Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-026-38258-x

REVIEW ARTICLE

Emerging contaminants in water pathways: sources, impacts, conventional, and cold-plasma-based cleaner technology assessment

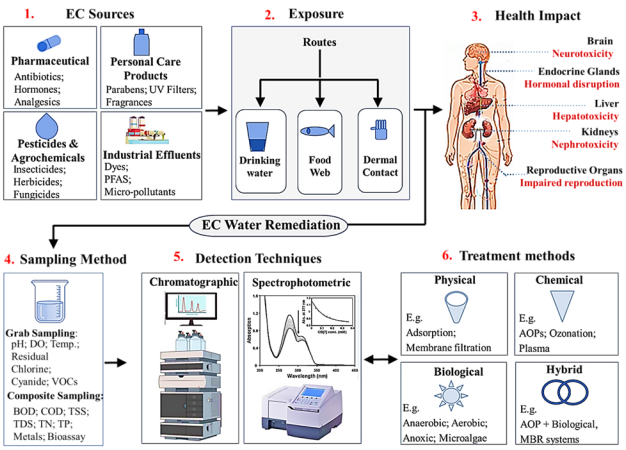
Mohammed Abdulsalam[1,2] · **Bernard Gitura Kimani**[1] · **Kiran Ahlawat**[1] · **Zdenko Machala**[1]

Received: 11 May 2026 / Accepted: 22 September 2026
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2026

Abstract

Emerging contaminants (EC) pose a major challenge to sustainable water and wastewater treatment because of their persistence, continuous release, biological activity, and resistance to conventional remediation. This review provides a critical assessment of EC occurrence, environmental fate, analytical detection, conventional treatment technologies, and cold plasma technology (CPT). Comparative analysis demonstrates that the principal challenge in EC remediation lies not in the absence of effective technologies but in the mismatch between contaminant properties and treatment mechanisms. Adsorption and membrane processes efficiently separate EC but generate secondary waste streams, biological treatment is constrained by microbial selectivity and slow degradation kinetics, and advanced oxidation processes achieve rapid oxidation but remain limited by energy demand, incomplete mineralization, transformation-product formation, and operational complexity. Hybrid systems improve treatment performance by integrating complementary mechanisms but increase process complexity and cost. CPT is critically evaluated as an emerging process-intensification platform capable of generating diverse reactive oxygen and nitrogen species in situ for broad-spectrum EC degradation. Current advances in plasma chemistry, reactor engineering, plasma–liquid interaction, and hybrid plasma systems are assessed alongside challenges related to energy efficiency, reactor scalability, standardized performance metrics, and real wastewater validation. The review identifies key mechanistic framework for developing efficient, scalable, and sustainable EC remediation technologies.

Graphical abstract



Keywords Emerging contaminants · Cold-plasma technology · Advanced micro-pollutant removal · Contaminant impacts · Degradation mechanism

Responsible Editor: Philippe Garrigues

Extended author information available on the last page of the article

Published online: 05 October 2026

Introduction

Rapid industrialization, urbanization, and population growth have increased the release of emerging contaminants (EC), including pharmaceuticals, personal care products (PCPs), pesticides, and endocrine-disrupting compounds, into aquatic environments. Unlike conventional pollutants, EC persist at trace concentrations, exhibit biological activity, and may induce ecological and human health risks, revealing the limitations of wastewater systems designed primarily for bulk organic removal (Manna and Sen 2022; Rad et al. 2024).

EC originate from diverse sources, including municipal wastewater, industrial discharge, agricultural runoff, and urban activities (Jiang et al. 2024; Puri et al. 2023). Although technologies such as activated carbon, membranes, and ozonation can achieve high removal under controlled conditions, their performance is strongly influenced by contaminant properties, water matrix, and operational parameters (Aghaeinejad-Meybodi et al. 2021; Lin et al. 2024). This variability highlights the need for treatment approaches that integrate pollutant destruction with engineering feasibility.

Existing water treatment technologies provide incomplete solutions. Biological processes are cost-effective but often ineffective for recalcitrant EC, while adsorption and membrane systems mainly transfer contaminants into secondary waste streams. Advanced oxidation processes (AOPs) enhance degradation through reactive species but remain constrained by energy demand, chemical requirements, catalyst stability, incomplete mineralization, and transformation-product formation (Abdulsalam et al. 2020; Sanito et al. 2022; Manna and Sen 2022; Sanusi et al. 2026). Therefore, removal efficiency alone is insufficient for evaluating treatment sustainability; mineralization, energy consumption, toxicity, and scalability must also be considered.

Cold plasma technology (CPT) has emerged as a chemical-free intensification strategy capable of generating reactive oxygen and nitrogen species (RONS) under ambient conditions. Plasma systems, including dielectric barrier discharge (DBD), pulsed corona, plasma jets, and gliding arcs, have demonstrated effective degradation of diverse EC (Abdulsalam et al. 2026; Ahlawat et al. 2026; Marković et al. 2015; Topolovec et al. 2022). However, translation from laboratory studies to practical application remains limited by inefficient plasma–liquid coupling, energy utilization, reactor scalability, transformation-product control, and inconsistent performance evaluation (Aggelopoulos 2022; Kooshki et al. 2024).

This review critically evaluates EC treatment pathways by integrating contaminant characteristics, conventional technologies, and CPT-based remediation. Emphasis is placed on degradation mechanisms, reactor engineering, operational trade-offs, and future strategies for developing scalable, energy-efficient, and sustainable plasma-assisted wastewater treatment systems (Fig. 1).

Classification of emerging contaminants

Emerging contaminants (EC) comprise chemically diverse compounds whose environmental behavior and treatment response are governed primarily by physicochemical properties rather than occurrence alone. As summarized in Fig. 2 and Supplementary Table S1, EC can be broadly classified into four functional groups: persistent hydrophobic organic contaminants, polar and ionizable pharmaceuticals, moderately persistent personal care products (PCPs), and polycyclic aromatic hydrocarbons (PAHs). This classification better reflects contaminant fate, mobility, persistence, bioaccumulation, and treatment limitations than classification based solely on chemical origin.

Persistent hydrophobic organic contaminants, including PFAS, polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and organochlorine pesticides, exhibit high hydrophobicity, chemical stability, and strong affinity for sediments and organic matter, promoting long-term persistence and bioaccumulation (Cao et al. 2022; Cojocaru et al. 2024; Fan et al. 2014; Zhang et al. 2019). In contrast, pharmaceuticals remain comparatively mobile because of their high polarity and pH-dependent ionization, resulting in continuous transport through wastewater systems and variable removal depending on molecular speciation rather than concentration (Vethaak et al. 2005; Cizmas et al. 2015; Khan et al. 2020; Nam et al. 2022; Nayak et al. 2023; Singh et al. 2023; Sanusi et al. 2023; Liu et al. 2024; Sikder et al. 2024).

PCPs occupy an intermediate position, exhibiting moderate persistence and variable polarity. Although many undergo partial biodegradation, their continuous discharge from domestic and industrial sources results in pseudo-persistent occurrence, while transformation products may contribute additional environmental risks (Chebii et al. 2024; Grant et al. 2024; Kim et al. 2023; Lee et al. 2024; Mahlalela et al. 2021; Reid et al. 2019; Saravanan et al. 2024; Semones et al. 2017; Sharma et al. 2019). Similarly, PAHs exhibit increasing persistence with molecular weight because fused aromatic structures enhance hydrophobicity, sediment partitioning, and resistance to biodegradation, thereby increasing bioaccumulation and toxicological concern (Abdel-Shafy and Mansour 2016; Lawal 2017; Mallah et al. 2022; Perono et al. 2022; Wallace et al. 2020; Cuvillier-Hot et al. 2018; Khan et al. 2022; Wang et al. 2022a, b; Dutta et al. 2024).

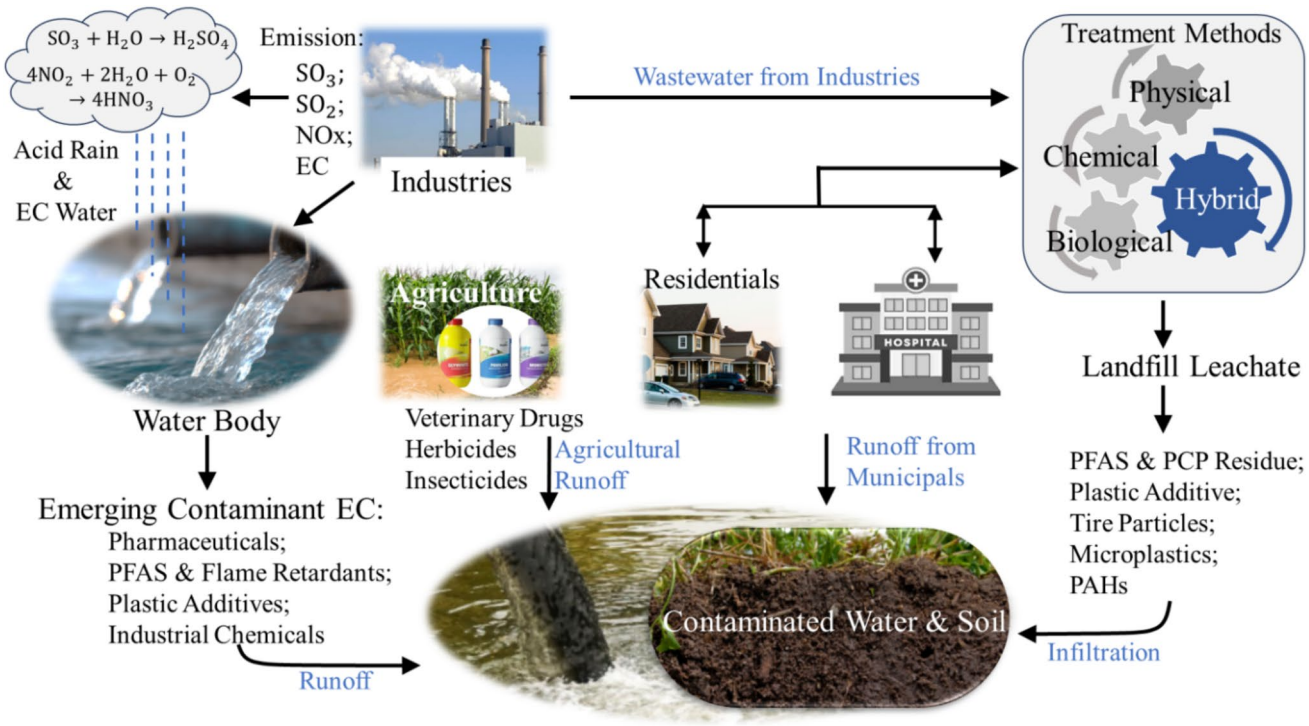


Fig. 1 Schematic illustration of the environmental circulation of water containing emerging contaminants (EC)

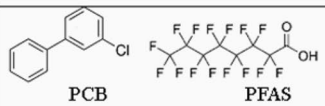
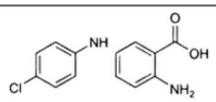
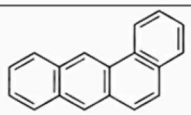
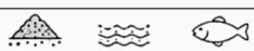
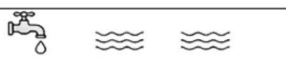
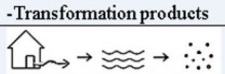
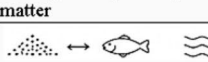
EC Classification	1. Persistent Hydrophobic Organic Contaminants (PHOC)	2. Polar & Ionizable Pharmaceutical Compounds	3. Moderately Persistent Personal Care Products (PCPS)	4. Polycyclic Aromatic Hydrocarbons (PAHs)
Chemical Structure	 PCB PFAS		Perfume, soap etc.	
Example	-PFAS(e.g. PFOA, PFOS) -Ploychlorinated biphenyls (PCBs) -Ploybrominated diphenyl ethers -Organochlorine pesticides (OCPs)	-Diclofenac -Carbamazepine -Sulfamethoxazole -Ciprofloxacin	-Triclosan -Methylparaben -UV filters -Synthetic musk	-Naphthalene -Antheracene -Benzo[a]pyrene -Fluoranthene
Key Characteristics	-Very high hydrophobicity (high log K_{ow}) -Very high persistence and stability -Strong bioaccumulation potential -Low water solubility	-High polarity and water solubility -Exist as ionized species -Low volatility -Poor biodegradability	-Moderate persistence -Variable polarity and functional groups -Bioactive at low concentrations -Transformation products	-High log K_{ow} -Persistent & chemistry stable -Carcinogenic & mutagenic -Strong affinity for organic matter
Dominant Environment	 Soil Sediment Food Web	 Effluent Surface Water Ground water	 Domestic Wastewater Surface Water Sediment Biota	 Sediment Food web Water
Treatment Challenges	-Strong sorption to organic matter -Low bioavailability limits biodegradation -Resistant to conventional treatment -Require advanced oxidation	-Pass through conventional systems -Low removal efficiency -High mobility in aqueous phase -Continuous input & pseudo-persistence	-Partial degradation in WWTPs -Formation of transformation products -Endocrine-disrupting potential -Require advanced technique	-Low aqueous & bioavailability -Strong sorption to sediments -Resistant to biodegradation -Require advanced oxidation
Treatment Complexity	Higher hydrophobicity →	Lower biodegradability →	Higher persistence →	Requires higher monitoring complexity

Fig. 2 Generation, exposure pathways, and organ-specific accumulation of polycyclic aromatic hydrocarbons (PAHs)

Collectively, Fig. 2 demonstrates that EC classification is fundamentally linked to treatment behavior. Hydrophobic contaminants are controlled largely by partitioning and bioaccumulation, whereas pharmaceuticals remain mobile because of their aqueous solubility and ionization, PCPs exhibit pseudo-persistence through continuous emissions, and PAHs combine high structural stability with strong sediment affinity. Consequently, treatment efficiency is governed primarily by contaminant physicochemical properties rather than treatment technology alone, explaining why no single process consistently achieves broad-spectrum EC removal.

Sources, pathways, and environmental fate of emerging contaminant

EC enter aquatic environments through interconnected point and non-point sources and continuously cycle among wastewater, surface water, soil, sediment, groundwater, and the atmosphere (Fig. 3). Their environmental fate depends more on physicochemical properties and transport processes than on source strength alone.

Point sources, including wastewater treatment plants (WWTPs), industrial and pharmaceutical effluents, hospitals, and landfill leachates, discharge concentrated contaminant mixtures. Because conventional WWTPs are not designed for complete EC removal, pharmaceuticals (e.g., ciprofloxacin and diclofenac) and PCPs (e.g., triclosan) are frequently detected in treated effluents at ng L^{-1}–μg L^{-1} concentrations (Table S1) (Ahmed et al. 2024; Gros et al. 2010; Lee et al. 2024; Naushad et al. 2019; Nayak et al. 2023; Sanusi et al. 2023, 2025; Saravanan et al. 2024; Stancova et al. 2014). Non-point sources, including agricultural runoff, urban stormwater, atmospheric deposition, and biosolid application, generate diffuse contaminant inputs that are more difficult to monitor and control (Cojocaru et al. 2024).

As illustrated in Fig. 3, contaminant transport is governed by molecular properties. Polar compounds remain relatively mobile in the aqueous phase, whereas hydrophobic contaminants partition into sediments, sludge, and biota, increasing persistence and bioaccumulation (Dhuldhaj et al. 2022). Consequently, apparent removal by adsorption, sedimentation, or filtration often reflects contaminant redistribution rather than destruction. Effective EC remediation should therefore prioritize mineralization, toxicity reduction, and long-term environmental risk rather than aqueous-phase removal alone.

Environmental fate and human health implications of emerging contaminants

EC affect ecosystems through interconnected soil–water–biota–human exposure pathways rather than isolated environmental compartments. As illustrated in Fig. 4 and summarized in Supplementary Table S2, contaminants

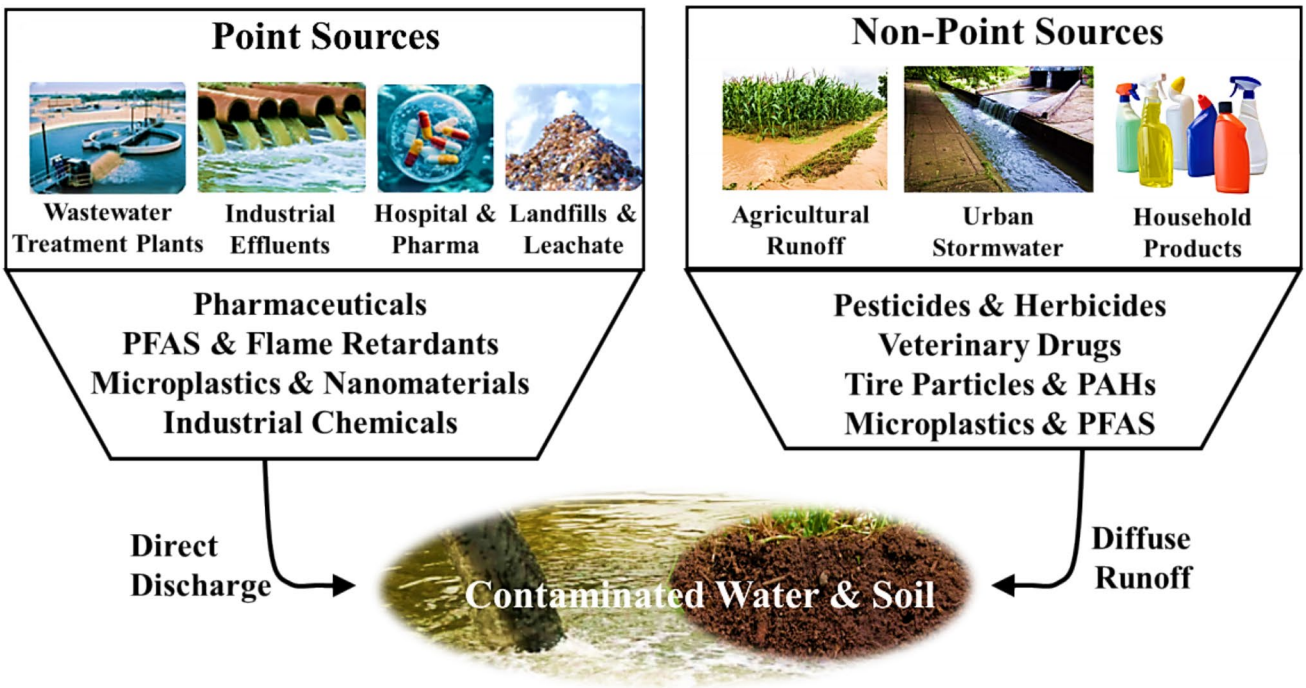


Fig. 3 Major point and non-point sources of emerging contaminants and their converging environmental pathways

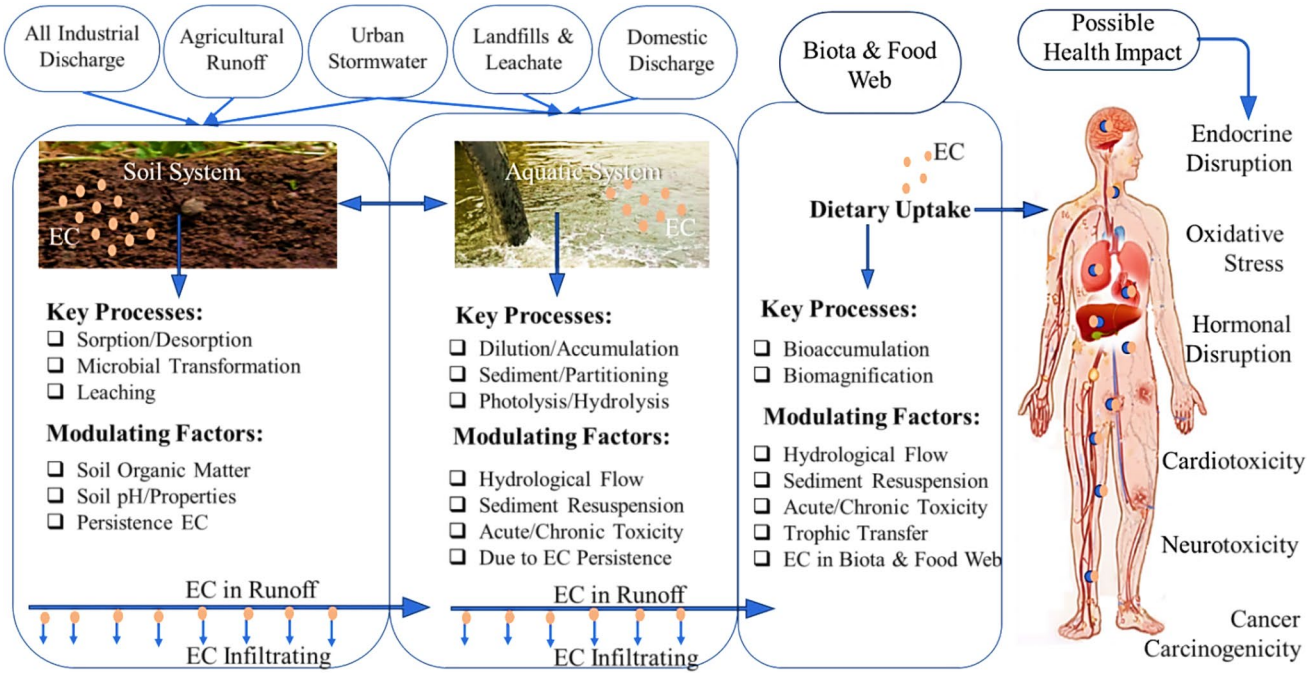


Fig. 4 Cross-compartmental transport, bioaccumulation, and health impacts of emerging contaminants across soil, aquatic, and human systems

released from wastewater treatment plants, industrial discharges, agriculture, and urban runoff undergo continuous transport, transformation, bioaccumulation, and redistribution, producing ecological and human-health effects even at trace concentrations (ng–µg L^{-1}). Consequently, environmental risk depends more on persistence, continuous emissions, physicochemical properties, and biological activity than contaminant concentration alone.

