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RESEARCH ARTICLE

From Biomass Waste to Aquatic Protection: Critical Review of Waste-Derived Activated Carbons for PPCP Removal in Municipal Wastewater

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Abstract –Pharmaceuticals and personal care products (PPCPs) enter aquatic ecosystems via municipal and industrial effluents, threatening aquatic life through bioaccumulation and ecotoxicity at trace concentrations (ng/L to µg/L). Converting waste biomass into waste-derived activated carbons (WD-ACs) offers a sustainable, cost-effective adsorption strategy that supports circular production models. The precise relationships between raw biomass choices, activation methods, multi-component wastewater matrices, and specific PPCP uptake pathways remain poorly defined. This review evaluates the occurrence, environmental risks, and WD-AC removal performance of 14 high-priority PPCPs spanning five major categories: non-steroidal anti-inflammatory drugs, antibiotics, cardiovascular and metabolic agents, stimulants, and personal care additives. Global monitoring data show widespread concentration variability across treatment streams. DeaWD-ACs achieve high adsorption capacities driven by pore filling, π–π stacking, hydrohobic partitioning, hydrogen bonding, and electrostatic attraction, current literature relies predominantly on synthetic matrices spiked at unrealistically elevated levels. To transition from bench-scale studies to full-scale engineering, researchers must validate performance in real wastewater at realistic environmental concentrations, alleviate organic matter fouling, ensure precursor supply chain security, and optimize continuous-flow reactor configurations. Scaling these systems also requires integrating end-of-life assessments, including media regeneration economics, leachate toxicity, bioaccessibility, and safe final disposal strategies.

Keywords –Emerging contaminants; Pharmaceuticals and personal care products (PPCPs); Biochar; Real wastewater matrices; Competitive adsorption; Circular economy; Micropollutants; Maximum adsorption capacity

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1. INTRODUCTION

The continuous release of pharmaceutical and personal care product (PPCP) residues and their active metabolites into aquatic environments has raised widespread concern due to their persistent health hazards and ecotoxicological risks (Ohoro et al., 2022). Reflecting this global issue, diverse PPCPs have been widely detected in surface waters and effluents across Spain (García et al., 2017), Canada (Montoya-Bautista et al., 2022; Tabe et al., 2016), China (Yan et al., 2014), Greece (Kosma et al., 2010), the United States (Khetan and Collins, 2007; Kostich et al., 2014), and Australia (Anim et al., 2020). Present at trace levels, typically in the range of several thousand nanograms per liter, PPCPs bioaccumulate and pose long-term risks to aquatic life (Wang et al., 2022). Their specific ecological impacts vary widely depending on compound-specific physicochemical characteristics (García et al., 2017). Recent studies highlight that exposure to individual PPCPs or their environmentally relevant mixtures can severely impair aquatic organisms (Wu et al., 2021; Sengar and Vijayanandan, 2022; Liu et al., 2025), frequently inducing genotoxicity and endocrine disruption (Couto et al., 2019). Of particular concern, antibiotic residues accelerate the proliferation of antibiotic resistance among target and non-target microbial species. Elevated concentrations of non-steroidal anti-inflammatory drugs (NSAIDs), such as ibuprofen and naproxen, exhibit life-threatening gastrointestinal ulcerogenic toxicities (Khetan and Collins, 2007). Beyond aquatic ecosystems, PPCP residues endanger terrestrial fauna and human populations via bioaccumulation through the food chain and contaminated drinking water supplies (Huijbregts et al., 2005).

Conventional wastewater treatment plants (WWTPs) serve as major point sources for PPCP entry into natural receiving waters (Hamid and Li, 2016). This operational inefficiency occurs because standard WWTPs are optimized to remove readily biodegradable, non-polar, and macroscopic organic loads, rendering them ineffective for trace PPCP elimination (Tarpani and Azapagic, 2018; Vasquez and Fatta-Kassinos, 2013). Biological treatment steps can also transform parent compounds into hazardous secondary metabolites. Pharmaceutically active compounds, including antibiotics, vaccines, and synthetic hormones, enter municipal waste streams via human and veterinary excretion, whereas personal care products, such as hand sanitizers and antibacterial agents, enter through routine hygiene practices (Zhi et al., 2021). To mitigate the release of these micropollutants, various advanced treatment techniques have been explored, including coagulation–sedimentation, ozonation, reverse osmosis, and adsorption (Pesqueira et al., 2020). Coagulation, ozonation, and membrane-based processes are often constrained by incomplete contaminant removal, high energy demands, or hazardous byproduct formation (Sun et al., 2017). Adsorption onto carbonaceous adsorbents is considered one of the most viable and efficient options, owing to their high specific surface areas, rich aromatic networks, functionalized surface chemistry, cost-effectiveness, and exceptional performance at trace contaminant levels (Zhu et al., 2022; Wang et al., 2022; Mohamed et al., 2023 a-d; Hamid et al., 2024; Nicomel and Li, 2026 a,b).

Commercial activated carbon (CAC) in granular or powder form remains a benchmark adsorbent for capturing low-molecular-weight organic micropollutants. Extending this technology, numerous studies have evaluated CACs derived from traditional organic precursors (such as coconut shells, coal, wood, and lignite) for PPCP removal from wastewater streams (Wong et al., 2018; Gupta and Khatri, 2019; Zhang et al., 2020). Despite the proven efficacy of CACs in trapping pharmaceuticals (Teodosiu et al., 2018), their full-scale application remains bottlenecked by high production costs and resource-intensive regeneration cycles, which are financially challenging for the municipal wastewater sector (Zhu et al., 2021).

To address these economic constraints, waste-derived activated carbons (WD-ACs) have gained significant interest as sustainable alternatives. Aligned with circular economy frameworks, WD-ACs are synthesized via the pyrolysis and activation of agricultural, municipal, and industrial waste materials, including WWTP sewage sludge (Bian et al., 2018), post-consumer plastics, and sawdust. Among these, sludge-based activated carbon (SBAC) can be converted from primary or secondary municipal sludge, yielding materials with desirable textural properties and thermal stability (Calisto et al., 2014). For instance, our research team successfully demonstrated the simultaneous removal of microplastics and low-concentration PPCPs using engineered SBACs (Montoya-Bautista et al., 2022). This circular treatment approach achieves effective PPCP removal by providing an eco-friendly management route for sewage sludge that might otherwise leach pollutants into receiving environments. Importantly, SBAC synthesis offers substantial cost advantages compared to traditional CAC manufacturing (Arena et al., 2016; Zhuang et al., 2022; Huang et al., 2022).

Despite growing interest in waste valorization, a systematic synthesis connecting PPCP removal across diverse WD-AC materials with their underlying ecotoxicological risks is lacking. To address this gap, this review investigates 14 target PPCP compounds selected based on their environmental persistence, ecotoxicological severity, and the availability of adsorption benchmark data (Levy et al., 2019; Żur et al., 2018). Notably, consumption rates for many of these target pharmaceuticals surged during and following the COVID-19 pandemic. The selected target compounds encompass three main pharmaceutical categories (NSAIDs, cardiovascular and metabolic regulators, and antibiotics), a stimulant, and personal care or packaging additives.

In addition to reviewing PPCP occurrence, toxicity, and adsorption capacities, this paper critically synthesizes literature findings across four primary operational domains: (1) methodological limitations in current bench-scale adsorption research; (2) fundamental uptake mechanisms and speciation dynamics; (3) key engineering barriers to full-scale deployment; and (4) practical operational feasibility. Ultimately, actionable perspectives are proposed to bridge the gap between laboratory batch testing and industrial implementation, offering concrete insights for environmental engineers, regulatory agencies, and researchers working toward sustainable water protection.

2. DATA SELECTION AND METHODS

A systematic literature search was conducted across major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, to retrieve relevant peer-reviewed studies. Initial database queries used targeted keyword combinations, including PPCP compounds, wastewater treatment plant, influent/effluent concentration, toxicity, and waste-derived activated carbon adsorption. To complement formal database queries, citation searching was implemented by manually screening reference lists and citing articles from key publications.

A total of 14 target PPCP compounds were selected based on high global usage rates, documented aquatic toxicity, and environmental persistence. Essential physicochemical properties, including water solubility, octanol–water partition coefficients (log Kow), and acid dissociation constants (pKa), were obtained primarily from the US EPA Estimation Programs Interface (EPI Suite™ v4.1) and supplemented by peer-reviewed literature. Complementary solid–water distribution coefficients (Kd) for secondary sludge were extracted from targeted experimental studies.

Inclusion criteria prioritized peer-reviewed articles published between 2009 and 2025 that reported empirical data regarding PPCP occurrence in WWTP influents and effluents, aquatic toxicity, or adsorptive removal. Regarding adsorbent selection, this review focused strictly on waste-derived activated carbons (WD-ACs) synthesized from agricultural residues, plastic waste, sewage sludge (such as sludge-based activated carbon), municipal solid waste, and industrial or

secondary waste streams including sawdust. Non-adsorptive treatment technologies and non-waste-derived sorbents (such as raw clay minerals, pristine unactivated minerals, or conventional commercial non-recycled carbons) fell outside the scope of this work and were excluded.

