of Environmental Chemical Engineering, 2024.
[15] Sajid, M., Bari, S., Saif Ur Rehman, M. et al. Adsorption characteristics of paracetamol removal onto activated carbon prepared from Cannabis sativum Hemp. Alexandria Engineering Journal, 2022, 61, 7203-7212.
[16] A review on recent advances of biochar from agricultural and forestry wastes: preparation, modification and applications in wastewater treatment. Journal of Environmental Chemical Engineering, 2023.
[17] The Production of Biochar and Its Impact on the Removal of Various Emerging Pollutants from Wastewater: A Review. PMC12737283, 2025.
[18] Zubair, M. et al. Biochar for Adsorptive Removal of Pharmaceuticals from Environmental Water. Handbook of Environmental Engineering, vol. 27, Springer, 2024.
[19] Adsorption Performance Assessment of Agro-Waste-Based Biochar for the Removal of Emerging Pollutants from Municipal WWTP Effluent. Molecules, 2025, 30(24), 4803.
[20] Comparative Study for Propranolol Adsorption on the Biochars from Different Agricultural Solid Wastes. PMC11204899, 2024.
[21] Removal of Acetaminophen Drug from Wastewater by Fe3O4 and ZSM-5 Materials. PMC10254380, 2023.
[22] Using Zeolite Materials to Remove Pharmaceuticals from Water. Materials, 2024, 17(15), 3848.
[23] Clinoptilolite-Based Adsorbents for Paracetamol Removal. PMC12692779, 2025.
[24] Liu, Z., Bahadoran, A., Alizadeh, A. et al. Sonocrystallization of a novel ZIF/zeolite composite adsorbent with high chemical stability for removal of the pharmaceutical pollutant azithromycin from contaminated water. Ultrasonics Sonochemistry, 2023.
[25] Pharmaceuticals Removal by Adsorption with Montmorillonite Nanoclay. PMC8468575, 2021.
[26] Chauhan, M., Saini, V.K., Suthar, S. Ti-pillared montmorillonite clay for adsorptive removal of amoxicillin, imipramine, diclofenac-sodium, and paracetamol from water. Journal of Hazardous Materials, 2020, 399, 122832.
[27] Linear and nonlinear investigations for the adsorption of paracetamol and metformin from water on acid-treated clay. PMC8245496, 2021.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 5, September 2026
Impact Factor: 8.2

[28] Sivarasan, G., Manikandan, V., Periyasamy, S. et al. Iron-engineered mesoporous biocarbon composite and its adsorption, activation, and regeneration approach for removal of paracetamol in water. Environmental Research, 2023, 227, 115723.
[29] Sustainable Zeolite-Silver Nanocomposites via Green Methods for Water Contaminant Mitigation and Modeling Approaches. PMC10856811, 2024.
[30] Biosorbent treatment of fluorene using activated carbon derived from the pyrolysis process of date pit wastes. PMC11427576, 2024.
[31] Waste-Coffee-Derived Activated Carbon as Efficient Adsorbent for Water Treatment. PMC9739668, 2022.
[32] High adsorption capacity of diclofenac and paracetamol using OMWW based W-carboxylate doped activated carbon. Ministry of Health and Prevention (UAE) research repository, 2025.