Soils function as dynamic reservoirs that regulate EC mobility through sorption, desorption, microbial transformation, volatilization, and leaching. Hydrophobic contaminants, including PAHs and PFAS, strongly partition into soil organic matter, whereas polar pharmaceuticals remain comparatively mobile depending on pH, moisture, and redox conditions (Sajjad et al. 2022; Sun et al. 2018). Although soil retention can temporarily reduce aqueous concentrations, environmental changes may remobilize contaminants through runoff, erosion, or infiltration. Chronic accumulation further disrupts microbial communities, enzymatic activity, nutrient cycling, and plant development (Gong et al. 2024; Liang et al. 2020; Reyes Contreras et al. 2019; Abdel-Shafy and Mansour 2016).

Aquatic environments subsequently serve as major transport and exposure pathways where contaminant fate is governed by advection, sedimentation, sorption–desorption, photolysis, hydrolysis, and biodegradation. Hydrophobic EC accumulate in sediments but remain environmentally relevant because resuspension and diffusion can reintroduce them into the water column (Nayak et al. 2023). More mobile pharmaceuticals and endocrine-disrupting compounds persist through continuous discharge and induce adverse effects including impaired fish development, endocrine disruption, and reproductive toxicity in aquatic organisms even at environmentally relevant concentrations (Sajjad et al. 2022; Nayak et al. 2023; Nam et al. 2022; Almazrouei et al. 2023; Jiang et al. 2024). Moreover, contaminant transformation does not necessarily reduce risk because degradation may generate persistent or more toxic intermediates.

These processes promote bioaccumulation and trophic transfer, extending EC impacts beyond the aquatic environment. Hydrophobic compounds, including synthetic musks, plasticizers, brominated flame retardants, and PAHs, accumulate in lipid-rich tissues and biomagnify through food webs (Kumar et al. 2023a, b; Priya et al. 2022). Their persistence and metabolic resistance increase long-term ecological risk, contributing to endocrine disruption, developmental disorders, oxidative stress, and coral bleaching (Hassan et al. 2024; Rathi et al. 2024; Dey et al. 2019; Wu et al. 2017). Human exposure represents the downstream consequence of these interconnected pathways through drinking water, food consumption, inhalation, and soil contact. Chronic exposure to complex contaminant mixtures has been associated with endocrine disruption, reproductive impairment, neurotoxicity, immunotoxicity, oxidative stress, carcinogenicity, and the spread of antimicrobial resistance (Gomes 2024; Konopka et al. 2022).

Collectively, Fig. 4 and Supplementary Table S2 demonstrate that EC risk is governed by interconnected processes

involving persistence, transport, bioaccumulation, transformation, and chronic exposure rather than parent-compound concentration alone. This explains why conventional treatment technologies frequently reduce aqueous concentrations without completely eliminating contaminants, transformation products, or secondary redistribution among water, sediments, sludge, and biota. Consequently, treatment performance should be evaluated using mineralization, toxicity reduction, and long-term environmental risk rather than removal efficiency alone.

Analytical detection and quantification of emerging contaminants

Reliable EC detection underpins environmental monitoring, risk assessment, regulatory compliance, and treatment evaluation. Because EC occur at trace concentrations (ng–µg L^{-1}), possess diverse physicochemical properties, and exist in complex matrices, analytical method selection depends on contaminant chemistry, matrix composition, and analytical objectives rather than sensitivity alone. As illustrated in Fig. 5 and Supplementary Table S3, current approaches range from rapid screening tools to advanced chromatographic and high-resolution mass spectrometric platforms, reflecting the fact that no single technique simultaneously provides broad applicability, quantitative accuracy, structural elucidation, and transformation-product identification.

Rapid screening methods provide cost-effective process monitoring but sacrifice sensitivity and molecular specificity. UV–visible spectrophotometry is widely applied for tracking degradation of chromophoric contaminants (Filik et al. 2011; Landebrit et al. 2024), whereas FTIR identifies functional-group transformations during oxidation and plasma treatment (Landebrit et al. 2024). Electrochemical, optical, and immunochemical sensors further enable portable, real-time monitoring with detection limits approaching 0.1 ng L^{-1} for selected pharmaceuticals (Delfino et al. 2021; Torrinha et al. 2020; Nepfumbada et al. 2023; Sanchis et al. 2018). However, matrix interference, electrode fouling, signal instability, and limited multiplexing restrict their application to targeted monitoring and process control rather than comprehensive EC characterization.

Targeted chromatographic methods remain the analytical benchmark because they combine high sensitivity with regulatory acceptance. LC–MS/MS provides robust quantification of polar and ionizable EC, including pharmaceuticals, antibiotics, and hormones, although analytical accuracy depends on effective sample preparation, matrix-effect correction, and isotope-labelled internal standards (Huang et al. 2021; Castaño-Ortiz et al. 2024). Conversely, GC–MS remains indispensable for volatile and hydrophobic

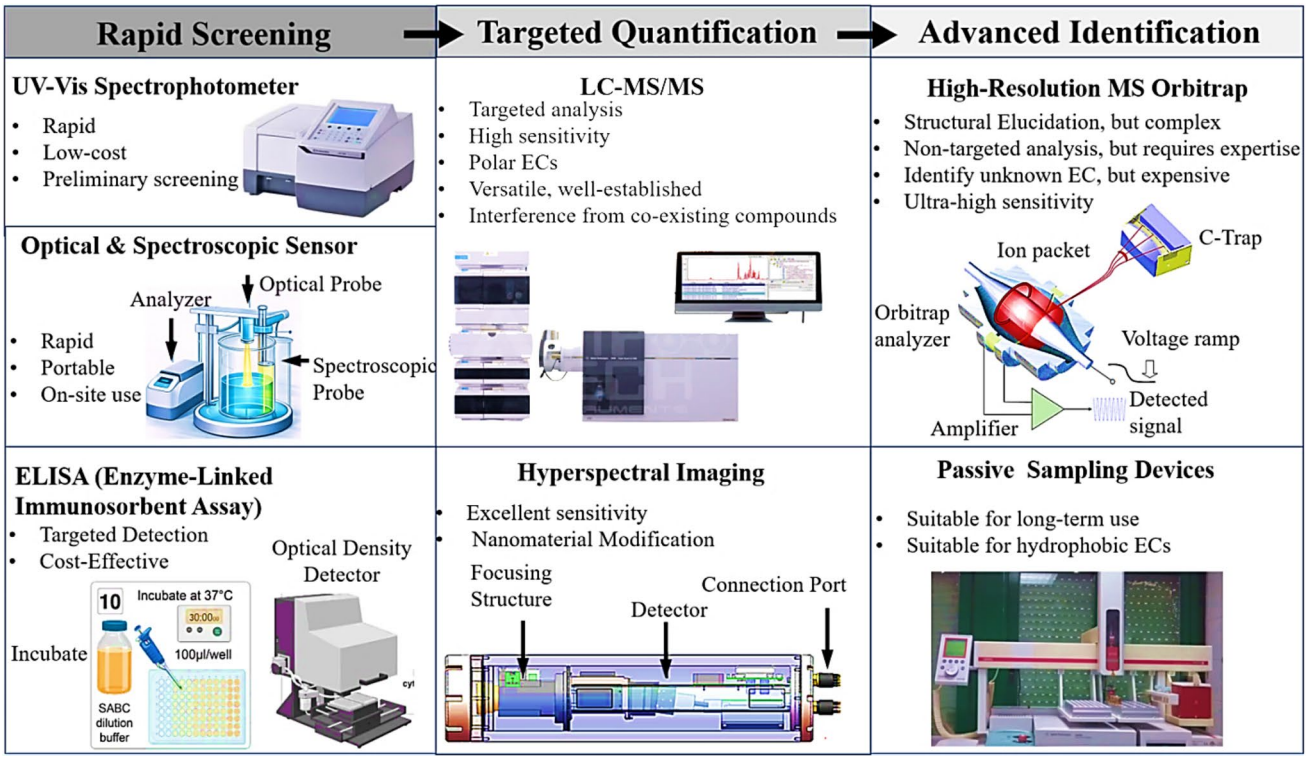


Fig. 5 Emerging contaminants detection techniques, categorized based on rapid screening, targeted quantification, and advanced identification

contaminants, including pesticides, PAHs, brominated flame retardants, and synthetic musks, despite additional derivatization requirements for polar analytes (Williams et al. 2026; Mallek and Barceló 2026). Capillary electrophoresis offers rapid separation with low reagent consumption but remains a niche technique because of lower sensitivity and stronger matrix effects (Nozal et al. 2004; Moreno-González et al. 2016).

A major limitation of targeted methods is their reliance on predefined analytes, restricting detection of unknown contaminants and transformation products. Consequently, high-resolution mass spectrometry (HRMS) has become increasingly important for suspect screening, non-target analysis, and retrospective identification of oxidation intermediates generated during advanced treatment (Williams et al. 2026; Mallek and Barceló 2026). Overall, no analytical platform independently provides complete EC characterization. Instead, reliable assessment requires integrated workflows that combine rapid screening, targeted quantification, and HRMS-based non-target analysis, with method selection driven by treatment objectives and contaminant properties rather than instrumental capability alone.

Treatment and remediation technologies for emerging contaminants

Persistent EC present significant treatment challenges due to chemical diversity, low biodegradability, and resistance to conventional processes. Treatment technologies vary in efficiency, scalability, and sustainability, often involving trade-offs between removal performance and operational feasibility. Table 1 summarizes representative studies, while this section provides a comparative, mechanistic, and engineering-focused evaluation.

Physicochemical treatment approaches

Adsorption-based processes

Adsorption is among the most established physicochemical technologies for EC removal because of its operational simplicity and compatibility with existing treatment infrastructure. Its performance is governed by adsorbent surface chemistry, contaminant speciation, and wastewater matrix composition. As summarized in Table 1, engineered nanomaterials and functionalized adsorbents have substantially improved removal efficiencies under optimized laboratory conditions (Harafan et al. 2022; Maria et al. 2021; Razzaq et al. 2024; Marcelino et al. 2022; Gholamiyan et al. 2020; Butkovskyi et al. 2017). However, these results are predominantly derived from single-solute systems, whereas dissolved organic matter, inorganic ions, and coexisting contaminants significantly reduce adsorption performance in real wastewaters and complicate reproducibility, particularly for bio-based adsorbents. More fundamentally, adsorption transfers contaminants to a solid phase rather than destroying them, necessitating adsorbent regeneration or disposal, a limitation analogous to contaminant accumulation on environmental microplastics (Cojocaru et al. 2024). Consequently, adsorption is better regarded as a polishing or pre-concentration process than a standalone remediation technology, underscoring the need for standardized testing and techno-economic validation under realistic operating conditions.

Membrane filtration processes

Membrane filtration, particularly nanofiltration (NF) and reverse osmosis (RO), is among the most effective technologies for EC removal, with rejection efficiencies frequently exceeding 90–95% for pharmaceuticals such as diclofenac and ibuprofen (Lopera et al. 2019). Separation is governed by size exclusion, electrostatic interactions, and membrane hydrophobicity; consequently, performance depends strongly on contaminant speciation, membrane properties, and water chemistry (Abdulsalam et al. 2020).

Current research emphasizes on membrane modification to improve separation performance and fouling resistance: MgO-incorporated and adsorption-assisted nano-composite membranes achieved > 90% removal of phthalates and other hydrophobic contaminants (Abdulsalam et al. 2020) (Song et al. 2023; Sirés and Brillas 2012), though at higher fabrication cost, process complexity, and maintenance requirements, with uncertainties regarding long-term membrane durability and nanoparticle stability. Despite their excellent removal performance, membrane processes fundamentally transfer rather than destroy contaminants, producing concentrated retentates requiring further treatment. Membrane fouling, concentrate management, and the high energy demand of RO therefore remain the principal barriers to large-term implementation. Consequently, advances should prioritize fouling-resistant materials, energy-efficient operation, and integrated concentrate treatment rather than incremental improvements in rejection efficiency alone.

Biological treatment systems

Biological degradation mechanisms and constraints

Biological treatment removes EC through biodegradation, co-metabolism, biosorption, and enzymatic transformation. The processes are governed by contaminant structure, microbial community composition, redox conditions, and operational parameters such as hydraulic retention time (HRT), sludge retention time (SRT), dissolved oxygen, pH,

Table 1 Comparative assessment of conventional and hybrid treatment technologies for EC remediation, highlighting dominant removal mechanisms, representative treatment performance, engineering limitations, technology readiness, and future research priorities

Process	Technology	Mechanism	EC	Performance	Limitations	Technology readiness	Future research priority	References
Adsorption	Amino-functionalized multi-walled carbon nanotubes (MWCNTs)	Surface adsorption & pore filling	Metolachlor	83% removal	Adsorbent saturation, regeneration requirement, secondary waste generation	Laboratory	Develop re-generable & selective adsorbents with lower regeneration energy	Harafan et al. (2022)
	AC & Magnetic AC (GAC/MAC)	Physical adsorption	Fluoxetine; cephalexin; chlortetracycline	> 90% removal; capacity 233.5 mg g^{-1}; effluent < 10 ng L^{-1}	Adsorbent exhaustion, regeneration cost, contaminant transfer rather than destruction	Commercial	Sustainable regeneration technologies & multifunctional adsorbents	Gholamiyan et al. (2020); Lin et al. (2024)
	AC-palygorskite nanoclays	Physical adsorption	Sulfamethoxazole	95% removal, 2 h	Regeneration challenges	Laboratory–pilot	Sustainable regeneration	(Butkovskyi et al. 2017)
	Graphene-sand	Physical adsorption	Tetracycline	Capacity of 46.4 mg g^{-1}	–	Laboratory–pilot		(Razzaq et al. 2024),
	Corn cob- and graphene-based adsorbents	Adsorption and surface complexation	Glyphosate, tetracycline	53.2% removal efficiency	Competitive adsorption in complex matrices; limited adsorption sites	Laboratory–pilot	Low-cost bio-based adsorbents with improved selectivity	Marcelino et al. (2022)
	Zero-valent iron nanoparticles	Adsorption coupled with reductive transformation	DDT & chlorinated pesticides	High removal under optimized conditions	Narrow operating pH window; nanoparticle recovery	Laboratory	Improve nanoparticle stability and recyclability	Tian et al. (2022); Zhang et al. (2019)
Membrane processes	NF	Size exclusion and charge repulsion	Diclofenac, ibuprofen	> 90% removal	Membrane fouling; concentrate management	Commercial	Fouling-resistant membranes & concentrate valorization	Kumar et al. (2022)
	Reverse osmosis	Molecular separation	UV filters, flame retardants	> 90% removal	High energy consumption; brine disposal	Commercial	Energy-efficient membrane operation & concentrate treatment	Sirés and Brillas (2012)
	AC-coupled NF	Size exclusion	Phthalates	> 90% removal				(Song et al. 2023)
	MgO–PVDF/PEG hybrid membrane	Membrane separation with adsorption	Mixed EC	High removal efficiency	Fabrication cost; membrane fouling	Pilot	Durable multifunctional membrane materials	Abdulsalam et al. (2020)

Table 1 (continued)

Process	Technology	Mechanism	EC	Performance	Limitations	Technology readiness	Future research priority	References
Biological treatment systems	Activated sludge	Biodegradation, co-metabolism and biosorption	Fluoxetine, bisphenol A, parabens	Approximately 41–83% removal depending on compound	Slow kinetics, selective biodegradation, long HRT, sludge generation	Full-scale	Enhance biodegradation of persistent EC and minimize sludge production	Liu and Sun (2022); Fang et al. (2020)
	White-rot fungi (*Pleurotus ostreatus*)	Ligninolytic enzymatic oxidation	α-HCH	Complete degradation within approximately 15 days	Long treatment time; limited scalability	Laboratory	Improve reactor design and fungal immobilization	Varela et al. (2021)
	Wood-decaying fungi (*Phlebia* spp.)	Extracellular enzymatic degradation	Chlordane	Significant degradation	Low degradation rate and long hydraulic retention time	Laboratory	Improve enzyme stability & continuous operation	Fan et al. (2014)
	Anaerobic–aerobic	Azo dyes nitro-aromatic contaminants		90–95% decolorization			Aromatic amines frequently exhibit greater toxicity	(Khan et al. 2022)
	Pseudomonas	Pharmaceuticals, dyes, endocrine		50–100% removal	10–25 days			Tiwari et al. 2017)
	Pseudomonas	Sertraline		90% removal	> 25 days			Mossa and Mohafrash 2023
	Microalgae–bacteria consortia	Bioaccumulation, biodegradation and nutrient assimilation	Antibiotics, pesticides	Up to 95% antibiotic removal	Biomass harvesting; seasonal variability	Pilot	Integrated biomass recovery & process intensification	Ferrando and Matamoros (2020)
	Constructed wetlands and rhizofiltration	Plant uptake, rhizospheric degradation and sediment sorption	Pharmaceuticals and mixed EC	Effective removal under suitable conditions	Large land requirement; seasonal fluctuations; contaminant accumulation	Pilot–field	Improve long-term stability & contaminant mineralization	Singh et al. (2025)

Table 1 (continued)

Process	Technology	Mechanism	EC	Performance	Limitations	Technology readiness	Future research priority	References
AOPs	Solar-Fenton	Hydroxyl radical oxidation	Chloramphenicol	85% removal within 60 min	Chemical consumption; iron sludge generation	Pilot	Minimize chemical demand while improving mineralization	Lofrano et al. (2021)
	TiO_2 photocatalysis	Photocatalytic oxidation	Fluoxetine, bisphenol A, atrazine	> 90% degradation	UV dependence; catalyst recovery; electron–hole recombination	Pilot	Visible-light-responsive photocatalysts & catalyst durability	Ruziwa et al. (2023); Mukhopadhyay et al. (2022); Ohko et al. (2001)
	Ozonation (O_3/UV, O_3/H_2O_2)	Radical-mediated oxidation	Ibuprofen, diclofenac	> 95% removal	High energy requirement; transformation-product formation	Pilot	Improve energy efficiency & by-product control	Ganzenko et al. (2020); Liu et al. (2021)
	Electrochemical oxidation	Direct anodic oxidation and electrogenerated oxidants	Tramadol, fluoxetine	90–96% degradation	High electricity demand; electrode fouling	Pilot	Long-life electrodes & lower energy consumption	Shahinfard et al. (2023); Atawa et al. (2025)
	Catalytic ozonation	Catalytic activation of ozone	Fluoxetine	Moderate to high degradation	Catalyst deactivation and ozone utilization efficiency	Laboratory	Robust catalysts for continuous operation	Aghaeinejad-Meybodi et al. (2021)
Hybrid and integrated systems	Activated sludge + Fenton oxidation	Sequential oxidation and biodegradation	Erythromycin, fluoxetine	Higher removal than biological treatment alone	Process integration complexity; oxidant consumption	Pilot	Optimize oxidation–biological coupling for energy-efficient treatment	Shaha et al. (2024)
	Photocatalysis + nanofiltration	Oxidation followed by membrane separation	Diclofenac, ibuprofen	Approximately 98% removal	High capital cost; membrane fouling	Pilot	Integrated low-energy hybrid reactors	Szymański et al. (2023)
	Reverse osmosis + activated sludge	Biological degradation and membrane polishing	Diclofenac & ibuprofen	90–95% removal	Multi-stage operation; high operating cost	Pilot	Simplified process integration & operational optimization	Lopera et al. (2019)
	Ozonation + biological filtration	Radical oxidation followed by biodegradation	Polycyclic aromatic hydrocarbons (PAHs)	Enhanced degradation and toxicity reduction	Increased operational complexity	Pilot–full scale	Long-term assessment of transformation products	Luo et al. (2019)
	Adsorption + membrane filtration	Adsorption combined with physical separation	Phthalates and mixed EC	> 90% removal	Adsorbent regeneration and membrane fouling	Pilot	Integrated regeneration strategies & fouling mitigation	Li et al. (2021)

and temperature (Rutere et al. 2020; Zekker 2022). Consequently, removal efficiency varies considerably among contaminant classes and treatment configurations.