Applying these selection criteria yielded 16 primary studies investigating target PPCP removal via WD-AC materials, 10 of which provided detailed evaluations of underlying adsorption mechanisms. We extracted operational variables and mechanistic pathways directly from these primary sources, and consulted supplementary literature to support our scientific interpretation, benchmarking, and discussion.

The compiled occurrence and treatment dataset captures a representative global perspective spanning 11 countries across diverse economic and geographic regions: Belgium, Canada, China, Greece, India, the Netherlands, New Zealand, South Africa, South Korea, Spain, and Vietnam. For toxicological assessments, preference was given to 24-h median lethal concentration (LC50) values in fish species. When 24-h fish toxicity endpoints were unavailable, criteria were broadened to include aquatic microorganisms or extended exposure durations (48-h and 96-h LC50). Although not exhaustive given the high volume of published research, this curated dataset provides a robust global framework for evaluating PPCP occurrence, ecotoxicity, and adsorptive management.

3. PROPERTIES, OCCURRENCE AND TOXICITY

3.1 Properties and uses of the selected PPCPs

The 14 widely consumed PPCPs selected for this review were categorized into five distinct functional groups: non-steroidal anti-inflammatory drugs (NSAIDs: ibuprofen, naproxen, and diclofenac), antibiotics (sulfamethoxazole and ciprofloxacin), cardiovascular and metabolic regulators (furosemide, gemfibrozil, glyburide, warfarin, and hydrochlorothiazide), a stimulant (caffeine), and personal care products and packaging-related additives (bisphenol A, triclosan, and triclocarban). The detailed physicochemical properties, chemical structures, and main applications of these target PPCPs are summarized in Table 1.

NSAIDs (ibuprofen, naproxen, and diclofenac) are prescribed or acquired over the counter to alleviate pain, fever, and systemic inflammation (Mestre et al., 2009; Elizalde-Velázquez et al., 2020). Sulfamethoxazole and ciprofloxacin are widely used broad-spectrum antibacterial agents. Sulfamethoxazole, a sulfonamide derivative, is frequently co-administered with trimethoprim in clinical settings and is extensively deployed in veterinary medicine and aquaculture (Wang & Wang, 2018). Ciprofloxacin, a broad-spectrum fluoroquinolone, is primarily prescribed to treat urinary tract, gastrointestinal, and systemic bacterial infections (Bojer et al., 2017). Upon discharge into natural ecosystems, these antibiotic residues can inhibit soil microbial activity and promote the proliferation of drug-resistant pathogens across animal populations (Faleye et al., 2019; Saxena et al., 2021).

Furosemide and hydrochlorothiazide belong to the loop and thiazide diuretic classes, respectively, and are prescribed to manage hypertension by stimulating urinary excretion of fluid and potassium ions (Carone et al., 2016; Herman et al., 2023). Gemfibrozil, a fibrate derivative, suppresses hepatic lipid synthesis to reduce circulating triglyceride levels (Mimeault et al., 2005). Glyburide is an oral hypoglycemic agent used to manage type 2 and gestational diabetes by triggering pancreatic insulin secretion (Kremer & Duff, 2004). Warfarin acts as a synthetic anticoagulant prescribed to mitigate thromboembolic risks (Holbrook et al., 2005). Caffeine is a natural central nervous system stimulant used clinically as a diuretic and pain-relieving adjuvant, as well as a dietary additive in beverages and foods (such as tea and chocolate) to combat fatigue and improve mental alertness (Bachmann et al., 2021; Mengesha et al., 2022). Bisphenol A, triclosan, and triclocarban are industrial chemicals widely incorporated into personal care formulations and consumer packaging. Specifically, triclocarban and triclosan function as broad-spectrum antimicrobial agents in soaps and lotions, whereas bisphenol A serves as a key monomer in plastic containers and food packaging materials (Chen et al., 2022).

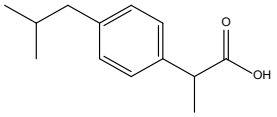
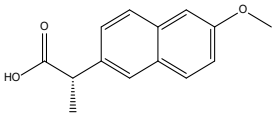
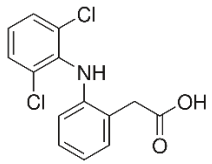
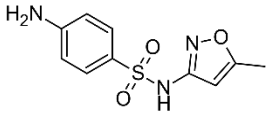
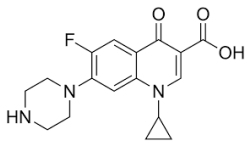
3.2 Occurrence of PPCPs in WWTPs

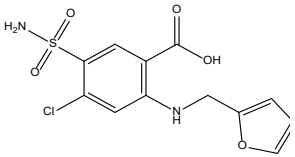
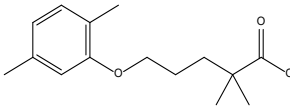
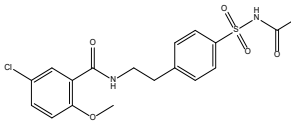
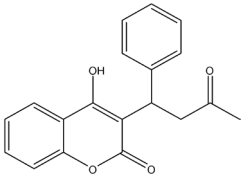
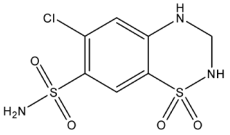
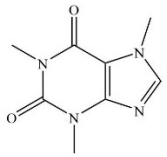
Target PPCPs are frequently detected across both influent and effluent streams of conventional WWTPs, highlighting the operational limitations of secondary biological and physical treatment processes. Table 2 summarizes reported environmental concentrations (ng/L) of the selected PPCPs in WWTP matrices across various countries. Because municipal WWTPs represent a primary discharge vector for micropollutants entering aquatic ecosystems, their occurrence and removal efficiencies have been investigated extensively (Hamid and Li, 2016; Anand et al., 2022).

Among the selected compounds, monitoring data are abundant for NSAIDs, antibiotics, caffeine, bisphenol A, and triclosan, whereas monitoring studies remain relatively limited for cardiovascular and metabolic regulators and triclocarban. In Canadian municipal effluents, ibuprofen, naproxen, sulfamethoxazole, caffeine, and triclosan were detected at concentrations ranging from approximately 0.01 µg/L to 2 µg/L (Baalbaki et al., 2016; Guerra et al., 2019). Driven by high population densities and substantial pharmaceutical consumption, WWTP effluents in India exhibit considerably higher PPCP levels (Mutiyar et al., 2018; Anand et al., 2022). Specifically, studies by Saxena et al. (2021) and Dubey et al. (2023) reported the occurrence of three NSAIDs, two antibiotics, triclosan, bisphenol A, caffeine, and gemfibrozil in Indian wastewater effluents at concentrations spanning 0.042 µg/L to 200 µg/L, consistently exceeding levels reported across other geographic regions.

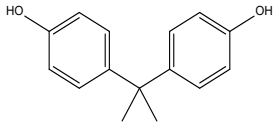
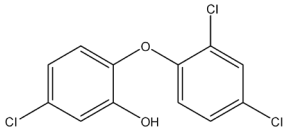
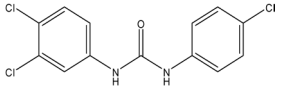
Across influent streams, caffeine, sulfamethoxazole, furosemide, and ciprofloxacin are frequently present at elevated concentrations, whereas the remaining target compounds typically stay below 10 µg/L. The high occurrence of caffeine reflects its widespread dietary presence in beverages and foods, alongside its inclusion in pharmaceutical formulations. Markedly elevated concentrations of antibiotics, particularly sulfamethoxazole

Table 1 Properties of studied pharmaceuticals and personal care products (PPCPs).