Conventional activated sludge effectively removes readily biodegradable pharmaceuticals, including ibuprofen, acetaminophen, and naproxen, whereas antibiotics, endocrine-disrupting compounds, fluorinated contaminants, and other structurally recalcitrant EC persist (Rutere et al. 2020). Although biosorption increases apparent removal, it primarily transfers contaminants to sludge, creating secondary disposal challenges rather than achieving mineralization (Zekker 2022). Similarly, co-metabolism extends degradation to compounds that cannot support microbial growth, but its dependence on auxiliary substrates and microbial adaptation reduces process stability under variable wastewater conditions and often requires longer SRT.

Redox conditions further influence degradation pathways and treatment outcomes. Aerobic systems generally favor greater mineralization, whereas anaerobic processes efficiently reduce compounds containing reducible functional groups, including azo dyes and nitro-aromatics. Although anaerobic treatment frequently achieves > 90% decolorization, reductive cleavage may generate persistent aromatic amines requiring subsequent aerobic polishing (Fang et al. 2020; Khan et al. 2022). Thus, biological performance should be evaluated using mineralization and toxicity reduction rather than parent-compound removal alone.

Operational conditions strongly influence process reliability. Neutral pH, mesophilic temperatures (20–35 °C), and stable dissolved oxygen promote biodegradation, whereas temperature fluctuations, shock loading, toxic mixtures, dissolved organic matter, and competing ions suppress microbial activity and introduce pronounced matrix effects that are seldom captured in laboratory studies (Khan et al. 2022; Zekker 2022). Furthermore, limited understanding of transformation products, antimicrobial resistance, and long-term performance under realistic wastewater conditions remains a major barrier to predicting full-scale treatment efficacy. Collectively, these limitations indicate that biological treatment alone is insufficient for persistent EC and is most effective when integrated with complementary physicochemical or AOPs.

Specialized biological systems

Specialized biological systems have been developed to overcome the limited substrate range of conventional activated sludge by exploiting broader metabolic pathways, extracellular enzymes, and synergistic microbial interactions. Although these systems improve the degradation of persistent pharmaceuticals, endocrine disruptors, and other recalcitrant EC, their engineering feasibility is often constrained by long treatment times, operational variability, and scale-up limitations.

Fungal systems, particularly white-rot fungi, achieve broad-spectrum bio-oxidation through extracellular enzymes such as laccases, lignin peroxidases, and manganese peroxidases. *Pleurotus ostreatus* has reported 50–100% removal of pharmaceuticals, dyes, and endocrine-disrupting compounds (Varela et al. 2021), while *Pseudomonas* spp. degrade structurally complex organics through diverse metabolic pathways (Tiwari et al. 2017). These systems typically require treatment periods of 10–25 days, substantially longer than conventional activated sludge, which can remove compounds such as sertraline within hours (Mossa and Mohafrash 2023), limiting their throughput for full-scale applications.

Microalgal systems integrate contaminant removal with nutrient recovery and carbon capture through bioaccumulation, enzymatic transformation, and algae–bacteria symbiosis. Removal efficiencies of up to 95% for antibiotics have been reported alongside simultaneous nitrogen and phosphorus removal (Ferrando and Matamoros 2020). Nevertheless, biomass harvesting, seasonal variability, light dependence, and fluctuating wastewater characteristics remain major barriers to continuous large-scale operation. Besides, constructed wetlands extend biological treatment by combining microbial degradation, plant uptake, rhizospheric processes, and sediment sorption (Singh et al. 2025). Their low energy demand favors decentralized applications, but removal frequently involves contaminant sequestration rather than mineralization, with performance strongly influenced by climate, hydraulic loading, and land availability (Singh et al. 2025; Zekker 2022).

Collectively, enhanced biological removal does not necessarily translate into complete contaminant destruction; transformation products remain poorly characterized, and long hydraulic retention times constrain practical implementation (Tiwari et al. 2017), so specialized biological systems are best suited as complementary treatment stages integrated with advanced physicochemical processes.

Operational limitations and challenges

Despite their sustainability and widespread application, biological treatment systems remain fundamentally constrained by microbial selectivity, slow degradation kinetics, and sensitivity to wastewater characteristics, resulting in variable performance across EC classes and treatment conditions. A major concern is the persistence of antibiotics and other bioactive compounds at sub-lethal concentrations, which can alter microbial communities and promote the proliferation of antibiotic-resistant bacteria and resistance genes (ARGs) (Rutere et al. 2020; Varela et al. 2021).

Process efficiency is further limited by matrix effects and operational requirements. Complex wastewater constituents

(including natural organic matter, inorganic ions, and contaminant mixtures) suppress microbial activity and reduce biodegradation efficiency (Reddy et al. 2014). So, effective treatment of persistent EC often requires extended hydraulic and sludge retention times, increasing reactor size, operating costs, and process complexity. In addition, fluctuations in pH, temperature, dissolved oxygen, and hydraulic loading reduce process stability under full-scale conditions. Another critical limitation is that biological treatment frequently achieves transformation rather than complete mineralization. Intermediate products may persist in treated effluents, whereas biosorption transfers contaminants to sludge, generating secondary waste streams requiring appropriate management. The environmental fate and toxicity of these transformation products and contaminated bio-solids remain insufficiently understood. It is best applied in integrated treatment methods.

Chemical approaches: advanced oxidation and electrochemical processes

Chemical treatment technologies, particularly advanced oxidation and electrochemical processes, are widely applied for the removal of persistent EC due to their ability to generate highly reactive species capable of degrading chemically stable compounds. Cross-study evidence (Table 1) demonstrates rapid degradation and high apparent removal efficiencies. Still, practical application is constrained by high energy demand, oxidant consumption, reaction selectivity, and formation of potentially toxic transformation products, requiring evaluation beyond efficiency metrics.

Radical-driven oxidation mechanisms and kinetic advantages

AOPs achieve rapid degradation of EC through the in situ generation of highly reactive oxidizing species, principally hydroxyl (•OH) and sulfate (SO_4•$^-$) radicals, together with singlet oxygen ($^1O_2$), superoxide (O_2•$^-$), and related reactive intermediates. Unlike biological systems, whose performance depends on microbial metabolism and contaminant biodegradability, AOPs employ non-selective oxidation capable of degrading structurally diverse pharmaceuticals, pesticides, endocrine disruptors, and PCPs.

The high oxidation potential and near diffusion-controlled kinetics of •OH enable rapid contaminant transformation, whereas SO_4•$^-$ exhibits greater selectivity and longer lifetime under certain water chemistries, extending oxidation efficiency in complex matrices (Ruziwa et al. 2023). Consequently, many AOPs achieve degradation within minutes rather than the hours or days required for biological treatment. For example, solar photo-Fenton oxidation removed approximately 85% of chloramphenicol within 60 min (Lofrano et al. 2021), while TiO_2 photocatalysis achieved > 91% fluoxetine degradation under UV irradiation (Ruziwa et al. 2023). Similarly, electrochemical oxidation removed 90% of tramadol within 20 min, and carbon nanotube-based electrodes achieved 96.25% fluoxetine degradation (Shahinfard et al. 2023; Atawa et al. 2025). These studies consistently demonstrate that radical-driven oxidation substantially accelerates degradation kinetics relative to biological processes.

Performance can be further enhanced through hybrid AOPs that combine complementary radical-generation pathways. UV/ozonation, photocatalytic ozonation, photo-Fenton, and persulfate activation generally outperform individual processes by increasing radical flux and improving oxidant utilization. For example, UV-assisted ozonation achieved > 95% removal of ibuprofen and diclofenac through enhanced ozone photolysis and hydroxyl radical production (Ganzenko et al. 2020). The improved degradation reported for hybrid systems is accompanied by greater reactor complexity, energy demand, and operational control requirements, indicating that kinetic enhancement alone does not necessarily translate into superior engineering performance.

Comparison among AOPs remains challenging because reported efficiencies are strongly influenced by contaminant properties, oxidant dosage, irradiation intensity, reactor configuration, water chemistry, and many studies report parent-compound removal without corresponding mineralization, toxicity, or electrical energy consumption data. Consequently, apparent differences between AOPs frequently reflect experimental conditions rather than intrinsic process superiority.

Catalyst innovation, oxidant selection, and process control

Recent AOP research has shifted from maximizing hydroxyl radical production toward engineering catalyst–oxidant systems that improve reactive-species selectivity, utilization efficiency, and resistance to water-matrix interference. Consequently, treatment performance is increasingly determined by catalyst architecture, oxidant activation pathways, electron-transfer efficiency, and process control rather than oxidant strength alone (Table 1).

Advanced catalysts, particularly MXene-based composites, illustrate this transition. MXene/$CoFe_2O_4$-activated peroxymonosulfate (PMS) achieved complete caffeine degradation within approximately 10 min under near-neutral conditions and maintained high removal efficiency in tertiary wastewater, indicating improved tolerance to matrix effects (Table 1) (Atri et al. 2024). Likewise, MXene-derived $TiNbO_x$ heterostructures completely degraded sulfamethoxazole while removing > 90% caffeine under UVA irradiation through enhanced charge separation and suppressed electron–hole recombination (Atri et al. 2024). Similar

improvements have been reported for heterojunction photocatalysts and persulfate-activated systems, demonstrating that catalyst engineering can substantially improve oxidant utilization and broaden operating conditions (Monfort and Wu 2021).

Nevertheless, enhanced catalytic performance often introduces practical trade-offs. Light-assisted systems require additional energy input, whereas catalyst fouling, metal leaching, deactivation, and regeneration remain significant barriers to long-term operation. Moreover, many high-performance catalysts are evaluated using synthetic wastewater, making their reported efficiencies difficult to extrapolate to real matrices containing natural organic matter and competing ions.

Catalyst innovation has expanded the capability of AOPs, but feasibility depends equally on its durability, regeneration, cost, and matrix resilience. Future studies should therefore prioritize standardized comparisons based on mineralization, energy consumption, catalyst lifetime, and life-cycle performance rather than removal efficiency alone.

Energy demand, by-product formation, and process integration challenges

Although AOPs achieve rapid degradation of diverse EC, their practical implementation remains constrained by energy demand, incomplete mineralization, transformation-product formation, and operational complexity. Reported removal efficiencies (> 80–95%) often reflect parent-compound disappearance rather than complete conversion to CO_2 and inorganic ions. Oxidation frequently proceeds through intermediate products whose persistence and toxicity may equal or exceed those of the parent contaminants, emphasizing that treatment performance should be assessed using mineralization, toxicity evolution, and by-product characterization rather than removal efficiency alone.

These limitations are strongly influenced by water chemistry. In ozone-based and radical-driven systems, pH, oxidant dosage, dissolved organic matter, bicarbonate, chloride, and other inorganic ions alter radical pathways and scavenging reactions, affecting both degradation efficiency and by-product formation (Liu et al. 2021). Consequently, oxidation performance reported for synthetic waters often overestimates that achievable in real wastewater. Energy consumption remains another major engineering constraint. UV/H_2O_2, photocatalysis, ozonation, electrochemical oxidation, and plasma-assisted oxidation all require continuous energy input, while reported energy efficiencies vary widely because reactor design, operating conditions, and evaluation metrics differ among studies. The absence of standardized indicators such as electrical energy per order (EE/O) and specific energy consumption therefore limits objective comparison across AOPs.

To address these challenges, hybrid systems combining ozonation, UV irradiation, persulfate activation, electrochemical oxidation, or plasma have been developed to improve radical utilization and contaminant mineralization (Kumar et al. 2023a, b; Luo et al. 2019; Wardenier et al. 2019). Although these integrated processes generally outperform standalone systems, they also increase equipment requirements, process control, maintenance, and capital costs. Similar trade-offs are observed in electrochemical systems, where electrode material, current density, and mass transfer largely determine treatment efficiency, durability, and operating cost (Chen et al. 2023).

The long-term value of AOPs depends less on maximizing degradation efficiency than on improving energy utilization, controlling transformation products, enhancing mineralization, and adopting standardized performance metrics under realistic wastewater conditions.

Critical synthesis of advanced oxidation technologies

Despite significant advances in ozonation, photocatalysis, Fenton chemistry, persulfate activation, and electrochemical oxidation, no single AOPs simultaneously achieves complete mineralization, low energy consumption, minimal by-product formation, operational simplicity, and economic scalability. Treatment performance remains highly dependent on reactor design, oxidant utilization efficiency, water matrix composition, and process integration strategies. Although catalyst innovation and hybridization continue to improve degradation efficiency, these advances frequently increase system complexity and operational costs. Consequently, the principal challenge facing AOP development is no longer the generation of reactive species but the efficient utilization of those species under realistic treatment conditions. These limitations have stimulated interest in emerging oxidation platforms capable of producing diverse reactive species in situ while reducing dependence on chemical additives and complex process integration.

Hybrid and integrated treatment systems

Hybrid treatment systems have emerged because the limitations of individual EC treatment technologies are complementary. Biological processes are sustainable but limited by microbial selectivity and slow kinetics; adsorption and membrane systems separate contaminants without destroying them, whereas AOPs provide rapid degradation but require higher energy and chemical inputs. By integrating these mechanisms, hybrid systems generally achieve higher removal, mineralization, and process robustness than standalone technologies, particularly for complex wastewater containing pharmaceuticals, pesticides, PCPs, and endocrine-disrupting compounds (Table 1).

Three principal hybrid configurations dominate current research. Oxidation–separation systems, such as photocatalysis coupled with nanofiltration, combine contaminant degradation with retention of residual pollutants and intermediates. For example, photocatalysis–nanofiltration achieved approximately 98% removal of diclofenac and ibuprofen while mitigating membrane fouling through partial degradation of organic foulants (Szymański et al. 2023). Oxidation–biological systems employ oxidative pretreatment to improve biodegradability; activated sludge integrated with Fenton oxidation achieved substantially higher erythromycin and fluoxetine removal than biological treatment alone by reducing contaminant recalcitrance (Shaha et al. 2024). Multi-stage treatment trains further integrate adsorption, oxidation, and biological processes to maximize inclusive treatment efficiency.

Although hybrid systems improve treatment performance by integrating complementary mechanisms, they inevitably increase operational complexity and cost, reinforcing the need for single-platform technologies capable of delivering multiple degradation pathways, such as cold plasma technology.

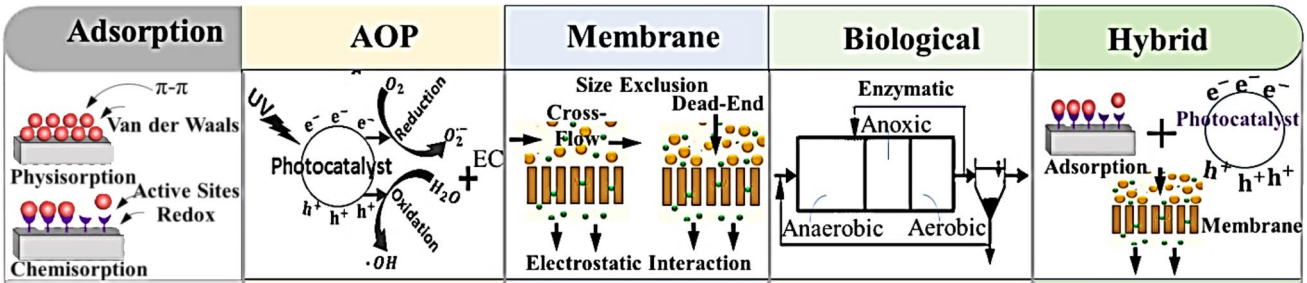
Critical synthesis of conventional EC treatment approaches

Figure 6 provides a systems-level comparison of conventional EC treatment technologies by integrating their dominant removal mechanisms, engineering strengths, operational limitations, and research needs. The comparison demonstrates that the principal challenge in EC remediation is not the absence of effective technologies but the mismatch between contaminant properties and existing treatment mechanisms (Abdulsalam et al. 2020; Gholamiyan et al. 2020; Katare et al. 2023; Mahgoub et al. 2024; Sinha and Dahiya 2022).

No single conventional treatment technology, whether standalone or hybrid, simultaneously achieves high removal efficiency, complete mineralization, low energy consumption, operational simplicity, and minimal secondary waste generation (Fig. 6). Therefore, treatment performance should be evaluated using integrated metrics encompassing mineralization, toxicity reduction, energy efficiency, operational stability, and economic feasibility, highlighting the need for multifunctional treatment platforms that integrate complementary degradation pathways within a single reactor—a key rationale for the development of cold plasma technology (Manna and Sen 2022; Shah et al. 2020; Wardenier et al. 2019).

Novel platform for sustainable EC removal: cold plasma technology

The persistent trade-offs among contaminant removal, mineralization, energy demand, secondary pollution, and scalability identified in Sect. 5 highlight the need for treatment



Adsorption	AOP	Membrane	Biological	Hybrid
Advantages	**Advantages**	**Advantages**	**Advantages**	**Advantages**
▪ Cheap ▪ Pesticides ▪ PAHs	▪ Rapid Degradation ▪ Efficiency ▪ Pharmaceuticals ▪ Pesticides	▪ High Throughput ▪ Particles ▪ Dissolves Solid ▪ Flame Retardants	▪ Cost-Effective ▪ Ecofriendly ▪ Organic Pollutant ▪ Low-Energy	▪ Improved Efficiency ▪ Diverse EC ▪ Thorough Polishing
Drawbacks	**Drawbacks**	**Drawbacks**	**Drawbacks**	**Drawbacks**
▪ Waste Disposal ▪ Inefficient Treatment	▪ Energy Demanding ▪ Secondary Waste	▪ Energy Demanding ▪ High Cost, Fouling ▪ Incomplete	▪ Longer Time ▪ Inefficient ▪ Large footprint	▪ Resource Intensive ▪ Complexity ▪ Secondary Waste ▪ Skilled Labour
Research Gap	**Research Gap**	**Research Gap**	**Research Gap**	**Research Gap**
▪ Polar EC Selective Adsorbent ▪ Sustainable Regeneration	▪ Toxicity of by-product ▪ Energy Efficiency ▪ Scalability	▪ Anti-fouling ▪ EC-Selectivity ▪ Membrane lifespan	▪ Engineered Microbial Consortia ▪ Enzyme Enhancement	▪ Cost-Energy Optimization ▪ Scalability Evaluation

Fig. 6 Mechanistic comparison of conventional treatment pathways for emerging contaminants highlighting strengths, limitations, and unresolved research gaps

platforms that integrate multiple degradation mechanisms within a single process. Cold plasma technology (CPT) has therefore emerged as a promising process-intensification platform for EC remediation. Unlike conventional advanced oxidation processes (AOPs), which often rely on external oxidants, catalysts, or irradiation, CPT simultaneously generates reactive oxygen and nitrogen species (RONS), ultraviolet photons, energetic electrons, and transient electric fields under near-ambient conditions, enabling concurrent oxidation, reduction, photochemical, and plasma–liquid interfacial reactions (Aggelopoulos 2022; Kooshki et al. 2024; Sanito et al. 2022).