Compound	Application	Chemical structure	M.W. (g/mol)	Solubility in water (mg/L)	p*Ka* [a]	log K_{ow}	log K_d (L/kg) [f] (secondary sludge)	References
NSAIDs								
Ibuprofen	Anti-inflammatory		206.29	21 [a]	4.91	3.97	0.9–2.65	(Sangster, 1997; Stuer-Lauridsen et al., 2000; Suárez et al., 2008; Takács-Novák et al., 1997; Ternes et al., 2004; Yalkowsky et al., 2010)
Naproxen	Anti-inflammatory		230.27	15.9 [a]	4.15	3.18	1.1–2.9	(Hansch et al., 1995; Park et al., 2017; Sangster, 1997; Suarez et al., 2010; Urase & Kikuta, 2005; Yalkowsky et al., 2010)
Diclofenac	Anti-inflammatory		296.15	2.37 [a]	4.15	4.51	1.2–3.2	(Elizalde-Velázquez et al., 2020; Fini et al., 1986; Park et al., 2017; Sangster, 1997; Scheytt et al., 2005; Suárez et al., 2008; Takács-Novák et al., 1997; Ternes et al., 2004)
Antibiotics								
Sulfamethoxazole	Antibiotic		253.28	610 [b]	1.85	0.89	2.1–2.6	(Göbel et al., 2005; Hansch et al., 1995; Le-Minh et al., 2010; Park et al., 2017; Qiang & Adams, 2004; Suárez et al., 2008; Teixeira et al., 2019; Yalkowsky et al., 2010)
Ciprofloxacin	Antibiotic		331.35	3×10^4 [c]	6.09	0.28	4.2–4.3	(Golet et al., 2003; Nowara et al., 1997; Park et al., 2017; Ross & Riley, 1990; Takács-Novák et al., 1992; Van Doorslaer et al., 2014)

Cardiovascular and Metabolic Regulators								
Furosemide	High blood pressure		330.74	73.1 [d]	3.9	2.03	2.1–2.2	(Li et al., 2020; Narumiya et al., 2013; Park et al., 2017; Sangster, 1997; Verlicchi et al., 2012; Yalkowsky et al., 2010)
Gemfibrozil	Cholesterol and triglyceride regulator		250.34	4.97	4.7	4.77	1.88–3.04	(Kosma et al., 2010; Radjenović et al., 2009; Urase & Kikuta, 2005; Verlicchi et al., 2012)
Glyburide	High blood sugar regulator		494.01	4.00 [e]	5.3	4.79	N/A	(Georgita et al., 2007; Yalkowsky et al., 2010)
Warfarin	Anticoagulant or blood thinner		308.34	17 [c]	5.0	2.70	1.43	(Barron et al., 2009; Hansch et al., 1995; Li et al., 2021; Tomlin, 1997; Ufer, 2005)
Hydrochlorothiazide	High blood pressure		297.73	722 [a]	7.9	−0.07	−1.25 to −1	(Hansch et al., 1995; Radjenović et al., 2009; Sangster, 1997; Stuer-Lauridsen et al., 2000; Yalkowsky et al., 2010)
Stimulant								
Caffeine	Stimulant to the central nervous system		194.19	2.16×10^4 [a]	10.4	−0.07	2–3	(Kosma et al., 2010; Narumiya et al., 2013; Park et al., 2017; Richards et al., 2017; Yalkowsky et al., 2010)

Personal care products and packaging

Bisphenol A (BPA)	Plastic additive		228.29	120 [a]	9.6	3.32	2.52	(Dorn et al., 1987; Hansch et al., 1995; Zeng et al., 2006; Zhao et al., 2008)
Triclosan	Antimicrobial pesticides		315.49	10 [c]	8.1	4.76	4.1–4.2	(CITI, 1992; Muñoz et al., 2009; Narumiya et al., 2013; Park et al., 2017; Yalkowsky et al., 2010)
Triclocarban	Antimicrobial pesticides		289.55	0.11 [c]	12.7	4.34	4.0–4.9	(ECHA, 2018; Narumiya et al., 2013; NCBI, 2026; Park et al., 2017; Wu et al., 2009)

M.W.: Molecular weight; N/A: Not available
pKa, acid dissociation constant; log K_{ow}, octanol–water partition coefficient; K_d, solid–water distribution coefficient
[a] reported at 25°C, [b] solubility reported at 37°C, [c] solubility reported at 20°C, [d] solubility reported at 30°C, [e] solubility reported at 27°C, [f] log K_d values are based on the following references: (Barron et al., 2009; Göbel et al., 2005; Golet et al., 2003; Narumiya et al., 2013; Park et al., 2017; Radjenović et al., 2009; Stuer-Lauridsen et al., 2000; Ternes et al., 2004; Urase & Kikuta, 2005; Zhao et al., 2008)

Table 2 Reported concentrations of pharmaceuticals and personal care products (PPCPs) in influent (untreated) and effluent (treated) wastewater.

Compound	Concentration ranges in wastewater		Country	Reference
	Influent (ng/L)	Effluent (ng/L)		
NSAIDs				
Ibuprofen	3640 ± 105	<6	Canada	(Baalbaki et al., 2016)
	34.8–406	BLD-99.4	China	(Sun et al., 2016)
	2800–25400	500–2600	Greece	(Kosma et al., 2010)
	1250 (winter)	250	India	(Dubey et al., 2023)
	1870 (summer)	374	India	(Dubey et al., 2023)
	7552	<248	New Zealand	(Kumar et al., 2019)
Naproxen	471 ± 36.0	20 ± 3	Canada	(Baalbaki et al., 2016)
	BLD-30.6	BLD-13.8	China	(Sun et al., 2016)
	0−648	BLD	Greece	(Papageorgiou et al., 2016)
	BLD-2000	BLD-700	Greece	(Kosma et al., 2010)
	2060 (winter)	1236	India	(Dubey et al., 2023)
	2190 (summer)	1314	India	(Dubey et al., 2023)
	4560	<272	New Zealand	(Kumar et al., 2019)
Diclofenac	3300 ± 900	2700 ± 300	Germany	(Raysyan et al., 2021)
	~62.5	~41.9	India	(Dubey et al., 2023)
	183	303	New Zealand	(Kumar et al., 2019)
	54–190	<LOQ-224	South Korea	(Park et al., 2017)
	313	164	Spain	(Alessandretti et al., 2021; Sadutto et al., 2021)
Antibiotics				
Sulfamethoxazole	1900	600	Belgium	(Lorenzo et al., 2018)
	1340000	200000	India	(Saxena et al., 2021)
	29–79	23–64	Netherlands	(Paulus et al., 2019)
	845–4569	59.3–353.9	South Africa	

	9800	6400	Vietnam	(Faleye et al., 2019; Wang et al., 2020)
				(Lien et al., 2016)
Ciprofloxacin	957	850	India	(Dubey et al., 2023)
	86–103	51–62	Netherlands	(Paulus et al., 2019)
	35341–88011	15.4–707.6	South Africa	(Faleye et al., 2019; Wang et al., 2020)
	42800	21500	Vietnam	(Lien et al., 2016)
Cardiovascular and Metabolic Regulators				
Furosemide	BDL-4813	BDL-1502	Greece	(Papageorgiou et al., 2016)
	310	100	Spain	(Alessandretti et al., 2021; Sadutto et al., 2021)
Gemfibrozil	0.7–26.6	BLD-2.1	China	(Sun et al., 2016)
	700–3300	BLD-1300	Greece	(Kosma et al., 2010)
	300	250	India	(Dubey et al., 2023)
Glyburide	NA	10.8–96.7	Spain	(López-Serna et al., 2012)
Warfarin	NA	54	Canada	(Kostich et al., 2014)
Hydrochlorothiazide	2090	1900	Spain	(Köpping et al., 2020)
Stimulant				
Caffeine	28960 ± 4658	1756 ± 226	Canada	(Baalbaki et al., 2016)
	20300 (winter)	4100	India	(Dubey et al., 2023)
	16000 (summer)	3200	India	(Dubey et al., 2023)
	38600	<300	New Zealand	(Kumar et al., 2019)
	6490	170	South Korea	(Park et al., 2017)
	6870	38	Spain	(Alessandretti et al., 2021; Sadutto et al., 2021)

Personal care products and packaging

Bisphenol A (BPA)	55.6–5850	BLD-123	China	(Sun et al., 2016)
	70,000	3000	India	(Saxena et al., 2021)
	175	77	Spain	(Alessandretti et al., 2021; Sadutto et al., 2021)
Triclosan	166 ± 26	31 ± 4	Canada	(Baalbaki et al., 2016)
	289–3930	10.3–1390	Canada	(Guerra et al., 2019)
	(Median: 1480)	(Median: 107)		
	1.3–211	25.9–111	China	(Sun et al., 2016)
	BLD-1000	BLD	Greece	(Kosma et al., 2010)
	400	100	India	(Dubey et al., 2023)
	103	23	New Zealand	(Kumar et al., 2019)
Triclocarban	4.70–76.2	27.6–109	China	(Sun et al., 2016)

LOQ: Limit of quantification; BLD: Below limits of detection

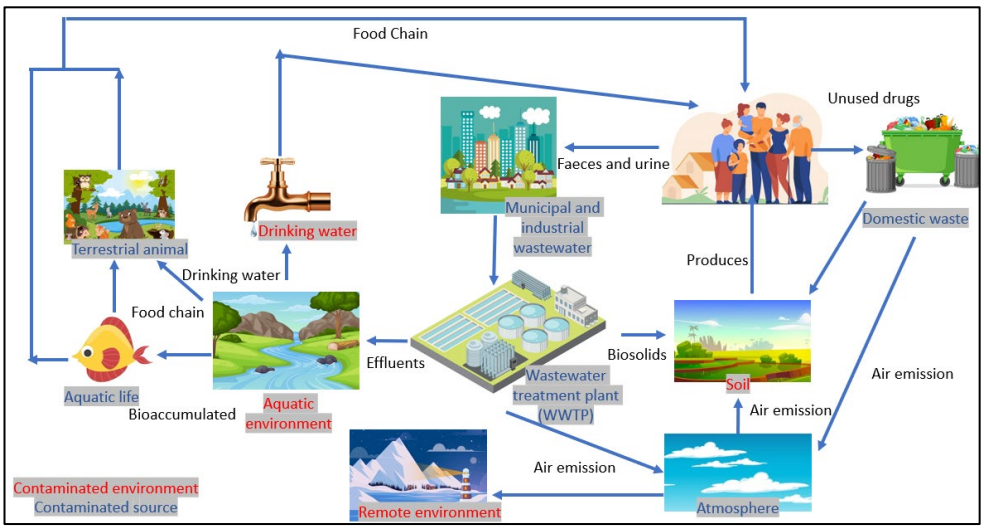


Figure 1. Sources, occurrences and potential pathways of PPCP

and ciprofloxacin, were reported between 2019 and 2021, coinciding with heightened clinical usage during the COVID-19 pandemic (Faleye et al., 2019; Saxena et al., 2021). Similarly, temporal monitoring within a WWTP–river–estuary system in Wuhan, China, revealed higher overall PPCP detection frequencies and concentrations relative to historical baseline records (Chen et al., 2021).

Figure 1 illustrates the environmental transport pathways and fate of PPCPs across air, water, and terrestrial compartments. PPCPs enter receiving aquatic bodies through discharged municipal effluents containing domestic wastewater, industrial flows, and excreted human waste. Due to incomplete removal during treatment, these micropollutants are continuously discharged into receiving surface waters. Once released, hydrophobic or poorly biodegradable compounds may be absorbed by aquatic organisms via dermal uptake and food-web transfer, resulting in bioaccumulation due to high octanol–water partition coefficients (Kow) (Kosma et al., 2010; Chen et al., 2021; Hawash et al., 2023).

Sewage sludge generated during treatment accumulates sorbed compounds with high solid–water distribution coefficients (Kd), such as triclosan and triclocarban (Sun et al., 2016). When these biosolids are applied as land fertilizers, residual PPCPs transfer to agricultural soils, where they can be absorbed by crops through root uptake and foliar deposition (Bartrons & Peñuelas, 2017). To a lesser extent, semi-volatile PPCPs enter the atmosphere via volatilization from surface waters or gaseous emissions during biosolid and spent activated carbon incineration (Wilkinson et al., 2017). Through these combined vectors, human populations face chronic exposure through drinking water consumption, agricultural produce, and bioaccumulated aquatic food chains.

3.3 Toxicity of PPCPs to aquatic organisms

Table 3 compiles reported median lethal concentration (LC50) values reflecting the acute toxicity of selected PPCPs toward diverse aquatic species. Assessing these ecotoxicological endpoints is essential, as treated municipal effluents are routinely discharged into surface water bodies, making aquatic biota the primary receptor for residual micropollutants. For most target compounds, acute LC50 values generally exceed 1 × 102 µg/L; these benchmark values are derived from standardized freshwater bioassays under laboratory conditions where background matrix interference is minimal. Because environmental PPCP levels in receiving rivers are substantially diluted relative to laboratory test dosages, observed acute lethal thresholds are considerably higher than typical WWTP effluent concentrations, indicating low risks of immediate mass mortality upon discharge. Yet, ambient environmental occurrence at low concentrations (ng/L to µg/L) does not imply ecological safety. Chronic exposure to trace PPCP levels presents substantial long-term hazards due to their high bioaccumulation potential, resistance to environmental degradation, and subtle sublethal toxicities (Isidori et al., 2007; Schnell et al., 2009; Fernández et al., 2013; Martinez Gomez et al., 2015). Prolonged exposure can induce developmental abnormalities, reproductive impairment, behavioral alterations, genotoxicity, and endocrine disruption in non-target organisms. Aside from individual compound toxicities, accurately evaluating the true ecotoxicological footprint of PPCPs in natural ecosystems remains methodologically challenging. In real-world receiving waters, aquatic organisms are exposed to dynamic, multi-component mixtures where synergistic or additive toxicities occur alongside fluctuating environmental parameters such as pH, dissolved organic matter, and ionic strength.

4. REMOVAL OF PPCPs VIA ADSORPTION

4.1 Removal per PPCP category

Converting organic waste fractions into functional adsorbents offers a sustainable waste-to-resource approach that minimizes land disposal, reduces solid waste management costs, and mitigates soil contamination. Table 4 summarizes reported experimental conditions and adsorption performances for target PPCPs across diverse WD-AC materials. Among the 16 evaluated studies, only two conducted testing in real wastewater matrices: Viegas et al. (2020) evaluated pulp processing effluent, whereas Montoya-Bautista et al. (2022) utilized secondary effluent from a municipal WWTP containing competing background organic matter. The remaining 14 studies relied on synthetic or s single-solute matrices. Compounding this limitation, batch experiments were routinely spike at the milligram per liter (mg/L) concentrations, which is orders of magnitude above environmentally relevant levels (ng/L to µg/L), yielding residual concentrations that reflect bench-scale convenience rather than real-world applicability.

Nonsteroidal anti-inflammatory drugs (NSAIDs):
Ibuprofen removal has been investigated using WD-ACs derived from industrial cork, plastic waste, sewage sludge, and agricultural residues (e.g., orange peels and cherry kernels). As summarized in Table 4, plastic-derived WD-AC exhibited the highest ibuprofen adsorption capacity, whereas cherry-kernel AC demonstrated the lowest uptake. Naproxen removal has been evaluated using sewage sludge and cherry-kernel precursors. Sludge-based activated carbon (SBAC) synthesized from thickened biosolids achieved 98% naproxen removal in real municipal wastewater effluent (Montoya-Bautista et al., 2022). In comparison, cherry-kernel AC yielded a maximum naproxen adsorption capacity of approximately 21.5 mg/g. Direct performance comparisons between these two materials remain constrained by significant disparities in initial compound concentrations and background matrices. Diclofenac uptake has been studied using ACs converted from tea waste, carob processing residues and agricultural byproducts. Assessing comparative removal efficiencies across different WD-ACs remains challenging due to varying experimental conditions; across evaluated materials, tea-waste AC generally exhibits lower diclofenac adsorption capacity than potato-peel AC under comparable initial solute loads.

Table 3 Acute Toxicity of studied pharmaceuticals and personal care product (PPCPs) to aquatic organisms.

Compound	Aquatic organism	LC_{50} (μg/L)	Exposure period (h)	Notes	Reference
NSAIDs					
Ibuprofen	Mrigal Carp	1.42×10^5	24		(Eissa et al., 2014; Saravanan et al., 2012)
	Brine shrimp	3.74×10^5	24		(Diaz-Sosa et al., 2020; Rajabi et al., 2015)
Naproxen	Zebrafish	1.48×10^5	96	Based on larvae	(Li et al., 2016)
	Brine shrimp	$>1 \times 10^5$	48		(Diaz-Sosa et al., 2020; Minguez et al., 2016)
Diclofenac	Zebrafish	1.42×10^4	48		(Vorgelegt von, 2019)
	D. Magna	8.23×10^5	24		(Du et al., 2016)
Antibiotics					
Sulfamethoxazole	Japanese rice fish	5.63×10^5	96		(Kim et al., 2007)
	Zebrafish	$>1 \times 10^6$	96		(Isidori et al., 2005)
Ciprofloxacin	Pond loach	1.69×10^5	24	Ciprofloxacin hydrochloride form	(Wang et al., 2025)
Cardiovascular and Metabolic					
Furosemide	Brine shrimp	2.73×10^5	24	Highest reported LC_{50} assumed to correspond to 24 h	(Diaz-Sosa et al., 2020)
Gemfibrozil	Zebra fish	2.3×10^4	24		(Henriques et al., 2016)
Glyburide		N/A			
Warfarin	Rainbow trout	6.5×10^4	24		(ECHA, 2016; Regnery et al., 2019)
Hydrochlorothiazide	Brine shrimp	1.56×10^6	24	Room temperature	(Diaz-Sosa et al., 2020)

Stimulant					
Caffeine	Freshwater rotifer (*Plationus patulus*)	4.19×10^5		Of the two populations tested, Rio Grande was reported here.	(Martinez Gomez et al., 2015)
	Freshwater cyclopoid copepod	5.28×10^6	96		(Lorenzo et al., 2019)
Personal Care Products and additives					
Bisphenol A	Fathead minnow (*Pimephales promelas)*	4.7×10^3	96	Flow-through test Cytotoxic effects of mixtures were observed	(Alexander et al., 1988)
Triclosan	Fathead minnow /	3.6×10^2	24	N/A	(Orvos et al., 2002)
	Freshwater rotifer (*Plationus patulus*)	3.2×10^2	48	Of the two populations tested, Rio Grande was reported here	(Martinez Gomez et al., 2015)
Triclocarban	Rainbow trout	1×10^2	96		(ACI, 2002; Villeneuve et al., 2017)

N/A: Not available

Table 4 Adsorption of pharmaceuticals and personal care products (PPCPs) using activated materials: summary of experimental conditions and performance.