The effectiveness of CPT, however, depends on the integration of plasma chemistry, reactor engineering, plasma–liquid coupling, and operating conditions rather than reactive species generation alone. Although CPT has demonstrated considerable potential for degrading diverse EC, challenges associated with energy efficiency, reactor scale-up, electrode durability, by-product formation, and standardized performance evaluation continue to limit large-scale implementation. Consequently, CPT should be regarded as a complementary engineering platform rather than a universal replacement for existing technologies. The following sections critically evaluate its reactor configurations, degradation mechanisms, treatment performance, and future engineering challenges.

Cold plasma system configurations

The performance of cold plasma technology (CPT) is governed not only by plasma chemistry but also by reactor configuration, which controls discharge stability, plasma–liquid interaction, reactive oxygen and nitrogen species (RONS) transfer, energy efficiency, and scalability. The principal reactor designs used for water treatment are summarized in Fig. 7(a–f).

Among these, dielectric barrier discharge (DBD) reactors remain the most extensively investigated because dielectric insulation suppresses arc formation, enabling stable atmospheric-pressure micro-discharges with efficient RONS generation (Pipliya et al. 2023). Their versatility has supported pharmaceutical degradation, wastewater disinfection, and plasma-assisted catalysis (Mouele et al. 2021). In contrast, pulsed corona discharge and gliding arc discharge (GAD) reactors generate more energetic plasmas for degrading refractory contaminants (Rezinkina et al. 2017; Nagassou et al. 2019), but electrode erosion and discharge instability reduce their long-term operational reliability (Sanito et al. 2022). Likewise, atmospheric-pressure plasma jets (APPJs), microwave, and radio-frequency (RF) systems provide localized or high-density plasmas (Judée et al. 2019; Streltsov et al. 2018; Yin et al. 2023), yet their application is constrained by limited plasma–liquid contact

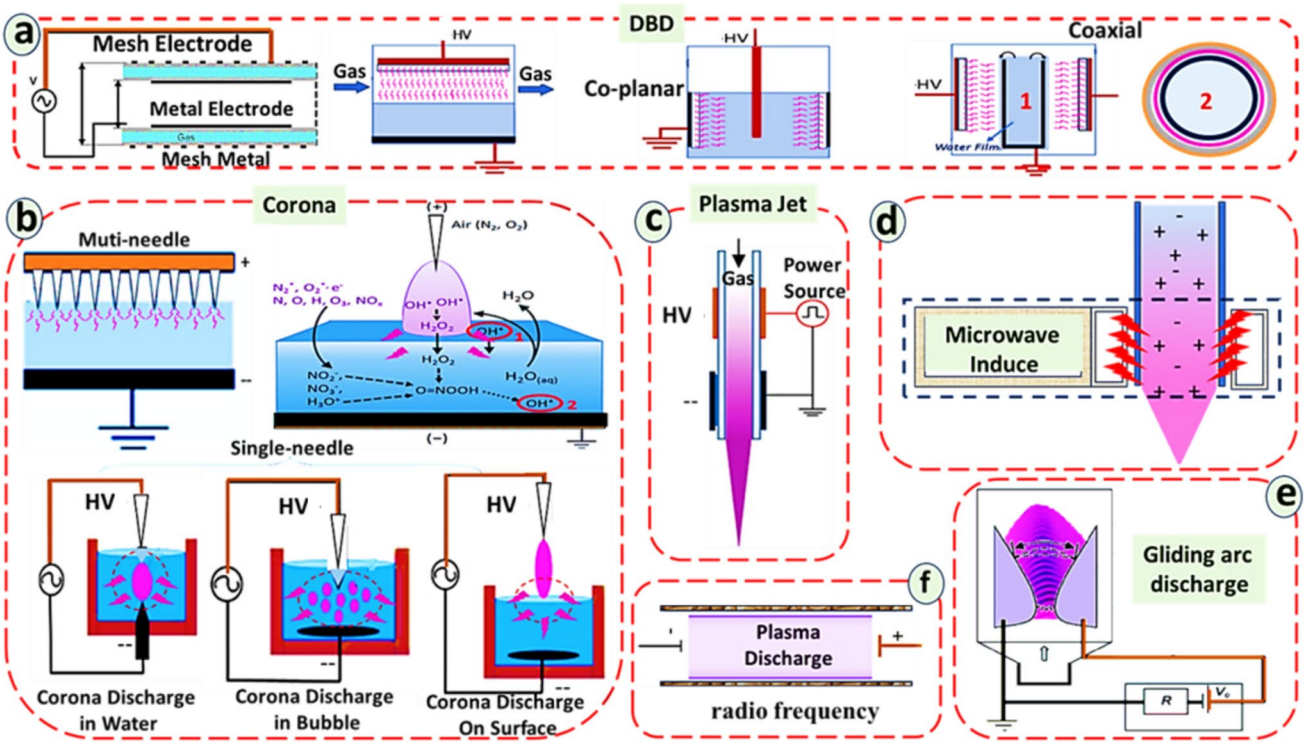


Fig. 7 Different types of the most reported cold plasma configurations (**a**) DBD; (**b**) corona; (**c**) APPJ; (**d**) microwave plasma; (**e**) GAD; and (**f**) RF plasma

or high capital and energy costs (Topolovec et al. 2022; Liu and Sun 2022).

Overall, reactor selection is determined by engineering trade-offs rather than degradation efficiency alone. Highly energetic discharges generally improve contaminant oxidation but increase energy consumption, electrode wear, and operational complexity, whereas continuous-flow systems often sacrifice plasma intensity to improve energy utilization. Consequently, DBD reactors currently offer the best balance between discharge stability, RONS generation, operational flexibility, and scale-up potential, explaining their predominance in EC remediation research (Abdollahzadeh et al. 2015; Mouele et al. 2021; Kanu et al. 2024). Future research should therefore prioritize improved plasma–liquid coupling, energy-efficient reactor designs, and standardized performance evaluation under realistic wastewater conditions.

Plasma–liquid interaction mechanisms and reactive species chemistry

Cold plasma degrades EC through the synergistic interaction of electron-driven reactions, reactive oxygen and nitrogen species (RONS) generation, and plasma–liquid mass transfer. Unlike conventional advanced oxidation processes (AOPs), where oxidation is dominated by a single pathway, CPT involves simultaneous gas-phase, interfacial, and liquid-phase reactions, making degradation highly dependent on reactor design, energy transfer, gas composition, and plasma–liquid coupling (Gong et al. 2020; Li et al. 2020, 2021; Xin et al. 2016). Figure 8 summarizes the sequential processes leading to contaminant oxidation and mineralization.

Step 1. Electron activation and primary radical formation

The applied electric field accelerates electrons, inducing excitation, ionization, and dissociation of H_2O, O_2, and N_2 molecules. This produces primary reactive species, including •OH, O•, H•, and N• radicals, which drive subsequent plasma reactions (Kaushik et al. 2023; Mohanan et al. 2024).

$$e^- + H_2O \rightarrow OH^\bullet + H + e^- \quad (1)$$

$$e^- + H_2O \rightarrow OH^\bullet + H^- \quad (2)$$

$$e^- + H_2O^+ \rightarrow OH^\bullet + H^\bullet \quad (3)$$

$$e^- + H_3O^+ \rightarrow OH^\bullet + H_2 \quad (4)$$

$$H^- + H_2O^+ \rightarrow OH^\bullet + H_2 \quad (5)$$

$$H^- + H_3O^+ \rightarrow OH^\bullet + H_2 + H^\bullet \quad (6)$$

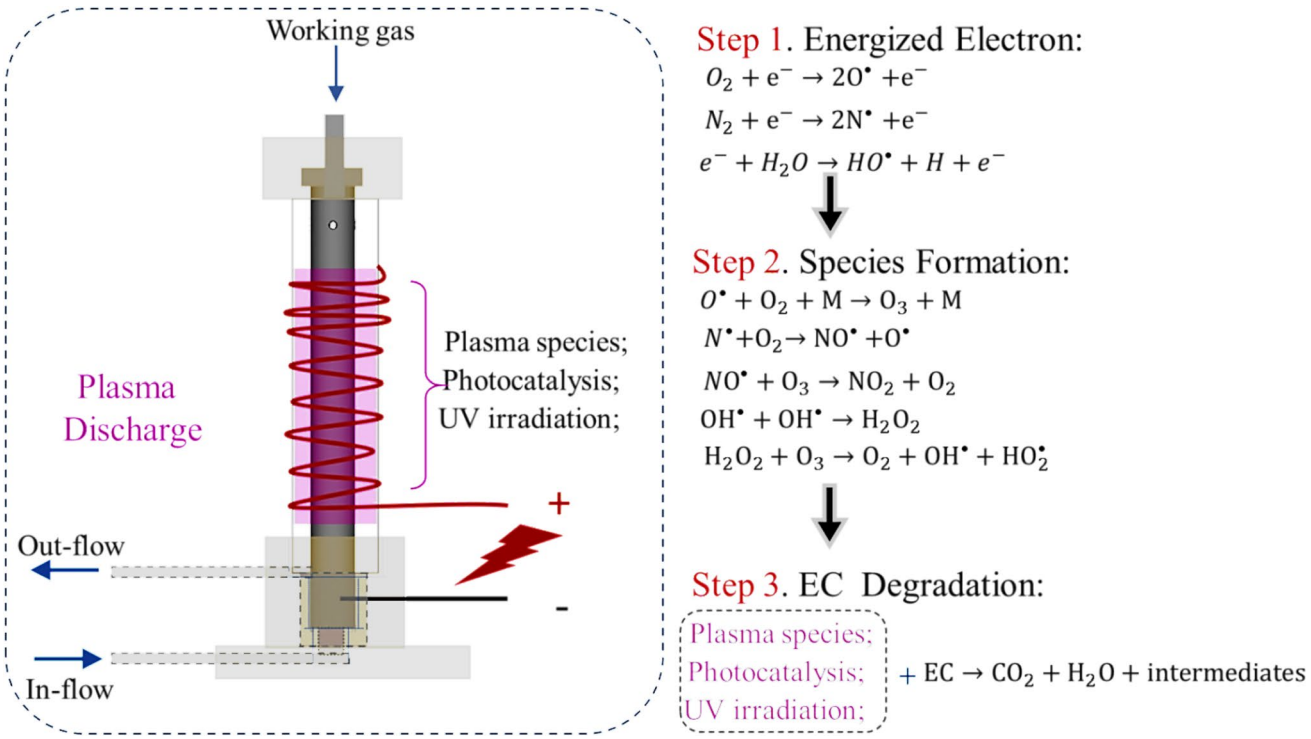


Fig. 8 Mechanism illustrating cold plasma degradation of emerging contaminants

$$O_2 + e^- \rightarrow 2O^{\bullet} + e^- \quad (7)$$

$$N_2 + e^- \rightarrow 2N^{\bullet} + e^- \quad (8)$$

The initial radical generation is governed by electron energy distribution, influenced by voltage, frequency, gas composition, pressure, and reactor geometry. Thus, similar power inputs may yield different oxidation efficiencies, as performance depends on reactive species generation rather than energy consumption alone.

Step 2. Secondary reactive oxygen and nitrogen species formation

Primary radicals undergo rapid secondary reactions, generating stable RONS such as O_3, H_2O_2, NO_2^-, NO_3^-, and $ONOO^-$ (Kaushik et al. 2023; Kumar et al. 2021; Mohanan et al. 2024). These species prolong oxidation beyond the plasma zone and enhance contaminant degradation in the aqueous phase.

$$O^{\bullet} + O_2 + M \rightarrow O_3 + M \quad (9)$$

$$OH^{\bullet} + OH^{\bullet} \rightarrow H_2 + O_2 \quad (10)$$

$$H_2O_2 + O_3 \rightarrow O_2 + OH^{\bullet} + HO_2^{\bullet} \quad (11)$$

$$N^{\bullet} + O_2 \rightarrow NO^{\bullet} + O^{\bullet} \quad (12)$$

$$NO_2 + h\nu \rightarrow NO^{\bullet} + O^{\bullet} \quad (13)$$

$$NO^{\bullet} + O_3 \rightarrow NO_2 + O_2 \quad (14)$$

The coexistence of short-lived radicals and long-lived oxidants is a key advantage of CPT. While •OH radicals drive rapid interfacial oxidation, more stable RONS sustain degradation in the bulk liquid after diffusion (Mohanan et al. 2024; Kaushik et al. 2023; Kumar et al. 2021). Their contribution depends on reactor design, water chemistry, pH, conductivity, dissolved organic matter, and discharge conditions.

Step 3. Plasma–liquid transport, EC oxidation, and mineralization

Reactive species transfer across the plasma–liquid interface via diffusion, convection, and bubble-mediated transport, with efficiency governed by reactor configuration (Kumar et al. 2021). In water, •OH radicals and other RONS rapidly degrade EC through hydroxylation, aromatic ring cleavage, dealkylation, and molecular fragmentation due to their high reactivity (10^6–10^9 M^{-1} s^{-1}).

$$EC + RONS \rightarrow intermediates \rightarrow CO_2 + H_2O$$

Long-lived oxidants such as O_3 and H_2O_2 sustain bulk-phase oxidation and mineralization, while reactive nitrogen species provide additional transformation pathways through nitration, nitrosation, and secondary oxidation (Kumar et al. 2021; Kumar et al. 2023a, b). UV radiation, electric fields, localized heating, shock waves, and cavitation further enhance degradation by improving molecular activation and mass transfer. Thus, CPT performance arises from the synergistic interaction of reactive species, plasma–liquid transport, and hydrodynamics rather than •OH chemistry or power input alone.

CPT-based EC degradation performance: comparative and mechanistic synthesis

Across reported studies (Tables 2, 3, 4), CPT achieves consistently high removal efficiencies for pharmaceuticals and PCPs, while pesticides—particularly halogenated and aromatic species—exhibit comparatively lower degradation. This trend is governed primarily by their molecular structure and functional group susceptibility to RONS, rather than treatment duration alone.

CPT performance for pesticide degradation

CPT enables pesticide degradation through synergistic RONS generation, UV irradiation, and plasma-induced physicochemical effects; however, reported efficiencies (> 90% in many studies; Table 2) are highly system-specific and depend on reactor design, pesticide structure, and water matrix.

DBD reactors provide superior discharge stability, scalability, and oxidation performance by sustaining micro-discharges and generating reactive oxygen and nitrogen species (RONS) (Giardina et al. 2019, 2024; Jose et al. 2019). Oxygen-fed plasmas typically enhance O_3 and •OH production, improving oxidation capacity compared with air- or nitrogen-fed systems, while pesticide resistance is largely determined by molecular structure, particularly aromatic and heterocyclic stability (Sarangapani et al. 2020; Cong et al. 2021; Moutiq et al. 2020).

Hybrid plasma systems (e.g., plasma–catalyst and plasma–ozonation) improve reactive-species utilization and mineralization but introduce additional cost and operational complexity (Vanraes et al. 2015; Lu et al. 2023).

Table 2 Comparative performance of cold plasma technologies for pesticide degradation in water

Pesticide	Compound(s)	Configuration	Operating conditions	Performance	Mechanistic finding	Critical insight	Reference
Carbamate	Carbofuran	Pulsed corona	Variable	~100% degradation	Rapid •OH generation	operating conditions were insufficiently reported	Jose et al. (2019)
Phenoxy herbicide	2,4-Dichlorophenoxyacetic acid	RF discharge + O_2	18 kV; 0.025 kHz	~100% degradation	Promoted ROS formation	Post-discharge oxidation improved efficiency	Liu and Sun (2022)
Triazine herbicide	Atrazine	Pulsed corona + Fenton	45 kV; 0.06 kHz	87.5% degradation	Plasma–Fenton increased ROS production	Hybrid oxidation enhanced degradation	Tang et al. (2018)
Triazine herbicide	Atrazine	DBD + nanofiber membrane	23 kV; 0.3 kHz	85% degradation	Combined oxidation & membrane interaction	Improved plasma–liquid contact	Vanraes et al. (2015)
Organochlorine	Endosulfan	DBD + catalyst	Variable	94% degradation; 48% mineralization	Catalyst promoted deeper oxidation	Demonstrated importance of evaluating mineralization	Reddy et al. (2014)
Organophosphate	Chlorpyrifos	DBD reactor	20 kV; 50 kHz	87–89% degradation	Stabilized discharge, oxidation	Suitable for continuous operation	Amsalu et al. (2024)
Triazine herbicide	Atrazine	Pulsed plasma + GTM photocatalyst	15 kV; 60 kHz	96.2% degradation	Z-scheme photocatalyst enhanced charge separation & RONS utility	Hybrid plasma–photocatalyst improved degradation	Shang et al. (2023)
Nitroaromatic compound	p-Nitrophenol	Microwave atmospheric plasma	2 W; 100–500 mg L^{-1}; pH 2–12	85% degradation	Setup promote oxidation over a broad concentration range	Performance influenced by solution chemistry	Zhao et al. (2021)
Organophosphate	Fenitrothion	Coaxial DBD reactor	28 kV; 48 kHz	87% degradation	Glow discharge generated stable RONS	Reactor geometry influenced discharge stability	Zhang et al. (2016)
Carbamates	Carbaryl, methiocarb, aminocarb	Atmospheric-pressure cold plasma	70–90 kV; 50 kHz	50.5–99.3% degradation	Molecular structure affects degradation kinetics	Different carbamates responded differently despite identical operating conditions	Moutiq et al. (2020)
Triazine herbicide	Atrazine	DBD + persulfate	26 kV; 50 kHz	96.5% degradation	Enhanced ROS production	Hybrid oxidation enhanced degradation efficiency	Lu et al. (2023)
Organophosphate	Chlorpyrifos	Plasma–ozone	2 kV; 52 kHz	50% degradation	Enhanced oxidation but incomplete mineralization	Reactor optimization required	Anbarasan et al. (2022)
Organophosphates	Chlorpyrifos; malathion	DBD	80 kV; atmospheric air; 2 min	62.7%; 64.6% degradation	Treatment time influences degradation;	Demonstrated importance of residence time	Cong et al. (2021)

Table 2 (continued)

Pesticide	Compound(s)	Configuration	Operating conditions	Performance	Mechanistic finding	Critical insight	Reference
Carbamates	Methiocarb; carbaryl; aminocarb	DBD	90 kV; atmospheric air; 5 min	99.6%; 50.5%; 99.3% degradation	Structural differences governed oxidation susceptibility		Moutiq et al. (2020)
Organophosphate phenolic	Dichlorvos; pentachlorophenol	DBD	40 W; O_2; 30 min	98.4%; 97.9% degradation	Enhanced ROS generation	Showcasing oxygen-fed conditions	Topolovec et al. (2022)
Organophosphate	Diazinon	Corona discharge	150 W; O_2; 5 min	99.5% degradation	High plasma density accelerated oxidation	Rapid degradation kinetics	Kyere-Yeboah et al. (2023)
Triazine chloroacetanilide phenylurea herbicides	Atrazine; alachlor; diuron	DBD	40 W; O_2; 30 min	93.9%; 96.1%; 97.4% degradation	Oxygen-fed DBD treated structurally different herbicides	DBD configuration Broad applicability	Wardenier et al. (2019)

Therefore, process evaluation should extend beyond degradation efficiency to include energy consumption, toxicity of intermediates, mineralization, and long-term stability.

CPT shows strong potential for pesticide removal, but inconsistent reporting of operational parameters limits cross-study comparison. Future research should emphasize standardized performance metrics, real wastewater validation, and reactor designs optimized for reactive-species transfer and energy efficiency.