Compound	Raw material	Activation procedure	Pyrolysis conditions	Solution matrix	Initial conc. (mg/L)	Post-treatment conc. (mg/L)	Batch test conditions	q_{max} (mg/g)	Reference
NSAIDs									
Ibuprofen	Polyethylene terephthalate (PET) plastic waste	Physical activation (CO_2, 10 mL/min to 38% burn-off	Calcined at 925°C (N_2, 1 h)	Synthetic (10% methanol and Milli-Q water).	60	0.5	T = 30°C; pH 4; 700 rpm; 4 h; Adsorbent ratio: 0.67 g/L	267	(Mestre et al., 2009)
Ibuprofen	Cork waste	Chemical activation (K_2CO_3, 1:1 w/w)	Calcined at 700°C (N_2, 1 h, 10°C/min); 88% burn-off	Synthetic (10% methanol and Milli-Q water).	60	15.1	T = 30°C; pH 4; 700 rpm; 4 h; Adsorbent ratio: 0.67 g/L	145	(Mestre et al., 2009)
Ibuprofen	WWTP: biosolid (Bio-SBAC) / thickened waste sewer sludge (TWSS-SBAC)	Chemical activation with $ZnCl_2$	Calcined at 500 °C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent, pH 7.7 (S1: TSS 13; COD 68; cBOD 11; NH_3-N 30.7 mg/L. S2: TSS 4000; COD 53; cBOD 4 mg/L	3.9×10^{-4}/3.8×10^{-4}	8.2×10^{-6} (Bio) 10.5×10^{-6} (TWSS)	T = 20 C ± 2 °C; 100 rpm; 0.5 h; Bio- (1 g/L and 10 g/L), TWSS-SBAC (1 g/L)	NA	(Montoya-Bautista et al., 2022)
Ibuprofen	Orange peels	Chemical activation (H_3PO_4 or KOH)	Calcined at 450 or 650°C (N_2, 1 h, 10°/min)	Synthetic wastewater	10	2.1	T = 25 °C; pH 2; 150 rpm; 6 h; Adsorbent ratio: NA	66	(Phasuphan et al., 2019) (Malesic-Eleftheriadou et al., 2022)

Ibuprofen	Cherry kernels	Chemical activation (50 wt% H_3PO_4) + acid functionalisation	Preheated at 180°C (45 min); calcined at 500°C (1 h, 10°/min)	Synthetic wastewater	10	~1.0 (Note 2)	T = 22 °C; pH 6; 140 rpm; 5 h; 2 g/L	21–22	(Pap et al., 2021)
Naproxen	Bio-SBAC / TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500 °C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent, pH 7.7 (S1: TSS 13; COD 68; cBOD 11; NH_3-N 30.7 mg/L. S2: TSS 4000; COD 53; cBOD 4 mg/L	5.0×10^{-6} / 4.0×10^{-6}	4.7×10^{-6} (Bio-)/ 3.7×10^{-6} (TWSS-SBAC)	T = 20 °C ± 2 °C; pH 7.7; 100 rpm; 0.5 h; Bio-SBAC (1 g/L and 10 g/L), TWSS-SBAC (1 g/L)	NA	(Montoya-Bautista et al., 2022)
Naproxen	Cherry kernels	Chemical activation (50 wt% H_3PO_4 + acid functionalisation	Preheated at 180°C (45 min); calcined at 500°C (1 h, 10°/min)	Synthetic wastewater	10	~0.1 (Note 2)	T = 22 °C; pH 6; 140 rpm; 5 h; Adorbent ratio: 2 g/L	21–22	(Pap et al., 2021)
Diclofenac (Sodium diclofenac)	Tea waste (TW)	Impregnation (1:1 w/w with $ZnCl_2$ (AC1), K_2CO_3 (AC2), KOH (AC3) and H_2SO_4 (AC4) overnight (28°C), then heated at 103°C for 24 h	Calcined at 600 °C (2 h); washed with 2 M HCl and DI water until pH of 6–7	Synthetic wastewater (pH 6.47.)	30	~10.8 (AC1) ~14.1 (AC2) ~14.7 (AC3) No data for AC4	T = 30 °C; pH: NA; Stirring: 50–200 rpm; Contact: 8 h; Adsorbent ratio: 0.1–0.3 g/L	62 (AC1) 52 (AC2) 49 (AC3) NA (AC4)	(Malhotra et al., 2018)
Diclofenac (Sodium diclofenac)	Potato-peel waste (PPW)	Chemical activation (K_2CO_3, 1:1 w/w) mixing for 2 h and drying at 100°C for 24 h	Calcined at 700°C (N_2, 1 h, 10°C/min); kept for 1 h under 150 cm^3/min N_2 flow. Washed with DI water up to pH 7. Dried at 100°C overnight	Synthetic wastewater (10 mg of adsorbent mixed with 25 L of DCF solution)	50	15	T = 20 °C ± 2 °C; pH 5; Stirring: 100 rpm; Contact: 24 h; Adsorbent ratio: 0.4 g/L	68.5 (occurred at ~ 25×10^3–60×10^3 µg/L initial conc.)	(Bernardo et al., 2016)

Diclofenac (Sodium diclofenac)	Carob processing waste (Solid recovered from the acid effluent.)	Steam activation generated at 90°C in a glass bubbler with DI water under N_2 flow of 5 cm^3/s	Calcined at 900°C (N_2, 1 h, 10°C/min).	Real wastewater effluent	1.5 x 10^{-3}	~8.1 x 10^{-4} (Calculated from predicted removal efficiency)	T = 23 °C; pH 7.3; 150 rpm; 1 h; Adsorbent ratio: 0.005–0.02 g/L	3.7	(Viegas et al., 2020)
Diclofenac	Orange peels	Chemical activation with H_3PO_4 or KOH	Calcined 450 or 650°C (N_2, 1 h at 10°C/min)	Synthetic wastewater	10	0.1	T = 25 °C; pH 2; 150 rpm; 6 h; Adsorbent ratio: NA	86	(Malesic-Eleftheriadou et al., 2022)
Diclofenac	Cherry kernels	Chemical activation (50 wt% H_3PO_4) + acid functionalisation	Preheated at 180°C (10°C/min, 45 min); calcined at 500°C (10°C/min, 1 h)	Synthetic wastewater	10	~0.5 (Note 2)	T = 22 °C; pH 6; 140 rpm; 5 h; Adsorbent ratio: 2 g/L	21–22	(Pap et al., 2021)
Antibiotics									
Sulfamethoxazole	Sugarcane bagasse	Chemical activation (5% w/v $ZnCl_2$, 24 h) at room temperature, followed by drying at 90°C for 2 h	Calcined at 600°C (N_2, 1 h); washed with 0.1 mol HCl and hot water, dried at 60°C for 24 h	Synthetic wastewater	100	32.7	T = 35 °C; pH 5–6; 150 rpm; 24 h; Adsorbent ratio: 0.4 g/L	294.1 (Note 1)	(Hu et al., 2022)
Sulfamethoxazole	Walnut shell	Two-stage pyrolysis; no chemical and chemical activation (K_2CO_3, 1:1 w/w)	Pyrolysis 1: 300°C (N_2, 1 h) Pyrolysis 2: After chemical activation, calcined at 690°C (1 h 10°C/min, N_2 (200 mL/min)); washed, dried at 105°C and sieved	Synthetic wastewater	40	NA	T = 30 °C; pH 5.5; 48 h	106.9	(Teixeira et al., 2019)
Sulfamethoxazole	Sawdust	Direct single-stage pyrolysis	Calcined at 500°C (4 h, 10°C/min)	Synthetic wastewater	10	0.08	T = 25 °C; pH 7; 250 rpm; 3 h; Adsorbent ratio: 5 g/L	2.6	(Silori et al., 2023)

Sulfamethoxazole	Sawdust and plastic waste (4:6 w/w)	Direct single-stage co-pyrolysis	Calcined at 500°C (4 h, 10°C/min)	Synthetic wastewater	10	6.5	T = 25 °C; pH 7; 250 rpm; 3 h; Adsorbent ratio: 5 g/L	0.9	(Silori et al., 2023)
Ciprofloxacin	Municipal solid waste (MSW)	Clay-amended (bentonite clay); ice-water bath thermal quenching	Calcined at 450°C (30 min, 15°C/min) in a muffle furnace	Synthetic wastewater	25	NA	T = 25 °C; pH 7–8; 150 rpm; 12 h; Adsorbent ratio: 1 g/L	286.6	(Ashiq et al., 2019)
Ciprofloxacin	MSW	Chemical activation ($ZnCl_2$)	Calcined at 600°C (2 h, 5°C/min) washed with HCl/ethanol and ultra-pure water	Synthetic wastewater	20	2.0	T = 25 °C; pH 6; 500 rpm; 25 h; Adsorbent ratio: 0.5 g/L	74.2	(Ma et al., 2021)
Ciprofloxacin	Shrimp waste	Chemical activation with KOH (1:3 w/w, > 88.2%), dried (80°C, 12 h), washed with HCl, acetone and DI H_2O to neural pH	Calcined at 400°C (2 h), after chemical activated, then 850°C (N_2, 1 h)	Real wastewater effluent	0.2	6×10^{-3}	T = 25 °C; pH 7; 150 rpm; 2 h; Adsorbent ratio: 0.07 g/L	442	(Salawu et al., 2022)
Ciprofloxacin	Sawdust	Direct single-stage pyrolysis	Wastes were air-dried, ground and sieved. The resulting material was heated to 500°C (10°C/min) for 4 h	Synthetic wastewater using 200 mg/L of stock solution	10	0.46	T = 25 °C; pH 7; 250 rpm; 3 h; Adsorbent ratio: 5 g/L	4.5	(Silori et al., 2023)
Ciprofloxacin	Sawdust and plastic waste (4:6 w/w)	Direct single-stage co-pyrolysis	Wastes were air-dried, ground and sieved. The resulting material was heated to 500°C (10°C/min) and held for 4 h	Synthetic wastewater using 200 mg/L of stock solution	10	4.1	T = 25 °C; pH 7; 250 rpm; 3 h; Adsorbent ratio: 5 g/L	4	(Silori et al., 2023)

Cardiovascular & Metabolic									
Furosemide	Bio-SBAC/ TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	4.3×10^{-4} / 2.4×10^{-4}	BRL	T = 20 °C ± 2 °C; pH 7.7; 100 rpm; 0.5 h; Adsorbent: Bio- (1 g/L and 10 g/L), TWSS-SBAC (1 g/L)	NA	(Montoya-Bautista et al., 2022)
Gemfibrozil	Bio-SBAC/ TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	2.7×10^{-5} /2.8×10^{-5}	BRL		NA	(Montoya-Bautista et al., 2022)
Glyburide	Bio-SBAC/ TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	5.0×10^{-6} /8.99×10^{-6}	BRL		NA	(Montoya-Bautista et al., 2022)
Hydro-chlorothiazide	Bio-SBAC/ TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	6.2×10^{-4} /7.7×10^{-4}	BRL (Bio)/1.29×10^{-8} (TWSS)		NA	(Montoya-Bautista et al., 2022)
Warfarin	Bio-SBAC/ TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	2.0×10^{-6} /1.5×10^{-6}	BRL		NA	(Montoya-Bautista et al., 2022)
Stimulant									
Caffeine	Ground coffee waste (CW)	Chemical activation (CW:KOH ratios 1:0, 2:1, 1:1, 2:3)	Calcined at 600°C, 700°C and 800°C (N_2), tubular furnace	Synthetic wastewater	25	2.4	T = 20 °C ± 2 °C; Adsorbent ratio: 0.1–1 g/L	274.2 (ratio 1:1 using 800 °C)	(Mengesha et al., 2022)

Caffeine	Rice husk/ Peanut shell/ Corn cob/ Coconut fibre	Direct pyrolysis	Unspecified thermal treatment	Synthetic wastewater (continuous flow)	30	NA as this was a continuous column experiment	Flow : 0.5, 1.0, 1.5 mL/min; Bed: 10, 15, 20 cm; Influent: 5, 10, 15 mg/L	0.6-4.4	(Tejedor et al., 2023)
Personal care products and Additives									
Bisphenol A	Bio-SBAC / TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	5.1×10^{-4} / 2.8×10^{-4}	BRL	T = 20 °C ± 2 °C; pH 7.7; 100 rpm; 0.5 h; Adsorbent ratio: Bio- (1 g/L and 10 g/L), TWSS-SBAC (1 g/L)	NA	(Montoya-Bautista et al., 2022)
Triclosan	Bio-SBAC / TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	4.5×10^{-5} / 4.1×10^{-5}	BRL	T = 20 °C ± 2 °C; pH 7.7; 100 rpm; 0.5 h; Adsorbent ratio: Bio- (1 g/L and 10 g/L), TWSS-SBAC (1 g/L)	NA	(Montoya-Bautista et al., 2022)
Triclocarban	Bio-SBAC / TWSS-SBAC	Chemical activation ($ZnCl_2$)	Calcined at 500°C (N_2, 2 h, 10°C/min)	Secondary WWTP effluent (S1/S2 matrices)	5.0×10^{-6} /4.0×10^{-6}	BRL	T = 20 °C ± 2 °C; pH 7.7; 100 rpm; 0.5 h; Adsorbent ratio: Bio- (1 g/L and 10 g/L), TWSS-SBAC (1 g/L)	NA	(Montoya-Bautista et al., 2022)

q_{max}, maximum adsorption capacity; NA, not available; BRL, below reported limit; cBOD: carbonaceous biochemical oxygen demand; COD: chemical oxygen demand; TSS: total suspended solids; TWSS: thickened waste sewer sludge; SBAC: sludge-based activated carbon

Note 1: Calculated using values from the Langmuir isotherm model and experimental conditions reported in the primary study.

Note 2: Removal efficiency was evaluated at spiked concentration in real wastewater, but the initial and residual concentrations were omitted. Therefore, the removal efficiency data from 10 µg/L spiked concentration were used for the remaining concentration calculation using the initial concentration in synthetic wastewater.

Antibiotics: Sulfamethoxazole adsorption has been evaluated using ACs derived from agricultural residues (including sugarcane bagasse and walnut shells), sawdust, and sawdust–plastic blends. Among these materials, sugarcane bagasse AC achieved a maximum adsorption capacity of 294 mg/g. Ciprofloxacin removal has been examined using WD-ACs synthesized from municipal solid waste, shrimp processing waste, sawdust, and sawdust–plastic mixtures. Shrimp-waste AC exhibited the highest ciprofloxacin uptake capacity at 442 mg/g, outperforming other WD-AC formulations evaluated for fluoroquinolones.

Stimulants: Caffeine removal using waste-derived activated carbons (WD-ACs) has been evaluated in both batch and continuous-flow systems using spent ground coffee waste (CW) and various agricultural residues, such as rice husks, peanut shells, corncobs, and coconut fibers (Mengesha et al., 2022; Tejedor et al., 2023). In these bench-scale evaluations, adsorbents were tested in synthetic water matrices containing initial caffeine concentrations of 25–30 mg/L. Ground coffee-waste AC exhibited a maximum adsorption capacity of 274.2 mg/g, drastically outperforming other tested agricultural waste materials, which yielded capacities of ≤4.4 mg/g. The superior performance of coffee-waste AC can be attributed to extended contact times during adsorption testing alongside tailored activation conditions. Thermal activation and pyrolysis parameters were omitted for several agricultural WD-ACs, likely accounting for their lower observed uptake capacities. To evaluate operational feasibility for scale-up, future research must prioritize systematic evaluations of percentage removal efficiencies in continuous-flow reactors.

Cardiovascular regulators, metabolic drugs, and personal care products: Relatively few studies have investigated the adsorptive removal of cardiovascular and metabolic regulators using WD-AC materials. For example, Montoya-Bautista et al. (2022) evaluated sludge-based activated carbon (SBAC) for the simultaneous removal of diverse active compounds, including gemfibrozil, glyburide, warfarin, furosemide, hydrochlorothiazide, bisphenol A, triclosan, and triclocarban. Removal efficiencies exceeded 90% in secondary municipal wastewater effluent across initial adsorbent loadings of 1 g/L and 10 g/L; fundamental adsorption mechanisms, uptake kinetics, and equilibrium isotherms were not determined. According to the World Health Organization, an estimated 1.28 billion adults aged 30–79 years live with hypertension globally (WHO, 2023). Given the ubiquitous long-term prescription of cardiovascular and metabolic pharmaceuticals, these active compounds will remain persistent in municipal wastewater streams. Global consumption of personal care additives, such as antimicrobial agents in hand sanitizers and soaps, continues to rise due to heightened public hygiene practices. Considering these high mass-flux discharge rates, systematic mechanistic research into WD-AC performance for trapping cardiovascular drugs, metabolic regulators, and personal care products is essential.

4.2 Factors influencing PPCP removal

The adsorptive uptake of individual PPCPs onto waste-derived activated carbons (WD-ACs) is governed by key operational parameters, including adsorbent surface characteristics, wastewater matrix composition (e.g., pH, dissolved organic matter, and initial pollutant concentrations), system temperature, and contact time. Among these, solution pH and system temperature are widely evaluated across bench-scale studies. In most systems, the optimal pH for adsorption is dictated by the acid dissociation constant (pK_a) of the target compound, which dictates its ionic speciation, alongside the point of zero charge (pHPZC) of the WD-AC, which governs surface charge density. For example, ibuprofen removal efficiency declines when solution pH exceeds the pHPZC of the carbon material; under these conditions, the drug shifts toward its anionic form, exhibiting higher water solubility and experiencing electrostatic repulsion from the negatively charged carbon surface (Mestre et al., 2009; Pap et al., 2021; Malesic-Eleftheriadou et al., 2022). Similar pH-dependent speciation trends and electrostatic inhibition occur for naproxen, diclofenac, sulfamethoxazole, and ciprofloxacin.