CPT performance for pharmaceutical degradation

Pharmaceuticals are among the most studied EC in CPT due to their diverse structures and oxidation behavior. Although CPT commonly achieves 85–99% removal (Table 3), parent-compound disappearance does not necessarily indicate mineralization or detoxification, as performance depends on molecular structure, reactor configuration, plasma–liquid interaction, and wastewater matrix.

DBD and corona discharge reactors dominate pharmaceutical treatment and remain the most mature configurations, while hybrid approaches provide enhanced oxidation through improved reactive-species utilization. Corona systems provide high radical densities and rapid degradation but suffer from discharge non-uniformity and limited scalability, whereas DBD reactors offer more stable plasma generation and better suitability for continuous operation (Ajo et al. 2016; Baloul et al. 2017). These differences highlight that reactor design and mass-transfer efficiency are as important as the contaminant reactivity.

Recent advances show that improving plasma–liquid coupling through thin-film, falling-film, continuous-flow, and microbubble configurations can enhance reactive-species utilization and mineralization more effectively than increasing discharge power alone (Verdini et al. 2024; Rajan et al. 2023). Hybrid systems integrating catalysts, persulfate activation, cavitation, or advanced electrodes further improve degradation but increase system complexity and cost (Guo et al. 2019; Zhang et al. 2022).

Pharmaceutical structure strongly influences treatment outcomes; aromatic rings, heterocycles, and electron-withdrawing groups often promote persistent intermediates, resulting in rapid parent degradation but incomplete mineralization (Kim et al. 2015; Pan and Qiao 2019). Therefore, removal efficiency alone may overestimate the CPT effectiveness.

Inconsistent reporting of CPT energy efficiency, transformation-product toxicity, mineralization, and long-term stability limits reliable comparison. Future research should prioritize standardized evaluation, real wastewater validation, and reactor optimization based on plasma–liquid coupling rather than power input alone.

Table 3 Comparative performance of cold plasma technologies for pharmaceutical degradation in water

Pharmaceutical	Compound(s)	Configurations	Operating conditions	Performance	Mechanistic finding	Critical insight	Reference
Antibiotic	Tetracycline	Corona discharge + O_2	15–25 kV, AC	94.95% degradation; 81.3% mineralization	Improved ROS generation	Demonstrated high oxidation efficiency but incomplete mineralization	Ouzar and Kim (2022)
Sulfonamide antibiotic	Sulfadiazine	Pulsed corona (wetted-wall reactor)	20–30 kV	~85% degradation after 30 min	Acidic conditions enhanced •OH-mediated oxidation	Plasma–liquid interface influenced degradation kinetics	Rong and Sun (2014)
Antiepileptic-lipid regulator	Carbamazepine; clofibric acid	Pulsed corona (batch/continuous flow)	20–30 kV	~95% degradation	Continuous-flow plasma improved oxidant utilization	Configuration influences efficiency	Ajo et al. (2016)
β-lactam antibiotics	Ampicillin; cloxacillin	Atmospheric plasma jet	15–25 kV	86.8–78.6% degradation	Acidic-pH enhanced RONS generation	Compound influences Performance	Rathore et al. (2024)
Antibiotic	Tetracycline	Pulsed coaxial DBD	10–30 kV	~95% degradation	Thin water-film configuration improved plasma–liquid interaction	Accelerated MT, degradation	Hao et al. (2006)
Analgesic	Paracetamol	Needle-to-plate DBD	15–20 kV	99% degradation; 12 g kWh^{-1} energy yield	promoted plasma stability, ROS, EY reported	Configuration enhanced EY	Baloul et al. (2017)
Pharmaceutical	Pentoxifylline	Pulsed coaxial DBD	10–20 kV	>92% degradation after 60 min	Extended plasma exposure enhanced degradation	Residence time remained is key design parameter	Magureanu et al. (2010)
Industrial pharmaceutical wastewater	Cyanide-containing wastewater	Batch vs thin-film DBD	15 kV; 50 Hz	~88% removal	Thin-film improved interaction	Demonstrated hydrodynamics importance	Rajan et al. (2023)
Diuretic	Furosemide	Hydrodynamic cavitation + electrodeless plasma discharge	Hybrid process	100% degradation within 10 min	Cavitation enhanced RONS transport	Accelerated degradation	Verdini et al. (2024)
Fluoroquinolone antibiotics	Ofloxacin; ciprofloxacin	Atmospheric cold plasma	70–80 kV	75–92% degradation	ROS degraded antibiotic residues	Applicable for mixed antibiotics	Sikder et al. (2024)
Fluoroquinolone	Fluoroquinolone derivatives	Plasma + graphene–TiO_2 photocatalyst	Hybrid photocatalysis	>93% degradation	Graphene improved charge separation & RONS utilization	Catalyst enhanced mineralization	Guo et al. (2019)
Sulfonamide	Sulfamethazine	Plasma-based reactor	60 min	66.9–86.4% degradation	Compound structure influenced degradation kinetics	Demonstrated variability among pharmaceutical classes	Kim et al. (2015)
Analgesic	Paracetamol	Air-fed plasma	30 min	53.3–100% degradation	Air plasma generated multiple ROS	Operating conditions influences efficiency	Pan and Qiao (2019)
Nitroaromatic pharmaceutical	p-Nitrophenol	Pulsed discharge plasma	60 min	92.9% degradation	Radical oxidation dominated degradation	Mineralization data not reported	Wang et al. (2015)

Table 3 (continued)

Pharmaceutical	Compound(s)	Configurations	Operating conditions	Performance	Mechanistic finding	Critical insight	Reference
Antibiotic	Tetracycline hydrochloride	Plasma + Ag/TiO_2/graphene oxide	UV-assisted hybrid	95.7% degradation	Nanocomposite improved ET	Synergistic oxidation	Wang et al. (2017a, b, c)
Glucocorticoids	Hydrocortisone; betamethasone; fluocinolone acetonide	Hybrid microbubble DBD	90 min	77–82% degradation	Microbubbles enhanced oxidant transfer	Persistent steroidal pharmaceuticals	Miruka et al. (2021)
Cephalosporin antibiotics	Cephalexin; cefazolin	Multi-pin corona discharge	20 min; 400 Hz	> 99% degradation	Multi-pin discharge increased plasma density	Configuration improved efficiency	Meropoulis et al. (2022)

EY, energy yield; *MT*, mass transfer; *ET*, electron transfer.

CPT performance for PCP degradation

PCPs represent a diverse EC group characterized by aromatic structures, hydrophobicity, and halogenated groups that enhance persistence and reduce biodegradability. Although CPT achieves > 80–99% removal for many PCPs (Table 4), degradation efficiency alone may overestimate treatment performance due to incomplete mineralization and persistent intermediates.

DBD reactors remain the dominant configuration for PCP removal because of stable atmospheric-pressure operation and efficient RONS generation. However, studies on triclosan, bisphenols, and parabens demonstrate that catalyst integration and reactor architecture can influence performance as strongly as plasma intensity (Nam et al. 2022; Wang et al. 2016). For hydrophobic PCPs, improving plasma–liquid contact is critical; microbubble systems, falling-film reactors, and thin-liquid configurations enhance interfacial transfer and reactive-species utilization, whereas plasma jets provide high degradation rates but face scalability limitations due to localized treatment zones (Wang et al. 2022a, b; Yu et al. 2017). Hybrid plasma systems incorporating semiconductor catalysts further improve oxidation through enhanced electron transfer and radical generation, but increased material costs and operational complexity remain major barriers (Chen et al. 2024; Ni et al. 2024). In addition, PCP structure strongly governs degradation pathways, with multi-ring, halogenated, and endocrine-active compounds often forming stable intermediates despite rapid parent removal.

DBD systems provide the best balance between stability, scalability, and oxidation performance, while catalyst-assisted and hydrodynamic strategies improve reactive-species utilization. However, cross-study comparison remains limited by inconsistent reporting of mineralization, toxicity of transformation products, energy efficiency, catalyst stability, and long-term reactor performance. Future research should therefore prioritize standardized assessment and scalable plasma–liquid coupling strategies.

Operational factors governing CPT performance

Figure 9 illustrates that CPT performance is controlled by the interdependent interaction of electrical input, induced plasma chemistry, reactor hydrodynamics, water matrix, and contaminant properties, which explains the variability observed among pesticide, pharmaceutical, and PCP degradation studies (Tables 2–4).

Electrical energy determines electron activation and RONS generation; however, excessive power input does not necessarily improve treatment due to radical recombination, thermal losses, and reduced energy efficiency. Therefore, optimization of energy density and reactive-species

Table 4 Comparative performance of cold plasma technologies for personal care product (PCP) degradation in water

PCP	Compound(s)	Configuration	Operating conditions	Performance	Mechanistic finding	Critical insight	Reference
Antimicrobial	Triclosan	DBD + AC fibers (ACFs)	60 W	93% degradation	AC enhanced ROS utilization	Sorptive interface improved plasma oxidation	Nam et al. (2022)
Antimicrobial	Triclosan	DBD + TiO_2-coated electrodes	80 W; 18 min	93% degradation	TiO_2 promoted photocatalytic oxidation & electron transfer	Plasma–photocatalyst coupling enhanced degradation	Xin et al. (2016)
Antimicrobial	Triclocarban	DBD + TiO_2-coated ACFs	30 min	Improved degradation with reduced residual concentration	Catalytic support oxidation but mineralization was incomplete	Showcase catalyst integration benefit	Wang et al. (2016)
Insect repellent	DEET	Water-falling-film DBD	27 min; gas bubbling effect	77% degradation	Enhanced RONS–liquid interfacial area; oxidation	Gas bubbling improved mass transfer	Yu et al. (2017)
Dye model compound	Azo dye	Atmospheric plasma jet	45 min	99% degradation	ROS + UV irradiation accelerated chromophore degradation	Suitable for localized treatment	Pandiyaraj et al. (2020)
Phenolic compound	Phenol	Nanotube–TiO_2 pulse plasma	20 kV; 60 min	98% degradation	Nanotube catalyst improved charge separation & RONS utilization	Hybrid plasma–photocatalysis enhanced oxidation	Zhang et al. (2013)
Endocrine-disrupting compound	Bisphenol	TiO_2–Co_3O_4 + DBD plasma	5 min	69.4% degradation	Composite-catalyst accelerated oxidation	Demonstrated rapid initial degradation	Chen et al. (2024)
Carbonyl compound	Formaldehyde	Carbon–TiO_2 plasma + visible light	3 h	73.7% degradation	Visible-light complemented plasma chemistry	Broadened oxidation pathways	Tan et al. (2022)
Volatile organic compound	Toluene	Multi-stage pulsed DBD	400 Hz	62.9% degradation; 0.90 g kWh^{-1} EY	Multi-stage plasma improved oxidation	Improved energy efficiency	Jiang et al. (2020)
Aromatic amine	Aniline	DBD	3 kV; pH 8.43; 100 mg L^{-1}	90.2% degradation after 12 min	Solution chemistry affected oxidation kinetics	pH optimization improved degradation	Sang et al. (2019)
Pesticide model compound	Imidacloprid	Surface-discharge cold plasma	pH 4	95.5 ± 0.6% degradation	Acidic conditions promoted ROS-driven oxidation	Demonstrated importance of pH control	Ni et al. (2024)
Dye model compound	Methyl orange	Thin water-fall DBD	300 L min^{-1}; pH 3.02	99% degradation	Thin-film reactor improved plasma–liquid contact	Hydrodynamics influences degradation	Wang et al. (2017a, b, c)
Dye model compound	Methylene blue	Air-fed DBD	30 min	97% degradation; 9.3 g kWh^{-1} EY	Adequate ROS generated	Reported energy yield enables	Wu et al. (2019)
Paraben	Butyl paraben	Air-assisted cold plasma	3 h	99.1% degradation; k = 0.0328 min^{-1}	First-order degradation kinetics observed	Predictable degradation behavior	Kim et al. (2024)
Paraben	Methylparaben	Cold plasma + ZnO–rGO	20 W; pH 7; 20 mg L^{-1}	99% degradation after 15 min	ZnO–rGO improved electron-transfer & ROS production	Nanocomposite accelerated degradation	Nian et al. (2019)

AC, activated carbon; *EY*, energy yield

utilization is more critical than maximizing the discharge power (Aggelopoulos 2022; Mohanan et al. 2024).

Reactor configuration represents a major performance determinant by controlling plasma–liquid contact and mass transfer. As reflected in Tables 2, 3, and 4, DBD, thin-film, microbubble, and catalyst-assisted systems often outperform conventional designs because they enhance reactive-species transfer rather than simply increasing plasma intensity (Verdini et al. 2024; Shang et al. 2023). Gas composition further regulates oxidation pathways, with oxygen enrichment promoting oxidative RONS formation, while nitrogen-containing plasmas favor reactive nitrogen chemistry; however, these benefits must be balanced against operational cost and by-product formation (Kumar et al. 2021). In real wastewater matrix, components such as dissolved organic matter, alkalinity, and inorganic ions can significantly suppress performance through radical scavenging, often causing greater efficiency losses than changes in operating power (Kooshki et al. 2024).

Inclusively, Fig. 9 highlights that CPT efficiency is not governed by a single operational parameter but by the synergy between reactive-species generation, plasma–liquid transport, and contaminant accessibility. Future optimization should therefore prioritize reactor engineering, energy efficiency, and transformation-product control rather than removal efficiency alone.

Transformation pathways, mineralization, and knowledge gaps in CPT

CPT-induced degradation of EC involves complex oxidative and sometimes also reductive pathways initiated by plasma-generated RONS; however, the pollutant disappearance does not necessarily indicate its complete destruction. Across Tables 2, 3, and 4, high removal efficiencies (> 90%) are frequently reported, while TOC reduction is often considerably lower, highlighting the gap between parent-compound degradation and true mineralization (Aggelopoulos 2022; Wardenier et al. 2019).

Transformation pathways are primarily governed by contaminant structure and oxidant availability. Hydroxyl radicals drive non-selective reactions including hydroxylation, hydrogen abstraction, and aromatic bond cleavage, while ozone and reactive nitrogen species contribute selective oxidation, nitration, and secondary transformation pathways (Kumar et al. 2021; Mohanan et al. 2024). However,

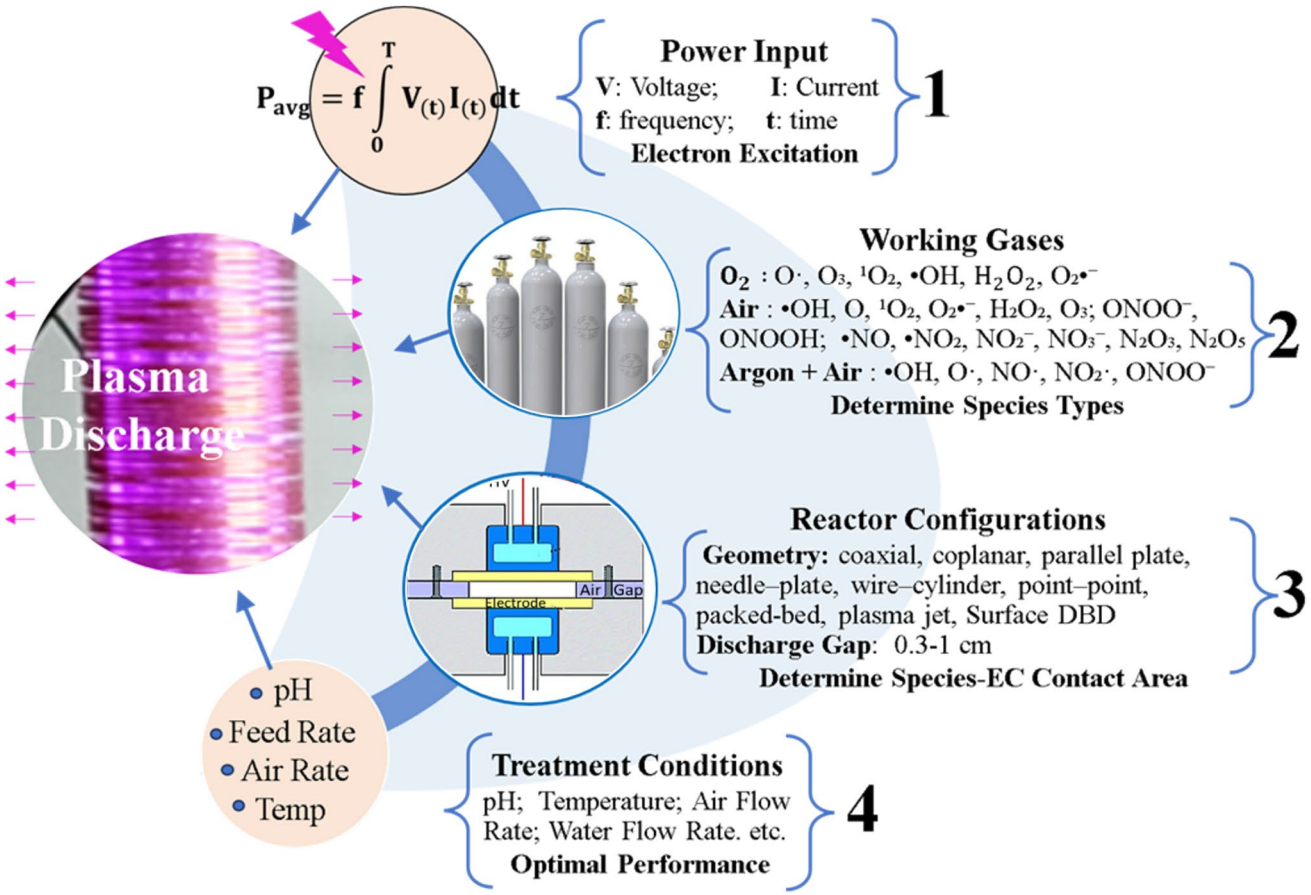


Fig. 9 Factors influencing cold plasma EC degradation performance

structurally persistent compounds containing halogenated groups, aromatic rings, or strong C–F/C–Cl bonds often generate stable intermediates, resulting in rapid parent removal but incomplete mineralization. Hybrid plasma systems incorporating catalysts, photocatalysis, persulfate activation, or adsorption can enhance reactive-species utilization and promote deeper oxidation, although with increased complexity and cost (Chen et al. 2024; Lu et al. 2023; Shang et al. 2023).

Transformation chemistry is also strongly influenced by water matrix composition. Dissolved organic matter, bicarbonate, chloride, and other inorganic species compete for reactive oxidants, altering degradation pathways and reducing treatment efficiency in real wastewater compared with simplified laboratory solutions (Tan et al. 2022; Yin et al. 2023). Therefore, reported CPT performance under idealized conditions may not accurately represent field applications.

Despite significant progress, mechanistic understanding remains limited because many studies focus primarily on removal efficiency rather than intermediate identification, toxicity evolution, and carbon mineralization. Future research should integrate advanced chemical characterization (e.g., LC–MS/MS), toxicity assessment, and reactor engineering to establish reliable links between plasma chemistry, transformation pathways, and environmental safety.

Comparative assessment, challenges, and future perspectives of conventional technologies and cold plasma treatment

Table 5 presents a multi-criteria comparison of conventional treatment technologies and cold plasma technology (CPT), highlighting that no single process simultaneously maximizes degradation efficiency, mineralization, energy efficiency, scalability, and sustainability. Consequently, technology selection should be based on treatment objectives, wastewater characteristics, and engineering feasibility rather than contaminant removal alone.

Conventional technologies remain indispensable for wastewater treatment because of their technological maturity and proven scalability. However, biological processes are often ineffective against persistent EC, while adsorption and membrane systems primarily transfer contaminants into secondary waste streams requiring further management (Kumar et al. 2022; Abdulsalam et al. 2020; Noman et al.

Table 5 Integrated comparative assessment, engineering implications, and future research priorities for conventional wastewater treatment technologies and cold plasma technology in emerging contaminant removal

Assessment criterion	Conventional technologies	CPT	Implication	Research gap & future direction
Primary mechanism	Biodegradation, adsorption, membrane separation, chemical oxidation	In situ RONS generation and plasma oxidation	Mechanism determines contaminant applicability	Improve mechanistic selectivity and reaction pathways
Removal efficiency	High for many bulk pollutants; variable for persistent EC	High for many refractory EC	Removal alone is insufficient	Standardized multi-metric evaluation
Mineralization capability	Often incomplete	Moderate to high, condition-dependent	Assess true pollutant destruction	TOC and carbon-balance reporting
Energy demand	Low to moderate	Moderate to high	Operating cost is critical for scale-up	Energy-efficient plasma reactors
Chemical requirement	Often requires chemicals or consumables	Usually no external oxidant required	Lower chemical handling burden	Optimize gas composition and discharge chemistry
Secondary pollution	Sludge, spent adsorbents, concentrates	Transformation products, nitrogenous by-products	End-of-treatment management is essential	Comprehensive toxicity assessment
Scale-up status	Commercially established	Mostly laboratory and pilot scale	Commercial readiness differs substantially	Pilot and demonstration-scale validation
Operational complexity	Generally moderate	High-voltage plasma operation	Requires skilled operation and control	Automation and intelligent control systems
Reactor durability	Generally well established	Electrode erosion and dielectric aging possible	Maintenance affects long-term economics	Durable electrode and dielectric materials
Treatment safety	Well characterized	Intermediates may be insufficiently characterized	Safety evaluation beyond removal efficiency	Transformation-pathway and ecotoxicity studies
Hybridization potential	Moderate to high	Very high	Hybrid systems can offset individual weaknesses	Integrated plasma-biological and plasma-membrane systems
Technology readiness	High (full-scale deployment)	Low to moderate (emerging technology)	Commercialization pathway differs markedly	Techno-economic and life-cycle assessment

2021; Rathi et al. 2024; Zamri et al. 2021). In contrast, AOPs and CPT chemically transform contaminants through highly reactive oxidation pathways. Unlike conventional AOPs that require externally supplied oxidants or catalysts, CPT generates reactive oxygen and nitrogen species (RONS) directly within the plasma discharge, enabling rapid degradation of diverse refractory contaminants without chemical addition (Aggelopoulos 2022; Ganzenko et al. 2020; Kooshki et al. 2024; Manna and Sen 2022). Nevertheless, rapid degradation does not necessarily ensure complete mineralization or detoxification, emphasizing the need to evaluate treatment beyond parent-compound removal.

A major limitation in objectively comparing treatment technologies is the absence of standardized performance metrics. Most studies emphasize removal efficiency while inconsistently reporting mineralization, energy consumption (SEC and EE/O), toxicity evolution, transformation products, reactor durability, and long-term operational stability. This lack of harmonized assessment complicates technology benchmarking and often overestimates treatment effectiveness.

Despite its outstanding oxidation capability, CPT remains constrained by engineering rather than chemical limitations. Challenges associated with plasma–liquid coupling, energy utilization, discharge uniformity, reactor durability, and scale-up continue to hinder industrial implementation (Kooshki et al. 2024; Shahid et al. 2021; Topolovec et al. 2022). Future research should therefore prioritize energy-efficient reactor architectures, standardized evaluation protocols, comprehensive toxicity assessment, and pilot-scale validation instead of pursuing higher removal efficiencies alone.

Rather than replacing existing technologies, CPT is more realistically positioned as a process-intensification or polishing technology within hybrid treatment systems. Integrating CPT with biological treatment, membranes, adsorption, photocatalysis, or other AOPs, together with intelligent process control, offers a more practical pathway toward energy-efficient, scalable, and sustainable treatment of emerging contaminants (Giardina et al. 2024; Wardenier et al. 2019).

Conclusion and future outlook

Emerging contaminants (EC) remain a major challenge because their structural diversity, persistence, and biological activity frequently exceed the capabilities of conventional water treatment technologies. This review demonstrates that no standalone treatment system simultaneously provides broad-spectrum contaminant removal, complete mineralization, low energy demand, operational simplicity, and economic scalability. Although adsorption, membrane filtration, biological treatment, advanced oxidation processes, and hybrid systems each offer distinct advantages, their performance is constrained by recurring trade-offs involving selectivity, energy consumption, secondary pollution, operational complexity, and incomplete mineralization. Cold plasma technology (CPT) has emerged as a promising process-intensification platform because it simultaneously generates multiple reactive species under near-ambient conditions, enabling diverse oxidation pathways for structurally complex EC. However, the evidence indicates that treatment performance depends more on reactor engineering, plasma–liquid coupling, reactive-species utilization, and wastewater matrix effects than on plasma generation or degradation efficiency alone. Accordingly, CPT should be regarded as a complementary technology that can be effectively integrated with biological, catalytic, membrane, or adsorption processes rather than as a universal replacement for existing treatment systems. Future progress will depend on developing scalable and energy-efficient reactors, standardized performance metrics that incorporate mineralization, toxicity, and specific energy consumption, comprehensive evaluation under real wastewater conditions, and intelligent process optimization through advanced materials, predictive modeling, and artificial intelligence. Addressing these priorities will be essential for translating CPT from laboratory-scale research into a reliable and sustainable technology for large-scale EC remediation.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-026-38258-x.

Acknowledgements The authors gratefully acknowledge the financial support provided by the EU Next Generation EU provided through the Recovery and Resilience Plan for Slovakia.

Author contributions Mohammed Abdulsalam: conceptualization, methodology, formal analysis, data curation, writing—original draft. Bernard Gitura Kimani: assisted in the conceptualization, formal analysis and writing. Kiran Ahlawat: data curation, writing—review. Zdenko Machala: supervision, project administration, validation, investigation, visualization, resources, and writing—review and editing.

Funding This paper was funded by the EUNextGeneration EU through the Recovery and Resilience Plan for Slovakia under project No. 09I03–03-V04–00373.

Data availability All the sourced information are critically studied and utilized in writing this review paper. The summary of the key data is presented in tables, alongside with analyzed figures to enhance elucidations. Additional information on the used literature will be made available upon request to the corresponding author.

Declarations

Ethical approval No ethical approval required for this study.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abdel-Shafy HI, Mansour MSM (2016) A review on polycyclic aromatic hydrocarbons: source, environmental impact, effect on human health and remediation. Egypt J Pet 25:107–123. https://doi.org/10.1016/j.ejpe.2015.03.011

Abdollahzadeh M, Rodrigues F, Pascoa JC, Oliveira PJ (2015) Numerical design and analysis of a multi-DBD actuator configuration for the experimental testing of ACHEON nozzle model. Aerosp Sci Technol 41:259–273. https://doi.org/10.1016/j.ast.2014.12.012

Abdulsalam M, Che Man H, Goh PS, Yunos KF, Zainal Abidin Z, Isma MI, Ismail AF (2020) Permeability and antifouling augmentation of a hybrid PVDF-PEG membrane using nano-magnesium oxide as a powerful mediator for POME decolorization. Polymers 12:549. https://doi.org/10.3390/polym12030549

Abdulsalam M, Ahlawat K, Chithran A, Galmiz O, Ďurina P, Roch T, Machala Z (2026) Enhanced plasma-photocatalysis degradation of coumarin using modified fountain dielectric barrier discharge and WO_3/ZnO nanoparticles. J Water Process Eng 86:109893

Aggelopoulos CA (2022) Recent advances of cold plasma technology for water and soil remediation: a critical review. Chem Eng J 428:131657. https://doi.org/10.1016/j.cej.2021.131657

Aghaeinejad-Meybodi A, Ebadi A, Khataee A, Dehghani Kiadehi A (2021) Comparative investigation on catalytic ozonation of Fluoxetine antidepressant drug in the presence of boehmite and γ-alumina nanocatalysts: operational parameters, kinetics and degradation mechanism studies. Chem Pap 75:421–430. https://doi.org/10.1007/s11696-020-01312-0

Ahlawat K, Chithran A, Kimani BG, Machala Z (2026) Decoupling nitrogen fixation from degradation: a dual-function DBD plasma-bubble system for sustainable wastewater treatment. J Water Process Eng 91:110553

Ahmed M, Eiman AE, Al-Ahmary KM, Aftab F, Sohail A, Raza H, Ali I (2024) Advances in green liquid chromatography for pharmaceutical analysis: a comprehensive review on analytical greenness to sustainable chemistry approaches. Microchem J 205:111400. https://doi.org/10.1016/j.microc.2024.111400

Ajo P, Krzymyk E, Preis S, Kornev I, Kronberg L, Louhi-Kultanen M (2016) Pulsed corona discharge oxidation of aqueous carbamazepine micropollutant. Environ Technol 37:2072–2081. https://doi.org/10.1080/09593330.2016.1141236

Almazrouei B, Islayem D, Alskafi F, Catacutan MK, Amna R, Nasrat S, Sizirici B, Yildiz I (2023) Steroid hormones in wastewater: sources, treatments, environmental risks, and regulations. Emerging Contaminants 9:100210. https://doi.org/10.1016/j.emcon.2023.100210

Amsalu K, Acharya T, Jaiswal A, Lamichhane P, Kifle R, Kaushik N, Lim SJ, Kim TC, Kaushik KN, Choi HE (2024) Abatement and biotoxicity assessment of chlorpyrifos residue from green coffee beans: effect of non-thermal plasma generated ozone and nitric oxide species. Chem Eng J 497:154364. https://doi.org/10.1016/j.cej.2024.154364

Anbarasan R, Jaspin S, Bhavadharini B, Pare A, Pandiselvam R, Mahendran R (2022) Chlorpyrifos pesticide reduction in soybean using cold plasma and ozone treatments. LWT 159:113193. https://doi.org/10.1016/j.lwt.2022.113193

Atawa O, Escudero-Curiel S, Amor HB, Ouakouak A, Hamdi N, Pazos M, Sanromán Á (2025) Efficient fluoxetine removal from water using Tunisian clay as adsorbent and its regeneration through NaOH-activated peroxymonosulfate. Chem Eng Sci 304:120998. https://doi.org/10.1016/j.ces.2024.120998

Atri S, Zazimal F, Gowrisankaran S, Dyrcikova Z, Caplovicova M, Roch T, Dvoranova D, Homola T, Plesch G, Brigante M, Monfort O (2024) Mxene-decorated spinel oxides as innovative activators of peroxymonosulfate for degradation of caffeine in WWTP effluents: insights into mechanisms. Chem Eng J 502:157814. https://doi.org/10.1016/j.cej.2024.157814

Baloul Y, Aubry O, Rabat H, Colas C, Maunit B, Hong D (2017) Paracetamol degradation in aqueous solution by non-thermal plasma. Eur Phys J Appl Phys 79:30802. https://doi.org/10.1051/epjap/2017160472

Butkovskyi A, Leal LH, Zeeman G, Rijnaarts HHM (2017) Micropollutants in source separated wastewater streams and recovered resources of source separated sanitation. Environ Res 156:434–442. https://doi.org/10.1016/j.envres.2017.03.044

Cao S, Zhang P, Cai M, Yang Y, Liu Y, Ge L, Ma H (2022) Occurrence, spatial distributions, and ecological risk of pyrethroids in coastal regions of South Yellow and East China Seas. Mar Pollut Bull 179:113725. https://doi.org/10.1016/j.marpolbul.2022.113725

Castaño-Ortiz JM, Gago-Ferrero P, Barceló D, Rodríguez-Mozaz S, Gil-Solsona R (2024) HRMS-based suspect screening of pharmaceuticals and their transformation products in multiple environmental compartments: an alternative to target analysis? J Hazard Mater 465:132974. https://doi.org/10.1016/j.jhazmat.2023.132974

Chebii F, K'oreje K, Okoth M, Lutta S, Masime P, Demeestere K (2024) Occurrence and environmental risks of contaminants of emerging concern across the River Athi Basin, Kenya, in dry and wet seasons. Sci Total Environ 914:169696. https://doi.org/10.1016/j.scitotenv.2023.169696

Chen C, Ma C, Yang Y, Yang X, Demeestere K, Nikiforov A, Van Hulle S (2023) Degradation of micropollutants in secondary wastewater effluent using nonthermal plasma-based AOPs: the roles of free radicals and molecular oxidants. Water Res 235:119881. https://doi.org/10.1016/j.watres.2023.119881

Chen X, Ma H, Wang R, Wang M, Zhu B, Cong Y, Zhu X, Wang G, Zhang Y (2024) Plasma-assisted assembly of Co_3O_4/TiO_2-NRs for photoelectrocatalytic degradation of bisphenol A in solution and muddy systems. Environ Pollut 340:122876. https://doi.org/10.1016/j.envpol.2023.122876

Cizmas L, Sharma VK, Gray CM, McDonald TJ (2015) Pharmaceuticals and personal care products in waters: occurrence, toxicity, and risk. Environ Chem Lett 13:381–394. https://doi.org/10.1007/s10311-015-0524-4

Cojocaru VC, Cristea IN, Paris IA, Ionescu IA, Chiriac FL (2024) Exploring sustainable solutions: dynamic adsorption, isotherm models, and kinetics of organic contaminants on polystyrene microplastics. Sustainability 16:7743. https://doi.org/10.3390/su16177743

Cong L, Huang M, Zhang J, Yan W (2021) Effect of dielectric barrier discharge plasma on the degradation of malathion and chlorpyrifos on lettuce. J Sci Food Agric 101:424–432. https://doi.org/10.1002/jsfa.10651

Cuvillier-Hot V, Gaudron SM, Massol F, Boidin-Wichlacz C, Pennel T, Lesven L, Net S, Papot C, Ravaux J, Vekemans X, Billon G, Tasiemski A (2018) Immune failure reveals vulnerability of populations exposed to pollution in the bioindicator species *Hediste diversicolor*. Sci Total Environ 613:1527–1542. https://doi.org/10.1016/j.scitotenv.2017.08.259

Delfino I, Diano N, Lepore M (2021) Advanced optical sensing of phenolic compounds for environmental applications. Sensors (Basel) 21:7563. https://doi.org/10.3390/s21227563

Dey S, Bano F, Malik A (2019) Pharmaceuticals and personal care product (PPCP) contamination—a global discharge inventory. Pharmaceuticals and Personal Care Products: Waste Management and Treatment Technology. Elsevier, pp 1–26. https://doi.org/10.1016/B978-0-12-816189-0.00001-9

Dhuldhaj UP, Singh R, Singh VK (2022) Pesticide contamination in agro-ecosystems: toxicity, impacts, and bio-based management strategies. Environ Sci Pollut Res 30:9243–9270. https://doi.org/10.1007/s11356-022-24381-y

Dutta S, Adhikary S, Bhattacharya S, Roy D, Chatterjee S, Chakraborty A, Banerjee D, Ganguly A, Nanda S, Rajak P (2024) Contamination of textile dyes in aquatic environment: adverse impacts on aquatic ecosystem and human health, and its management using bioremediation. J Environ Manage 353:120103. https://doi.org/10.1016/j.jenvman.2024.120103

Fan R, Zhang F, Wang H, Zhang L, Zhang J, Zhang Y, Yu C, Guo Y (2014) Reliable screening of pesticide residues in maternal and umbilical cord sera by gas chromatography-quadrupole time of flight mass spectrometry. Sci China Chem 57:669–677. https://doi.org/10.1007/s11426-013-5023-5

Fang Z, Gao Y, Wu X, Xu X, Sarmah AK, Bolan N, Gao B, Shaheen SM, Rinklebe J, Ok YS, Xu S, Wang H (2020) A critical review on remediation of bisphenol S (BPS) contaminated water: efficacy and mechanisms. Crit Rev Environ Sci Technol 50:476–522. https://doi.org/10.1080/10643389.2019.1629802

Ferrando L, Matamoros V (2020) Attenuation of nitrates, antibiotics and pesticides from groundwater using immobilised microalgae-based systems. Sci Total Environ 703:134740. https://doi.org/10.1016/j.scitotenv.2019.134740

Filik H, Giray D, Ceylan B, Apak R (2011) A novel fiber optic spectrophotometric determination of nitrite using safranin O and cloud point extraction. Talanta 85:1818–1824. https://doi.org/10.1016/j.talanta.2011.07.052

Ganzenko O, Trellu C, Oturan N, Huguenot D, Péchaud Y, Van Hullebusch ED, Oturan MA (2020) Electro-Fenton treatment of a complex pharmaceutical mixture: mineralization efficiency and biodegradability enhancement. Chemosphere 253:126659. https://doi.org/10.1016/j.chemosphere.2020.126659

Gholamiyan S, Hamzehloo M, Farrokhnia A (2020) RSM optimized adsorptive removal of erythromycin using magnetic activated carbon: adsorption isotherm, kinetic modeling and thermodynamic studies. Sustain Chem Pharm 17:100309. https://doi.org/10.1016/j.scp.2020.100309

Giardina A, Tampieri F, Biondo O, Marotta E, Paradisi C (2019) Air non-thermal plasma treatment of the herbicides mesotrione and metolachlor in water. Chem Eng J 372:171–180. https://doi.org/10.1016/j.cej.2019.04.098

Giardina A, Lofrano G, Libralato G, Siciliano A, Marotta E, Paradisi C (2024) Air non-thermal plasma, a green approach for the treatment of contaminated water: the case of sulfamethoxazole. Front Environ Chem 5:1416702. https://doi.org/10.3389/fenvc.2024.1416702

Gomes MP (2024) The convergence of antibiotic contamination, resistance, and climate dynamics in freshwater ecosystems. Water 16:2606. https://doi.org/10.3390/w16182606

Gong X, Lin Y, Li X, Wu A, Zhang H, Yan J, Du C (2020) Decomposition of volatile organic compounds using gliding arc discharge plasma. J Air Waste Manag Assoc 70:138–157. https://doi.org/10.1080/10962247.2019.1698476

Gong X, Xiong L, Xing J, Deng Y, Qihui S, Sun J, Qin Y, Zhao Z, Zhang L (2024) Implications on freshwater lake-river ecosystem protection suggested by organic micropollutant (OMP) priority list. J Hazard Mater 461:132580. https://doi.org/10.1016/j.jhazmat.2023.132580

Grant GJ, Lim HW, Mohammad TF (2024) A review of ultraviolet filters and their impact on aquatic environments. Photochem Photobiol Sci. https://doi.org/10.1007/s43630-024-00674-8

Gros M, Petrović M, Ginebreda A, Barceló D (2010) Removal of pharmaceuticals during wastewater treatment and environmental risk assessment using hazard indexes. Environ Int 36:15–26. https://doi.org/10.1016/j.envint.2009.09.002

Guo H, Jiang N, Wang H, Shang K, Lu N, Li J, Wu Y (2019) Enhanced catalytic performance of graphene-TiO2 nanocomposites for synergetic degradation of fluoroquinolone antibiotic in pulsed discharge plasma system. Appl Catal B Environ 248:552–566. https://doi.org/10.1016/j.apcatb.2019.01.052

Hao X-L, Zhou M-H, Zhang Y, Lei L-C (2006) Enhanced degradation of organic pollutant 4-chlorophenol in water by non-thermal plasma process with TiO2. Plasma Chem Plasma Process 26:455–468. https://doi.org/10.1007/s11090-006-9028-0

Harafan A, Gangwar RK, Maliyekkal SM (2022) Abatement of pesticides in drinking water by nanoscale carbon materials. In: Separation Science and Technology, pp. 139–161. https://doi.org/10.1016/B978-0-323-90763-7.00001-9

Hassan S, Thacharodi A, Priya A, Meenatchi R, Hegde TA, R T, Nguyen H, Pugazhendhi A (2024) Endocrine disruptors: unravelling the link between chemical exposure and women's reproductive health. Environ Res 241:117385. https://doi.org/10.1016/j.envres.2023.117385

Huang H, Liu H, Xiong S, Zeng F, Bu J, Zhang B, Liu W, Zhou H, Qi S, Xu L, Chen W (2021) Rapid transport of organochlorine pesticides (OCPs) in multimedia environment from karst area. Sci Total Environ 775:145698. https://doi.org/10.1016/j.scitotenv.2021.145698

Jiang N, Zhao Y, Shang K, Lu N, Li J, Wu Y (2020) Degradation of toluene by pulse-modulated multistage DBD plasma: key parameters optimization through response surface methodology (RSM) and degradation pathway analysis. J Hazard Mater 393:122365. https://doi.org/10.1016/j.jhazmat.2020.122365