On the other hand, caffeine removal remains largely insensitive to wastewater pH, indicating that its binding mechanism is predominantly mediated by non-electrostatic interactions, such as hydrophobic forces and n–π electron donor-acceptor interactions (Mengesha et al., 2022). System temperature also plays a critical role: adsorption capacity and overall removal efficiency for ibuprofen, naproxen, diclofenac, and sulfamethoxazole increase at elevated temperatures, confirming an endothermic uptake process (Teixeira et al., 2019; Pap et al., 2021; Hu et al., 2022; Malesic-Eleftheriadou et al., 2022).

4.3 Adsorption mechanisms

The capture of PPCPs onto waste-derived activated carbons (WD-ACs) proceeds through two primary pathways: physical adsorption and chemical adsorption (Rajapaksha et al., 2019). Physical adsorption is predominantly driven by pore filling within micro- and mesoporous networks, whereas chemical adsorption is mediated by specific surface forces, including π–π stacking, n–π electron donor-acceptor interactions, electrostatic forces, hydrophobic partitioning, and hydrogen bonding.

Figure 2 illustrates these representative interaction pathways. Under real-world wastewater conditions, a single PPCP molecule frequently undergoes simultaneously uptake via multiple synergistic mechanisms. Table 5 summarizes the specific adsorption mechanisms reported for ibuprofen, naproxen, diclofenac, sulfamethoxazole, ciprofloxacin, and caffeine onto diverse WD-AC materials. Target compounds lacking verified empirical mechanistic evaluations in the reviewed literature were excluded from Table 5. Across all three evaluated NSAIDs, uptake involves all five fundamental mechanisms illustrated in Figure 2 (Bernardo et

al., 2016; Chakraborty et al., 2018; Avcu et al., 2021; Pap et al., 2021).

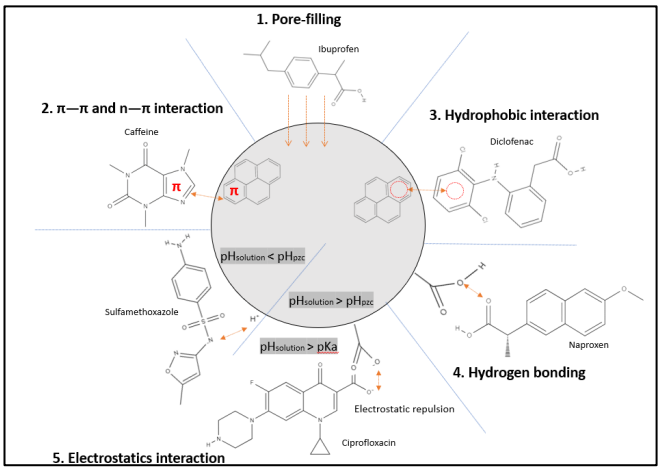


Figure 2. Proposed adsorption mechanisms of selected PPCPs onto WD-AC.

Target micropollutants can occupy both external surface sites and internal pore networks of WD-ACs, with larger molecular dimensions can restrict access to narrower micropores via steric exclusion. Among the investigated NSAIDs, diclofenac features a smaller molecular width (0.7–0.9 nm) compared to ibuprofen (0.6–1.1 nm) and naproxen (0.8–1.2 nm), directly influencing its intraparticle diffusion rate and pore-filling capacity (Pap et al., 2021). Pore diffusion similarly plays a governing role in caffeine capture, as evidenced by notable reductions in total pore volume following adsorption (Tejedor et al., 2023).

Chemical interactions further dictate binding strength and selectivity across target compounds. Dispersive π–π interactions occur between the aromatic rings of PPCP solutes and the graphitic basal planes of the carbon matrix. At the same time, n–π donor-acceptor interactions alongside secondary binding mechanisms (Avcu et al., 2021; Pap et al., 2021; Hu et al., 2022; Mengesha et al., 2022; Silori et al., 2023; Tejedor et al., 2023). Hydrophobic interactions between non-polar molecular domains and hydrophobic carbon surfaces also drive pollutants out of the aqueous phase, contributing substantially to NSAID adsorption (Mondal et al., 2016; Pap et al., 2021). Hydrogen bonding further stabilizes the adsorbed state via dipole-dipole attractions between electronegative heteroatoms (or surface functional groups) and polar hydrogen atoms; excluding caffeine, all target compounds in Table 5 participate in hydrogen bonding (Mondal et al., 2016; Pap et al., 2021; Hu et al., 2022; Silori et al., 2023). Electrostatic forces are governed by the interplay between solution pH, solute pKa, and the point of zero charge (pHPZC) of the carbon. When solution pH exceeds both compound pKa and adsorbent pHPZC, both the PPCP solute and carbon surface carry net negative charges, generating electrostatic repulsion that suppresses overall uptake (Mestre et al., 2009; Bernardo et al., 2016; Mondal et al., 2016; Avcu et al., 2021; Pap et al., 2021; Hu et al., 2022; Silori et al., 2023).

4.4 Critical insights

Methodological limitations in current adsorption research

Precursor Blending and Co-pyrolysis Limitations: Studies evaluating waste-derived activated carbons (WD-ACs) for PPCP removal have predominantly focused on optimizing pyrolysis conditions, activation mechanisms, or surface chemical modifications. Limited research has investigated co-pyrolysis or the strategic blending of precursor materials prior to thermal conversion (Mestre et al., 2009; Silori et al., 2023; Tejedor et al., 2023). From an industrial operational perspective, evaluating multi-precursor blends is essential. Single-feedstock sourcing (such as reliance on orange peels, spent coffee grounds, or tea waste) exposes production facilities to supply chain vulnerabilities, seasonal availability fluctuations, and localized sourcing bottlenecks (Malesic-Eleftheriadou et al., 2018; Malhotra et al., 2018; Phasuphan et al., 2019). Co-pyrolysis of precursor blends enhances feedstock flexibility, mitigating supply risks and stabilizing full-scale WD-AC manufacturing economics

Synthetic Matrices and Environmentally Irrelevant Concentrations: A ubiquitous methodological drawback across the reviewed literature is the reliance on synthetic water matrices prepared in deionized or ultrapure water (Mestre et al., 2009; Bernardo et al., 2016; Pap et al., 2018; Ashiq et al., 2019; Phasuphan et al., 2019; Teixeira et al., 2019; Hu et al., 2022). Among the 16 evaluated studies, only two conducted testing in real wastewater matrices: Viegas et al. (2020) evaluated pulp processing effluent, whereas Montoya-Bautista et al. (2022) utilized secondary effluent from a municipal WWTP containing competing background organic matter. The remaining 14 studies relied exclusively on synthetic or single-solute matrices. Compounding this limitation, batch experiments were routinely spiked at milligram per liter (mg/L) levels, which is orders of magnitude above environmentally relevant concentrations (ng/L to µg/L), yielding performance metrics that reflect bench-scale convenience rather than field applicability. Even when real wastewater matrices were employed, target micropollutants were frequently spiked at artificially elevated levels (e.g., Phasuphan et al., 2019), distorting mass-transfer driving forces and competitive sorption dynamics.

Adsorption in Municipal Wastewater Matrices: A small subset of studies evaluated PPCP adsorption within real municipal matrices, offering valuable empirical benchmarks for process design. Research utilizing secondary treated effluent (Pap et al., 2021; Montoya-Bautista et al., 2022; Salawu et al., 2022) aligns directly with tertiary treatment polishing steps where activated carbon unit operations are

typically installed. In a distinct operational approach, Viegas et al. (2020) conducted adsorption testing within mixed liquor collected directly from an activated sludge bioreactor. Assessing adsorbent performance in mixed liquor provide essential kinetic and capacity data for direct powdered activated carbon dosing into biological basins, a hybrid process configuration receiving increased engineering consideration.

Table 5 Possible adsorption mechanisms of selected PPCPs onto waste-derived activated carbon.