Jiang T, Wu W, Ma M, Hu Y, Li R (2024) Occurrence and distribution of emerging contaminants in wastewater treatment plants: a global review over the past two decades. Sci Total Environ 951:175664. https://doi.org/10.1016/j.scitotenv.2024.175664

Jose J, Ramanujam S, Philip L (2019) Applicability of pulsed corona discharge treatment for the degradation of chloroform. Chem Eng J 360:1341–1354. https://doi.org/10.1016/j.cej.2018.10.199

Judée F, Vaquero J, Guégan S, Fouassier L, Dufour T (2019) Atmospheric pressure plasma jets applied to cancerology: correlating electrical configuration with in vivo toxicity and therapeutic efficiency. J Phys D Appl Phys 52:245201. https://doi.org/10.1088/1361-6463/ab0fbb

Kanu S, Chowdhury S, Laskar M, Singh AS, Allamsetty S, Parashar SKS (2024) Design and development of compact high-voltage source required for non-thermal plasma jet generation. In: Proceedings of the 2024 6th International Conference on Energy, Power and Environment (ICEPE), pp. 1–5. https://doi.org/10.1109/ICEPE63236.2024.10668875

Katare AK, Tabassum A, Sharma AK, Sharma S (2023) Treatment of pharmaceutical wastewater through activated sludge process—a critical review. Environ Monit Assess 195:1466. https://doi.org/10.1007/s10661-023-11967-3

Kaushik N, Mitra S, Baek EJ, Nguyen LN, Bhartiya P, Kim JH, Choi EH, Kaushik NK (2023) The inactivation and destruction of viruses by reactive oxygen species generated through physical and cold atmospheric plasma techniques: current status and perspectives. J Adv Res 43:59–71. https://doi.org/10.1016/j.jare.2022.03.002

Khan HK, Rehman MYA, Malik RN (2020) Fate and toxicity of pharmaceuticals in water environment: an insight on their occurrence in South Asia. J Environ Manage 271:111030. https://doi.org/10.1016/j.jenvman.2020.111030

Khan AU, Zahoor M, Rehman MU, Shah AB, Zekker I, Khan FA, Ullah R, Albadrani GM, Bayram R, Mohamed HRH (2022) Biological mineralization of methyl orange by *Pseudomonas aeruginosa*. Water 14:1551. https://doi.org/10.3390/w14101551

Kim K-S, Kam SK, Mok YS (2015) Elucidation of the degradation pathways of sulfonamide antibiotics in a dielectric barrier discharge plasma system. Chem Eng J 271:31–42. https://doi.org/10.1016/j.cej.2015.02.073

Kim H, Kim D, An Y-J (2023) Microplastics enhance the toxicity and phototoxicity of UV filter avobenzone on *Daphnia magna*. J Hazard Mater 445:130627. https://doi.org/10.1016/j.jhazmat.2022.130627

Kim H-J, Lee T-H, Hong Y, Lee J-C, Kim H-W (2024) Enhanced oxidation of parabens in an aqueous solution by air-assisted cold plasma. Chemosphere 361:142570. https://doi.org/10.1016/j.chemosphere.2024.142570

Konopka JK, Chatterjee P, LaMontagne C, Brown J (2022) Environmental impacts of mass drug administration programs: exposures, risks, and mitigation of antimicrobial resistance. Infect Dis Poverty 11:78. https://doi.org/10.1186/s40249-022-01000-z

Kooshki S, Pareek P, Janda M, Machala Z (2024) Selective reactive oxygen and nitrogen species production in plasma-activated water via dielectric barrier discharge reactor: an innovative method for tuning and its impact on dye degradation. J Water Process Eng 63:105477. https://doi.org/10.1016/j.jwpe.2024.105477

Kumar A, Škoro N, Gernjak W, Puač N (2021) Cold atmospheric plasma technology for removal of organic micropollutants from wastewater—a review. Eur Phys J D 75:283. https://doi.org/10.1140/epjd/s10053-021-00283-5

Kumar R, Qureshi M, Vishwakarma DK, Al-Ansari N, Kuriqi A, Elbeltagi A, Saraswat A (2022) A review on emerging water contaminants and the application of sustainable removal technologies. Case Stud Chem Environ Eng 6:100219. https://doi.org/10.1016/j.cscee.2022.100219

Kumar A, Škoro N, Gernjak W, Jovanović O, Petrović A, Živković S, Lumbaque EC, Farré MJ, Puač N (2023a) Degradation of diclofenac and 4-chlorobenzoic acid in aqueous solution by cold atmospheric plasma source. Sci Total Environ 864:161194. https://doi.org/10.1016/j.scitotenv.2022.161194

Kumar M, Sridharan S, Sawarkar AD, Shakeel A, Anerao P, Mannina G, Sharma P, Pandey A (2023b) Current research trends on emerging contaminants pharmaceutical and personal care products (PPCPs): a comprehensive review. Sci Total Environ 859:160031. https://doi.org/10.1016/j.scitotenv.2022.160031

Kyere-Yeboah K, Bique IK, Qiao X (2023) Advances of non-thermal plasma discharge technology in degrading recalcitrant wastewater pollutants: a comprehensive review. Chemosphere 320:138061. https://doi.org/10.1016/j.chemosphere.2023.138061

Landebrit L, Sanchez R, Soccalingame L, Palazot M, Kedzierski M, Bruzeau S, Albignac M, Ludwig W, Ghiglione JF, Ter Halle A (2024) Small microplastics have much higher mass concentrations than large microplastics at the surface of nine major European rivers. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-024-34486-1

Lawal AT (2017) Polycyclic aromatic hydrocarbons: a review. Cogent Environmental Science 3:1339841. https://doi.org/10.1080/23311843.2017.1339841

Lee JS, Lee JS, Kim HS (2024) Toxic effects of triclosan in aquatic organisms: a review focusing on single and combined exposure of environmental conditions and pollutants. Sci Total Environ 920:170902. https://doi.org/10.1016/j.scitotenv.2024.170902

Li S, Dang X, Yu X, Abbas G, Zhang Q, Cao L (2020) The application of dielectric barrier discharge non-thermal plasma in VOCs abatement: a review. Chem Eng J 388:124275. https://doi.org/10.1016/j.cej.2020.124275

Li Z, Wang Y, Guo H, Pan S, Puyang C, Su Y, Qiao W, Han J (2021) Insights into water film DBD plasma driven by pulse power for ibuprofen elimination in water: performance, mechanism and degradation route. Sep Purif Technol 277:119415. https://doi.org/10.1016/j.seppur.2021.119415

Liang J, Tang S, Gong J, Zeng G, Tang W, Song B, Zhang P, Yang Z, Luo Y (2020) Responses of enzymatic activity and microbial communities to biochar/compost amendment in sulfamethoxazole polluted wetland soil. J Hazard Mater 385:121533. https://doi.org/10.1016/j.jhazmat.2019.121533

Lin P, Liao Z, Wu G, Yang L, Fu J, Luo Y (2024) Recent advances in biofiltration for PPCP removal from water. Water 16:1888. https://doi.org/10.3390/w16131888

Liu Y, Sun B (2022) Unusual catalytic effect of $Fe3^{+}$ on 2,4-dichlorophenoxyacetic acid degradation by radio frequency discharge in aqueous solution. Water 14:1719. https://doi.org/10.3390/w14111719

Liu Z, Demeestere K, Hulle SV (2021) Comparison and performance assessment of ozone-based AOPs in view of trace organic contaminants abatement in water and wastewater: a review. J Environ Chem Eng 9:105599. https://doi.org/10.1016/j.jece.2021.105599

Liu J, Wang Z, Zhao C, Lu B, Zhao Y (2024) Phytohormone gibberellins treatment enhances multiple antibiotics removal efficiency of different bacteria-microalgae-fungi symbionts. Bioresource Technol 394:130182. https://doi.org/10.1016/j.biortech.2023.130182

Lofrano G, Faiella M, Carotenuto M, Murgolo S, Mascolo G, Pucci L, Rizzo L (2021) Thirty contaminants of emerging concern identified in secondary treated hospital wastewater and their removal by solar Fenton (like) and sulphate radicals-based advanced oxidation processes. J Environ Chem Eng 9:106614. https://doi.org/10.1016/j.jece.2021.106614

Lopera EA, Ruiz GS, Alonso QJM (2019) Removal of emerging contaminants from wastewater using reverse osmosis for its subsequent reuse: pilot plant. J Water Process Eng 29:100800. https://doi.org/10.1016/j.jwpe.2019.100800

Lu H, Gao W, Deng C, Liu X, Li W, Yu Z, Ding H, Zhang L (2023) Degradation of atrazine in river sediment by dielectric barrier discharge plasma (DBDP) combined with a persulfate oxidation system: response surface methodology, degradation mechanisms, and pathways. Environ Sci Pollut Res 30:51303–51313. https://doi.org/10.1007/s11356-022-24927-0

Luo J, Liu T, Zhang D, Yin K, Wang D, Zhang W, Liu C, Yang C, Wei Y, Wang L, Luo S, Crittenden JC (2019) The individual and co-exposure degradation of benzophenone derivatives by UV/H2O2 and UV/PDS in different water matrices. Water Res 159:102–110. https://doi.org/10.1016/j.watres.2019.05.019

Magureanu M, Piroi D, Mandache NB, David V, Medvedovici A, Parvulescu VI (2010) Degradation of pharmaceutical compound pentoxifylline in water by non-thermal plasma treatment. Water Res 44:3445–3453. https://doi.org/10.1016/j.watres.2010.03.020

Mahgoub SM, Essam D, Eldin ZE, Moaty SAA, Shehata MR, Farghali A, Abdalla SEB, Othman SI, Allam AA, El-Ela FIA, Mahmoud R (2024) Carbon supported ternary layered double hydroxide nanocomposite for fluoxetine removal and subsequent utilization of spent adsorbent as antidepressant. Sci Rep 14:3990. https://doi.org/10.1038/s41598-024-53781-y

Mahlalela LC, Casado C, Marugán J, Septien S, Ndlovu T, Dlamini LN (2021) Coupling biological and photocatalytic treatment of atrazine and tebuthiuron in aqueous solution. J Water Process Eng 40:101918. https://doi.org/10.1016/j.jwpe.2021.101918

Mallah MA, Changxing L, Mallah MA, Noreen S, Liu Y, Saeed M, Xi H, Ahmed B, Feng F, Mirjat AA, Wang W, Jabar A, Naveed M, Li J-H, Zhang Q (2022) Polycyclic aromatic hydrocarbon and its effects on human health: an overview. Chemosphere 296:133948. https://doi.org/10.1016/j.chemosphere.2022.133948

Mallek M, Barceló D (2026) Analysis and risks of emerging contaminants and microplastics in natural and treated waters and human health: a critical review. JoX 16:93. https://doi.org/10.3390/jox16030093

Manna M, Sen S (2022) Advanced oxidation process: a sustainable technology for treating refractory organic compounds present in industrial wastewater. Environ Sci Pollut Res 30:25477–25505. https://doi.org/10.1007/s11356-022-19435-0

Marcelino NVA, Dos Santos HVR, Cuba RMF, Teran FJC (2022) Effect of H_3PO_4 oxidation of corn cob biochar on the adsorption of a commercial glyphosate formulation. Desalin Water Treat 274:102–114. https://doi.org/10.5004/dwt.2022.28801

Maria PJ, Nagarajan V, Chandiramouli R (2021) Chemosensing nature of black phosphorene nanotube towards C14H9Cl5 and C10H5Cl7 molecules – a first-principles insight. Comput Theor Chem 1196:113109. https://doi.org/10.1016/j.comptc.2020.113109

Marković M, Jović M, Stanković D, Kovačević V, Roglić G, Gojgić-Cvijović G, Manojlović D (2015) Application of non-thermal plasma reactor and Fenton reaction for degradation of ibuprofen. Sci Total Environ 505:1148–1155. https://doi.org/10.1016/j.scitotenv.2014.11.017

Meropoulis S, Giannoulia S, Skandalis S, Rassias G, Aggelopoulos CA (2022) Key study on plasma-induced degradation of cephalosporins in water: process optimization, assessment of degradation mechanisms and residual toxicity. Sep Purif Technol 298:121639. https://doi.org/10.1016/j.seppur.2022.121639

Miruka AC, Zhang A, Wang Q, Zhu D, Wang Z, Sun Z, Héroux P, Liu Y (2021) Degradation of glucocorticoids in water by a synergistic system of peroxymonosulfate, microbubble and dielectric barrier discharges. J Water Process Eng 42:102175. https://doi.org/10.1016/j.jwpe.2021.102175

Mohanan A, Snoeckx R, Cha MS (2024) Temperature-dependent kinetics of plasma-based CO2 conversion: interplay of electron-driven and thermal-driven chemistry. Chemsuschem. https://doi.org/10.1002/cssc.202401526

Monfort O, Wu Y (2021) Photocatalytic processes for environmental applications. Processes 9:2080. https://doi.org/10.3390/pr9112080

Moreno-González D, Lupión-Enríquez I, García-Campaña AM (2016) Trace determination of tetracyclines in water samples by capillary zone electrophoresis combining off-line and on-line sample preconcentration: CE and CEC. Electrophoresis 37:1212–1219. https://doi.org/10.1002/elps.201500440

Mossa A-T, Mohafrash S (2023) Disposal of expired empty containers and waste from pesticides. Egypt J Chem 0:0–0. https://doi.org/10.21608/ejchem.2023.222647.8249

Mouele ESM, Tijani JO, Badmus KO, Pereao O, Babajide O, Fatoba OO, Zhang C, Shao T, Sosnin E, Tarasenko V, Laatikainen K, Petrik LF (2021) A critical review on ozone and co-species, generation and reaction mechanisms in plasma induced by dielectric barrier discharge technologies for wastewater remediation. J Environ Chem Eng 9:105758. https://doi.org/10.1016/j.jece.2021.105758

Moutiq R, Pankaj SK, Wan Z, Mendonca A, Keener K, Misra NN (2020) Atmospheric pressure cold plasma as a potential technology to degrade carbamate residues in water. Plasma Chem Plasma Process 40:1291–1309. https://doi.org/10.1007/s11090-020-10093-z

Mukhopadhyay A, Duttagupta S, Mukherjee A (2022) Emerging organic contaminants in global community drinking water sources and supply: a review of occurrence, processes and remediation. J Environ Chem Eng 10:107560. https://doi.org/10.1016/j.jece.2022.107560

Nagassou D, Mohsenian S, Bhatta S, Elahi R, Trelles JP (2019) Solar–gliding arc plasma reactor for carbon dioxide decomposition: design and characterization. Sol Energy 180:678–689. https://doi.org/10.1016/j.solener.2019.01.070

Nam S-N, Choong CE, Hoque S, Farouk TI, Cho J, Jang M, Snyder SA, Meadows ME, Yoon Y (2022) Catalytic non-thermal plasma treatment of endocrine disrupting compounds, pharmaceuticals, and personal care products in aqueous solution: a review. Chemosphere 290:133395. https://doi.org/10.1016/j.chemosphere.2021.133395

Naushad VA, Bierens JJ, Nishan KP, Firjeeth CP, Mohammad OH, Maliyakkal AM, ChaliHadan S, Schreiber MD (2019) A systematic review of the impact of disaster on the mental health of medical responders. Prehosp Disaster Med 34:632–643. https://doi.org/10.1017/S1049023X19004874

Nayak A, Bhushan B, Kotnala S (2023) Evaluation of hydroxyapatite-chitosan-magnetite nanocomposites for separation of pharmaceuticals from water: a mechanistic and comparative approach. Journal of Hazardous Materials Advances 10:100308. https://doi.org/10.1016/j.hazadv.2023.100308

Nepfumbada C, Mthombeni NH, Sigwadi R, Ajayi RF, Feleni U, Mamba BB (2023) Functionalities of electrochemical fluoroquinolone sensors and biosensors. Environ Sci Pollut Res Int 31:3394–3412. https://doi.org/10.1007/s11356-023-30223-2

Ni J-B, Jia X-F, Zhang J-Y, Ding C-J, Tian W-L, Peng W-J, Zielinska S, Xiao H-W, Fang X-M (2024) Efficient degradation of imidacloprid by surface discharge cold plasma: mechanism of interaction between ROS and molecular structure and evaluation of residual toxicity. J Hazard Mater 465:133066. https://doi.org/10.1016/j.jhazmat.2023.133066

Nian P, Peng L, Feng J, Han X, Cui B, Lu S, Zhang J, Liu Q, Zhang A (2019) Aqueous methylparaben degradation by dielectric barrier discharge induced non-thermal plasma combined with ZnO-rGO nanosheets. Sep Purif Technol 211:832–842. https://doi.org/10.1016/j.seppur.2018.10.048

Noman E, Al-Gheethi A, Mohamed SRM, Talip BA, Hossain MdS, Altowayti AHW, Ismail N (2021) Sustainable approaches for removal of cephalexin antibiotic from non-clinical environments: a critical review. J Hazard Mater 417:126040. https://doi.org/10.1016/j.jhazmat.2021.126040

Nozal L, Arce L, Simonet BM, Ríos A, Valcárcel M (2004) Rapid determination of trace levels of tetracyclines in surface water using a continuous flow manifold coupled to a capillary electrophoresis system. Anal Chim Acta 517:89–94. https://doi.org/10.1016/j.aca.2004.04.050

Ohko Y, Ando I, Niwa C, Tatsuma T, Yamamura T, Nakashima T, Kubota Y, Fujishima A (2001) Degradation of bisphenol A in water by TiO2 photocatalyst. Environ Sci Technol 35:2365–2368. https://doi.org/10.1021/es001757t

Ouzar A, Kim I-K (2022) Tetracycline degradation by nonthermal plasma: removal efficiency, degradation pathway, and toxicity evaluation. Water Sci Technol 86:2794–2807. https://doi.org/10.2166/wst.2022.339

Pan X, Qiao X (2019) Influences of nitrite on paracetamol degradation in dielectric barrier discharge reactor. Ecotoxicol Environ Saf 180:610–615. https://doi.org/10.1016/j.ecoenv.2019.04.037

Pandiyaraj KN, Vasu D, Padmanabhan PVA, Deshmukh RR, Kandavelu V, Saravanan D, Tabaei PSE, Cools P, De Geyter N, Morent R (2020) Non-thermal atmospheric pressure plasma jet-assisted degradation of azo dye–acid orange 7 (AO7): influence of operating parameters and toxicity evaluation. Desalin Water Treat 185:344–354. https://doi.org/10.5004/dwt.2020.25409

Perono GA, Petrik JJ, Thomas PJ, Holloway AC (2022) The effects of polycyclic aromatic compounds (PACs) on mammalian ovarian function. Curr Res Toxicol 3:100070. https://doi.org/10.1016/j.crtox.2022.100070

Pipliya S, Kumar S, Babar N, Srivastav PP (2023) Recent trends in non-thermal plasma and plasma activated water: effect on quality attributes, mechanism of interaction and potential application in food and agriculture. Food Chem Adv 2:100249. https://doi.org/10.1016/j.focha.2023.100249

Priya AK, Gnanasekaran L, Rajendran S, Qin J, Vasseghian Y (2022) Occurrences and removal of pharmaceutical and personal care products from aquatic systems using advanced treatment—a review. Environ Res 204:112298. https://doi.org/10.1016/j.envres.2021.112298

Puri M, Gandhi K, Kumar MS (2023) Emerging environmental contaminants: a global perspective on policies and regulations. J Environ Manage 332:117344. https://doi.org/10.1016/j.jenvman.2023.117344

Rad LR, Irani M, Anbia M (2024) Membrane filtration and adsorption of doxorubicin hydrochloride and fluoxetine hydrochloride from water using polysulfone/MIL-125-NH2 (Ti) nanofibrous membranes. J Mol Liq 408:125429. https://doi.org/10.1016/j.molliq.2024.125429

Rajan A, Boopathy B, Radhakrishnan M, Rao L, Schlüter OK, Tiwari BK (2023) Plasma processing: a sustainable technology in agri-food processing. Sustain Food Technol 1:9–49. https://doi.org/10.1039/D2FB00014H

Rathi B, Senthil Kumar P, Parthasarathy V, Gokul R, Dharani R, Lavanya R, Rangasamy G (2024) Current research progress in the biological removal of emerging contaminants from the water environment. Water Practice and Technology 19:3154–3181. https://doi.org/10.2166/wpt.2024.189

Rathore V, Pandey A, Patel S, Savjani J, Butani S, Dave H, Nema SK (2024) Penicillin antibiotic (ampicillin and cloxacillin) degradation using non-thermal pencil plasma jet. Water Air Soil Pollut 235:44. https://doi.org/10.1007/s11270-023-06846-z

Razzaq U, Nguyen T-B, Saleem MU, Le V-R, Chen C-W, Bui X-T, Dong C-D (2024) Recent progress in electro-Fenton technology for the remediation of pharmaceutical compounds in aqueous environments. Sci Total Environ 946:174253. https://doi.org/10.1016/j.scitotenv.2024.174253

Reddy MKP, Sk M, Subrahmanyam C (2014) Catalytic non-thermal plasma reactor for mineralization of endosulfan in aqueous medium: a green approach for the treatment of pesticide contaminated water. Chem Eng J 238:157–163. https://doi.org/10.1016/j.cej.2013.08.087

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol Rev 94:849–873. https://doi.org/10.1111/brv.12480

Reyes Contreras C, López D, Leiva AM, Domínguez C, Bayona JM, Vidal G (2019) Removal of organic micropollutants in wastewater treated by activated sludge and constructed wetlands: a comparative study. Water 11:2515. https://doi.org/10.3390/w11122515

Rezinkina M, Rezinkin O, D'Alessandro F, Danyliuk A, Guchenko A, Lytvynenko S (2017) Experimental and modelling study of the dependence of corona discharge on electrode geometry and ambient electric field. J Electrostat 87:79–85. https://doi.org/10.1016/j.elstat.2017.03.008

Rong S, Sun Y (2014) Wetted-wall corona discharge induced degradation of sulfadiazine antibiotics in aqueous solution. J Chem Technol Biotechnol 89:1351–1359. https://doi.org/10.1002/jctb.4211

Rutere C, Knoop K, Posselt M, Ho A, Horn M (2020) Ibuprofen degradation and associated bacterial communities in hyporheic zone sediments. Microorganisms 8:1245. https://doi.org/10.3390/microorganisms8081245

Ruziwa DT, Oluwalana AE, Mupa M, Meili L, Selvasembian R, Nindi MM, Sillanpää M, Gwenzi W, Chaukura N (2023) Pharmaceuticals in wastewater and their photocatalytic degradation using nano-enabled photocatalysts. J Water Process Eng 54:103880. https://doi.org/10.1016/j.jwpe.2023.103880

Sajjad M, Huang Q, Khan S, Khan MA, Liu Y, Wang J, Lian F, Wang Q, Guo G (2022) Microplastics in the soil environment: a critical review. Environ Technol Innov 27:102408. https://doi.org/10.1016/j.eti.2022.102408

Sanchis A, Salvador J-P, Marco M-P (2018) Multiplexed immunochemical techniques for the detection of pollutants in aquatic environments. TrAC, Trends Anal Chem 106:1–10. https://doi.org/10.1016/j.trac.2018.06.015

Sang W, Cui J, Feng Y, Mei L, Zhang Q, Li D, Zhang W (2019) Degradation of aniline in aqueous solution by dielectric barrier discharge plasma: mechanism and degradation pathways. Chemosphere 223:416–424. https://doi.org/10.1016/j.chemosphere.2019.02.029

Sanito RC, You S-J, Wang Y-F (2022) Degradation of contaminants in plasma technology: an overview. J Hazard Mater 424:127390. https://doi.org/10.1016/j.jhazmat.2021.127390

Sanusi IO, Olutona GO, Wawata IG, Onohuean H (2023) Occurrence, environmental impact and fate of pharmaceuticals in groundwater and surface water: a critical review. Environ Sci Pollut Res 30:90595–90614. https://doi.org/10.1007/s11356-023-28802-4

Sanusi IO, Olutona GO, Wawata IG (2025) Geospatial monitoring and human health risk assessment of pharmaceutical residues in groundwater and surface water in Kampala and Mbarara Districts, Uganda. Environ Geochem Health 47:30. https://doi.org/10.1007/s10653-024-02336-1

Sanusi IO, Dangana RS, Okon MB (2026) Techniques and applications of advanced oxidation processes for degrading pollutants in wastewater using biochar-based catalysts: a critical review. Discov Sustain 7:821. https://doi.org/10.1007/s43621-026-03260-3

Sarangapani C, Scally L, Gulan M, Cullen PJ (2020) Dissipation of pesticide residues on grapes and strawberries using plasma-activated water. Food Bioprocess Technol 13:1728–1741. https://doi.org/10.1007/s11947-020-02515-9

Saravanan A, Thamarai P, Deivayanai VC, Karishma S, Shaji A, Yaashikaa PR (2024) Current strategies on bioremediation of personal care products and detergents: sustainability and life cycle assessment. Chemosphere 354:141698. https://doi.org/10.1016/j.chemosphere.2024.141698

Semones MC, Sharpless CM, MacKay AA, Chin Y-P (2017) Photodegradation of UV filters oxybenzone and sulisobenzone in wastewater effluent and by dissolved organic matter. Appl Geochem 83:150–157. https://doi.org/10.1016/j.apgeochem.2017.02.008

Shah AI, Din Dar MU, Bhat RA, Singh JP, Singh K, Bhat SA (2020) Prospectives and challenges of wastewater treatment technologies to combat contaminants of emerging concerns. Ecol Eng 152:105882. https://doi.org/10.1016/j.ecoleng.2020.105882

Shaha SN, Nangare SN, Patil PO, Khan ZG, Bari SB, Chaudhari NB, Mahajan MR (2024) A review on different analytical strategies for the detection of sertraline: current challenges and future perspective. Microchem J 205:111303. https://doi.org/10.1016/j.microc.2024.111303

Shahid MK, Kashif A, Fuwad A, Choi Y (2021) Current advances in treatment technologies for removal of emerging contaminants from water – a critical review. Coord Chem Rev 442:213993. https://doi.org/10.1016/j.ccr.2021.213993

Shahinfard H, Shabani-Nooshabadi M, Reisi-Vanani A, Darabi R (2023) Electrochemical sensor based on CuO/reduced graphene nanoribbons and ionic liquid for simultaneous determination of tramadol, olanzapine and acetaminophen. Carbon Lett 33:1433–1444. https://doi.org/10.1007/s42823-023-00512-4

Shang Y, Jiang N, Liu Z, Li C, Sun H, Guo H, Peng B, Li J (2023) Pulsed discharge plasma assisted with Z-scheme graphene-TiO2-MnFe2O4 for simultaneous removal of atrazine and Cr(VI): performance and mechanism. Chem Eng J 452:139342. https://doi.org/10.1016/j.cej.2022.139342

Sharma BM, Bečanová J, Scheringer M, Sharma A, Bharat GK, Whitehead PG, Klánová J, Nizzetto L (2019) Health and ecological risk assessment of emerging contaminants (pharmaceuticals, personal care products, and artificial sweeteners) in surface and groundwater (drinking water) in the Ganges River Basin, India. Sci Total Environ 646:1459–1467. https://doi.org/10.1016/j.scitotenv.2018.07.235

Sikder S, Toha M, Anik AH, Sultan MB, Alam M, Parvin F, Tareq SM (2024) A comprehensive review on the fate and impact of antibiotic residues in the environment and public health: a special focus on the developing countries. Water Environ Res 96:e10987. https://doi.org/10.1002/wer.10987

Singh A, Chaurasia D, Khan N, Singh E, Chaturvedi Bhargava P (2023) Efficient mitigation of emerging antibiotics residues from water matrix: integrated approaches and sustainable technologies. Environ Pollut 328:121552. https://doi.org/10.1016/j.envpol.2023.121552

Singh H, Balusamy SR, Sukweenadhi J, Saravanan M, Aruchamy M, Mijakovic I, Singh P (2025) Smart hybrid nanomaterials for chronic infections: microbiome-responsive and sustainable therapeutic platforms. J Nanobiotechnol 23:698. https://doi.org/10.1186/s12951-025-03712-4

Sinha N, Dahiya P (2022) Removal of emerging contaminants from pharmaceutical wastewater through application of bionanotechnology. Development in wastewater treatment research and processes. Elsevier, pp 247–264. https://doi.org/10.1016/B978-0-323-85583-9.00004-1

Sirés I, Brillas E (2012) Remediation of water pollution caused by pharmaceutical residues based on electrochemical separation and degradation technologies: a review. Environ Int 40:212–229. https://doi.org/10.1016/j.envint.2011.07.012

Song Q, Li Y, Xie W, Gao C, Liu L, Liu B (2023) Catalytic degradation of carbamazepine by metal organic frameworks (MOFs) derived magnetic catalyst Fe@PC in an electro-Fenton coupled membrane filtration system: performance, pathway, and mechanism. Sep Purif Technol 309:122988. https://doi.org/10.1016/j.seppur.2022.122988

Stancova V, Plhalova L, Bartoskova M, Zivna D, Prokes M, Marsalek P, Blahova J, Skoric M, Svobodova Z (2014) Effects of mixture of pharmaceuticals on early life stages of tench (*Tinca tinca*). BioMed Res Int. https://doi.org/10.1155/2014/253468

Streltsov AV, Berthelier J-J, Chernyshov AA, Frolov VL, Honary F, Kosch MJ, McCoy RP, Mishin EV, Rietveld MT (2018) Past, present and future of active radio frequency experiments in space. Space Sci Rev 214:118. https://doi.org/10.1007/s11214-018-0549-7

Sun J, Pan L, Tsang DCW, Zhan Y, Zhu L, Li X (2018) Organic contamination and remediation in the agricultural soils of China: a critical review. Sci Total Environ 615:724–740. https://doi.org/10.1016/j.scitotenv.2017.09.271

Szymański K, Mozia S, Ayral A, Brosillon S, Mendret J (2023) Hybrid system coupling ozonation and nanofiltration with functionalized catalytic ceramic membrane for ibuprofen removal. Environ Sci Pollut Res 30:69042–69053. https://doi.org/10.1007/s11356-023-27225-5

Tan Y, Zhao W, Sun L, Zhang R, Hou J, Fu S, Xu W, Zhang R (2022) Photocatalytic abatement of formaldehyde under visible light irradiation via bamboo carbon/TiO2 modified by plasma at low temperature. J Clean Prod 369:133280. https://doi.org/10.1016/j.jclepro.2022.133280

Tang S, Yuan D, Rao Y, Li N, Qi J, Cheng T, Sun Z, Gu J, Huang H (2018) Persulfate activation in gas phase surface discharge plasma for synergetic removal of antibiotic in water. Chem Eng J 337:446–454. https://doi.org/10.1016/j.cej.2017.12.117

Tian F, Tang J, Zeng J, Luo Z, Zhang L, Tang F, Han Z, Yang X (2022) Degradation of atrazine by Ni-doped sulfidated microscale zerovalent iron: mechanistic insights for enhanced reactivity and selectivity. Chem Eng J 435:135120. https://doi.org/10.1016/j.cej.2022.135120

Tiwari B, Sellamuthu B, Ouarda Y, Drogui P, Tyagi RD, Buelna G (2017) Review on fate and mechanism of removal of pharmaceutical pollutants from wastewater using biological approach. Bioresource Technol 224:1–12. https://doi.org/10.1016/j.biortech.2016.11.042

Topolovec B, Škoro N, Puač N, Petrovic M (2022) Pathways of organic micropollutants degradation in atmospheric pressure plasma processing – a review. Chemosphere 294:133606. https://doi.org/10.1016/j.chemosphere.2022.133606

Torrinha Á, Oliveira TMBF, Ribeiro FWP (2020) Application of nanostructured carbon-based electrochemical (bio)sensors for screening of emerging pharmaceutical pollutants in waters and aquatic species: a review. Nanomaterials Basel 10:1268. https://doi.org/10.3390/nano10071268

Vanraes P, Willems G, Daels N, Van Hulle SWH, De Clerck K, Surmont P, Lynen F, Vandamme J, Van Durme J, Nikiforov A, Leys C (2015) Decomposition of atrazine traces in water by combination of non-thermal electrical discharge and adsorption on nanofiber membrane. Water Res 72:361–371. https://doi.org/10.1016/j.watres.2014.11.009

Varela RA, Vázquez Contreras FP, De Los Santos Villalobos S, Alvarez Valencia LH, Ulloa Mercado RG, Serrano Palacios D (2021) Removal of endosulfan in a sequencing batch reactor: addition of granular activated carbon as improvement strategy. Water Environ J 35:390–401. https://doi.org/10.1111/wej.12637

Verdini F, Abramova A, Boffa L, Calcio Gaudino E, Cravotto G (2024) The unveiling of a dynamic duo: hydrodynamic cavitation and cold plasma for the degradation of furosemide in wastewater. Sci Rep 14:6805. https://doi.org/10.1038/s41598-024-57038-6

Vethaak AD, Lahr J, Schrap SM, Belfroid AC, Rijs GBJ, Gerritsen A, De Boer J, Bulder AS, Grinwis GCM, Kuiper RV, Legler J, Murk TAJ, Peijnenburg W, Verhaar HJM, De Voogt P (2005) An integrated assessment of estrogenic contamination and biological effects in the aquatic environment of The Netherlands. Chemosphere 59:511–524. https://doi.org/10.1016/j.chemosphere.2004.12.053

Wallace SJ, De Solla SR, Head JA, Hodson PV, Parrott JL, Thomas PJ, Berthiaume A, Langlois VS (2020) Polycyclic aromatic compounds (PACs) in the Canadian environment: exposure and effects on wildlife. Environ Pollut 265:114863. https://doi.org/10.1016/j.envpol.2020.114863

Wang T, Qu G, Sun Q, Liang D, Hu S (2015) Evaluation of the potential of p-nitrophenol degradation in dredged sediment by pulsed discharge plasma. Water Res 84:18–24. https://doi.org/10.1016/j.watres.2015.07.022

Wang J, Sun Y, Feng J, Xin L, Ma J (2016) Degradation of triclocarban in water by dielectric barrier discharge plasma combined with TiO_2/activated carbon fibers: effect of operating parameters and byproducts identification. Chem Eng J 300:36–46. https://doi.org/10.1016/j.cej.2016.04.041

Wang B, Xu M, Chi C, Wang C, Meng D (2017) Degradation of methyl orange using dielectric barrier discharge water falling film reactor. J Adv Oxid Technol. https://doi.org/10.1515/jaots-2017-0021

Wang S, Wang J, Sun Y (2017b) Degradation of chlorinated paraben by integrated irradiation and biological treatment process. J Environ Manage 189:29–35. https://doi.org/10.1016/j.jenvman.2016.11.067

Wang Y, Li J, Ding C, Sun Y, Lin Y, Sun W, Luo C (2017) Synthesis of surface plasma photocatalyst Ag-loaded TiO_2 nanowire arrays/graphene oxide coated carbon fiber composites and enhancement of the photocatalytic activity for tetracycline hydrochloride degradation. J Photochem Photobiol A Chem 342:94–101. https://doi.org/10.1016/j.jphotochem.2017.04.002

Wang X, Mei J, Luo J, Huang Y, Dionysiou DD (2022a) Process intensification of tetrabromobisphenol S removal with a bubble-film hybrid plasma reactor. Chem Eng J 427:131736. https://doi.org/10.1016/j.cej.2021.131736

Wang X, Zhang Z, Zhang R, Huang W, Dou W, You J, Jiao H, Sun A, Chen J, Shi X, Zheng D (2022) Occurrence, source, and ecological risk assessment of organochlorine pesticides and polychlorinated biphenyls in the water–sediment system of Hangzhou Bay and East China Sea. Mar Pollut Bull 179:113735. https://doi.org/10.1016/j.marpolbul.2022.113735

Wardenier N, Liu Z, Nikiforov A, Van Hulle SWH, Leys C (2019) Micropollutant elimination by O_3, UV and plasma-based

AOPs: an evaluation of treatment and energy costs. Chemosphere 234:715–724. https://doi.org/10.1016/j.chemosphere.2019.06.033

Williams ML, Fitzgerald A, Alonso D (2026) Comparison of solid phase microextraction coatings for headspace extraction of volatile perfluoroalkyl substances using one-dimensional and comprehensive two-dimensional gas chromatography. Anal Chim Acta 1403:345389. https://doi.org/10.1016/j.aca.2026.345389

Wu M, Xie D, Xu G, Sun R, Xia X, Liu W, Tang L (2017) Benzophenone-type UV filters in surface waters: an assessment of profiles and ecological risks in Shanghai, China. Ecotoxicol Environ Saf 141:235–241. https://doi.org/10.1016/j.ecoenv.2017.03.013

Wu L, Xie Q, Lv Y, Wu Z, Liang X, Lu M, Nie Y (2019) Degradation of methylene blue via dielectric barrier discharge plasma treatment. Water 11:1818. https://doi.org/10.3390/w11091818

Xin L, Sun Y, Feng J, Wang J, He D (2016) Degradation of triclosan in aqueous solution by dielectric barrier discharge plasma combined with activated carbon fibers. Chemosphere 144:855–863. https://doi.org/10.1016/j.chemosphere.2015.09.054

Yin Y, Xu H, Zhu Y, Zhuang J, Ma R, Cui D, Jiao Z (2023) Recent progress in applications of atmospheric pressure plasma for water organic contaminants' degradation. Appl Sci 13:12631. https://doi.org/10.3390/app132312631

Yu Z, Sun Y, Zhang G, Zhang C (2017) Degradation of DEET in aqueous solution by water falling film dielectric barrier discharge: effect of three operating modes and analysis of the mechanism and degradation pathway. Chem Eng J 317:90–102. https://doi.org/10.1016/j.cej.2017.02.068

Zamri MFMA, Bahru R, Suja' F, Shamsuddin AH, Pramanik SK, Fattah IMR (2021) Treatment strategies for enhancing the removal of endocrine-disrupting chemicals in water and wastewater systems. J Water Proc Eng 41:102017. https://doi.org/10.1016/j.jwpe.2021.102017

Zekker I (2022) Editorial to efficient catalytic and microbial treatment of water pollutants. Water 14:995. https://doi.org/10.3390/w14060995

Zhang Y, Xin Q, Cong Y, Wang Q, Jiang B (2013) Application of TiO_2 nanotubes with pulsed plasma for phenol degradation. Chem Eng J 215–216:261–268. https://doi.org/10.1016/j.cej.2012.11.045

Zhang X, Lee BJ, Im HG, Cha MS (2016) Ozone production with dielectric barrier discharge: effects of power source and humidity. IEEE Trans Plasma Sci 44:2288–2296. https://doi.org/10.1109/TPS.2016.2601246

Zhang S, He Y, Wu L, Wan J, Ye M, Long T, Yan Z, Jiang X, Lin Y, Lu X (2019) Remediation of organochlorine pesticide-contaminated soils by surfactant-enhanced washing combined with activated carbon selective adsorption. Pedosphere 29:400–408. https://doi.org/10.1016/S1002-0160(17)60328-X

Zhang J, Xia A, Yao D, Guo X, Lam SS, Huang Y, Zhu X, Zhu X, Liao Q (2022) Removal of oxytetracycline and ofloxacin in wastewater by microalgae-bacteria symbiosis for bioenergy production. Bioresource Technol 363:127891. https://doi.org/10.1016/j.biortech.2022.127891

Zhao C, Xue L, Zhou Y, Zhang Y, Huang K (2021) A microwave atmospheric plasma strategy for fast and efficient degradation of aqueous p-nitrophenol. J Hazard Mater 409:124473. https://doi.org/10.1016/j.jhazmat.2020.124473

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Mohammed Abdulsalam[1,2] · Bernard Gitura Kimani[1] · Kiran Ahlawat[1] · Zdenko Machala[1]

✉ Mohammed Abdulsalam
mohammed.abdulsalam@fmph.uniba.sk

[1] Division of Environmental Physics, Faculty of Mathematics, Physics, and Informatics, Comenius University in Bratislava, Mlynská Dolina, Bratislava 842 48, Slovakia

[2] Agricultural and Bio-Resources Engineering Department, Engineering Faculty, Ahmadu Bello University, Zaria 810107, Nigeria