PPCP	Pore filling	π–π/n–π bond	Hydrophobic interaction	Hydrogen bonding	Electrostatic interaction	Reference
Ibuprofen	✓[1]	✓[1][2][7]	✓[1][2]	✓[1][2]	✓[1][2][7]	[1](Pap et al., 2021) [2](Mondal et al., 2016) [7](Mestre et al., 2009)
Naproxen	✓[1]	✓[1]	✓[1]	✓[1]	✓[1]	[1](Pap et al., 2021)
Diclofenac	✓[1]	✓[1][5][6]	✓[1][5]	✓[1]	✓[1][5][6]	[1](Pap et al., 2021) [5](Avcu et al., 2021) [6](Bernardo et al., 2016)
Sulfamethoxazole		✓[8][9][10]		✓[8][9]	✓[8][9]	[8](Hu et al., 2022) [9](Silori et al., 2023) [10] (Ma et al., 2021)
Ciprofloxacin		✓[9][10]		✓[9]	✓[9]	[9](Silori et al., 2023) [10](Ma et al., 2021)
Caffeine	✓[3][4]	✓[3][4]				[3](Mengesha et al., 2022) [4](Tejedor et al., 2023)

Theoretical knowledge and speciation dynamics

Numerous studies have evaluated the macro-level effects of temperature and pH on adsorption capacity (Mestre et al., 2009; Teixeira et al., 2019; Malesic-Eleftheriadou et al., 2022). Fundamental understanding regarding PPCP speciation within multi-component wastewater matrices remains limited. Accurate prediction of contaminant removal requires a detailed accounting of both solution pH and ionic strength, as both parameters govern the chemical speciation of ionizable PPCPs. Among the literature summarized in Table 4, few studies comprehensively examined speciation and its mechanistic impacts. For instance, Ma et al. (2021) examined the pH-dependent speciation of ciprofloxacin and tetracycline, whereas Mengesha et al. (2022) investigated the speciation of caffeine and its corresponding impacts on adsorption behavior.

Because distinct ionic species of a single compound possess different net electrical charges, shifts in speciation directly alter electrostatic attraction or repulsion toward the adsorbent surface, alongside cross-interactions with co-occurring

matrix constituents. Apart from these electrostatic forces, the precise pathways through which speciation affects non-electrostatic adsorption mechanisms (such as hydrophobic partitioning, n–π electron donor–acceptor interactions, and hydrogen bonding) remain insufficiently defined. Future fundamental research must systematically isolate these non-electrostatic pathways to build robust predictive models describing how changes in PPCP speciation dictate the individual contribution of each mechanism across complex wastewater chemistries.

Full-scale implementation and practical feasibility

Bench-scale studies summarized in Table 4 highlight the promise of waste-derived activated carbon adsorption for PPCP removal; translating these laboratory findings into full-scale operations presents severe engineering and economic challenges. First, localized precursor availability and long-term supply chain security, particularly for seasonal agricultural biomass, are rarely evaluated within regional operational contexts (Tejedor et al., 2023). Scaling up energy-intensive thermal pyrolysis and chemical activation processes presents additional technological barriers in resource-constrained communities, which often lack the capital investment, specialized technical expertise, and energy infrastructure required to construct, operate, and maintain advanced carbon manufacturing facilities.

Economic viability and adsorbent reusability represent further critical considerations for full-scale deployment. Select studies estimated initial production costs (Phasuphan et al., 2019; Pap et al., 2021) or explored spent media regeneration (Mengesha et al., 2022), but thorough assessments of regeneration economics are still rare, despite their central role in overall lifecycle expenditure (Malhotra et al., 2018). Alternative implementation configurations, such as the direct dosing of powdered activated carbon (PAC) into activated sludge bioreactors proposed by Viegas et al. (2020), offer promising operational integration options. This hybrid strategy requires extensive validation across varying solids retention times and sludge handling conditions prior to widespread adoption.

A major physical constraint insufficiently captured in bench-scale testing is long-term media fouling and pore clogging caused by background natural organic matter (NOM) (de Ridder et al., 2011). Pore blockage by NOM severely diminishes available surface adsorption sites and accessible pore volume, with the severity of fouling heavily dictated by the specific wastewater matrix in contact with the media (e.g., direct exposure to mixed liquor versus polished secondary effluent). In operational practice, bench-scale studies evaluated adsorption performance across broad pH ranges spanning 2 to 12 (Mestre et al., 2009; Phasuphan et al., 2019; Mengesha et al., 2022); optimal removal efficiencies were frequently reported at pH levels significantly outside typical municipal wastewater conditions (pH 6.5–8.5). In full-scale operations, the chemical consumption and operational expenditures associated with continuous pH adjustment often outweigh marginal gains in adsorption capacity. This highlights the practical necessity of prioritizing adsorbents that demonstrate high removal performance at ambient, unadjusted wastewater pH.

4.5 Direction for future research

Addressing the methodological, theoretical, and practical gaps identified across current adsorption literature requires pivoting from isolated bench-scale optimization toward real-world deployment. Future investigations should prioritize four core operational domains to advance waste-derived activated carbon technologies for scalable micropollutant control.

Precursor co-pyrolysis and feedstock supply chain modeling

Future studies should systematically explore the co-pyrolysis and chemical activation of precursor blends rather than relying exclusively on single feedstocks. Research must characterize how varying blending ratios of abundant agricultural, municipal, and industrial solid wastes influence the pore architecture, surface functionalization, and mechanical durability of the resulting carbons. To ensure commercial scalability, regional techno-economic and supply chain analyses are needed to evaluate the seasonal availability and transport logistics of biomass precursors, ensuring proposed adsorbents remain reliable and economically viable at industrial scales.

Standardizing testing in real wastewater matrices at environmentally relevant concentrations

To resolve performance overestimations driven by ultrapure water testing, experimental protocols must prioritize real wastewater streams, such as secondary treated effluent and biological mixed liquor. Research should specifically evaluate PPCP removal at environmentally realistic trace concentrations (ranging from ng/L to µg/L) rather than artificially elevated milligram-per-liter spiked dosages. Long-term continuous-flow column studies and pilot-scale trials are essential to establish realistic mass-transfer kinetics, breakthrough behavior, and competitive sorption dynamics between target PPCPs and background dissolved organic matter (DOM).

Mechanistic elucidation of speciation shifts and non-electrostatic pathways

Fundamental research is required to decouple the interrelated chemical mechanisms governing ionizable PPCP adsorption in multi-component systems. Investigators should combine advanced surface characterization techniques with molecular modeling (e.g., Density Functional Theory) to isolate how shifts in solution pH and ionic strength alter compound speciation and non-electrostatic interactions, including π–π electron donor–acceptor mechanisms, hydrophobic partitioning, and hydrogen bonding. Developing predictive thermodynamic models that account for both contaminant speciation and background matrix interference will enable

accurate forecasting of removal performance across diverse wastewater chemistries.

Process integration, fouling mitigation, and lifecycle techno-economics

Operational feasibility requires developing adsorbents that operate efficiently at ambient wastewater conditions (pH 6.5–8.5), eliminating the chemical and monetary expenditures associated with upstream pH manipulation. To ensure operational longevity, research must investigate long-term media fouling mechanisms, specifically quantifying the kinetics of pore blockage by natural organic matter (NOM) and developing sustainable, low-energy media regeneration protocols (e.g., thermal, chemical, or biological regeneration). Rigorous, full-scale life cycle assessments (LCAs) and techno-economic analyses (TEAs) should be routinely integrated into experimental studies to evaluate the cradle-to-grave environmental impacts and life cycle costs of WD-AC deployment.

5. CONCLUSION

Widely detected pharmaceuticals and personal care products (PPCPs) pose persistent ecotoxicological risks to aquatic ecosystems, necessitating scalable advanced tertiary wastewater treatment. Waste-derived activated carbons (WD-ACs) offer a sustainable, cost-effective platform capable of achieving high adsorption capacities across diverse micropollutant classes. The primary mechanisms governing PPCP capture depend on a combination of micro- and mesopore filling, π–π stacking, n–π electron donor–acceptor interactions, hydrophobic partitioning, hydrogen bonding, and electrostatic forces, with the specific pathway governed by compound speciation and carbon surface chemistry.

Moving these materials from bench-scale success to industrial deployment requires resolving critical methodological and operational barriers. Experimental protocols must move away from idealized ultrapure water systems to evaluate PPCP removal at environmentally realistic trace concentrations within real wastewater matrices. Feedstock vulnerabilities inherent to single-precursor processing should be mitigated through co-pyrolysis of waste blends. Full-scale deployment depends on controlling natural organic matter (NOM) fouling, establishing economic media regeneration protocols, and maintaining adsorption capacity at unadjusted ambient pH.

Deploying WD-ACs effectively requires an integrated lifecycle approach. Future work should optimize reactor configurations (such as continuous-flow fixed-bed columns operated in series or direct bioreactor dosing), evaluate spent adsorbent leachability and toxicity, and establish sustainable end-of-life options—including low-energy regeneration or safe land application where environmentally feasible. As regulatory bodies enforce increasingly stringent discharge standards and total maximum daily loads globally, these advanced engineered carbons provide a practical means to protect receiving aquatic ecosystems.

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AUTHOR CONTRIBUTION

Jane Wu: Conceptualization, Data collection, Writing – Original draft, Visualization; **Zeina Baalbaki**: Formal analysis, Investigation, Writing – Original draft, Writing – Review and Editing, Visualization; **Qiao Xiong**: Formal analysis, Writing – Original draft, Writing – Review and Editing; **Nina Ricci Nicomel**: Conceptualization, Methodology, Supervision, Visualization; **Loretta Y. Li**: Conceptualization, Methodology, Investigation, Formal analysis, Writing – Original draft, Writing – Review and Editing, Visualization, Supervision, Funding acquisition

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest concerning the publication of this article.

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