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CRITICAL REVIEW

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Non-thermal plasma for the removal of pharmaceuticals from water: a systematic evaluation of configurations, efficiency, and implementation barriers

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Pharmaceutical pollution in aquatic environments represents a persistent global challenge, as conventional wastewater treatment plants fail to remove recalcitrant compounds such as antibiotics. Non-thermal plasma-based technologies have gained significant attention as efficient and versatile approaches for degrading emerging contaminants through chemical oxidation and mineralisation, typically without the addition of chemical reagents. However, a comprehensive synthesis of their effectiveness and limitations is still needed to evaluate their environmental relevance. This systematic review critically assesses 62 peer-reviewed research studies published between 2009 and 2025, covering 21 pharmaceutical classes and multiple plasma configurations. The review additionally examines temporal and geographic research trends, mechanistic pathways, transformation product toxicity, and antimicrobial resistance implications. Dielectric barrier discharge (DBD) plasma dominates the literature (51.6%), followed by corona discharge (19.4%) and atmospheric plasma jets (11.3%). High parent compound removal or degradation (>90%) is consistently reported across pharmaceutical classes, with antibiotics (33%) being the most frequently studied. Despite this progress, most investigations remain at laboratory scale, and considerable variability and limited standardisation persist in performance metrics, mineralisation efficiency, toxicity assessment, and energy reporting. Energy efficiency remains a principal constraint, hindering meaningful comparison with established treatment technologies and comprehensive techno-economic assessment. Future research should prioritise energy-efficient reactor design, standardised methodologies, system scale-up, testing in real wastewater matrices, and integration within sustainable energy–water systems to support the transition from laboratory research to full-scale implementation. Overall, this review highlights the potential of non-thermal plasma technologies for pharmaceutical removal while identifying key challenges that must be addressed to facilitate their practical deployment.

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Water impact

This review advances understanding of cold plasma technologies in water treatment to remove emerging contaminants, including pharmaceuticals such as antibiotics. By synthesising 62 studies across multiple plasma configurations, it highlights high removal efficiencies (>90%) while identifying variability in performance, mineralisation, toxicity, and energy metrics. The findings underscore the potential of cold plasma to improve water quality, with further research needed on wastewater matrices and toxicity assessment of degradation products.

1. Introduction

1.1 Pharmaceutical pollution in aquatic environments

Pharmaceuticals represent a cornerstone of modern medicine and contribute to increased life expectancy, reduced mortality, and improved health outcomes worldwide. However, this growth in consumption, combined with population expansion and global economic development, has resulted in widespread contamination of environmental matrices, including water, soil, sludge, and sediments, through multiple pathways (Fig. 1).[1] The global pharmaceutical market was valued at USD 1646 billion in 2024 and is projected to reach USD 2350 billion by 2030, underscoring the sustained expansion of pharmaceutical production, consumption, and global distribution.[2]

A primary concern is the high recalcitrance of pharmaceutical compounds in aquatic and terrestrial ecosystems, which results

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from their chemical stability, resistance to biodegradation, and incomplete removal in conventional wastewater treatment plants. Pharmaceuticals such as antibiotics, non-steroidal anti-inflammatory drugs (NSAIDs), analgesics, hormones, endocrine disruptors, antiretrovirals, and antimetabolites have been detected in drinking water, tap water, groundwater, and surface water on all continents (Fig. 2 and 3).[3–7]

Pharmaceutical compounds are classified as emerging contaminants due to limited monitoring frameworks and incomplete regulatory coverage, together with their potential risks to human and ecological health. Although the long-term effects remain under investigation, recent studies demonstrate that even low concentrations can induce adverse effects in organisms and ecosystems. Reported impacts include teratogenicity, carcinogenicity, bioaccumulation, antibiotic resistance, hormonal disruption, and neurological disorders (Table 1).

1.2 Plasma-based water treatment technologies

Addressing pharmaceutical pollution requires a multifaceted strategy that includes improved manufacturing and disposal practices, enhanced wastewater treatment, and increased public awareness. Conventional wastewater treatment plants apply chemical (*e.g.*, chlorination, coagulation/flocculation, ion exchange, chemical oxidation, and catalysis), biological (*e.g.*, activated sludge), and physical processes (*e.g.*, filtration and membrane separation such as reverse osmosis and thermal sterilisation), each with specific advantages and limitations.[8–10] Chemical processes introduce additional reagents and may generate harmful by-products. Filtration requires costly infrastructure and is not effective for all contaminants, including viral particles. Boiling is time-consuming and impractical at scale. Given the limited removal efficiency for recalcitrant pharmaceuticals, conventional systems are frequently supplemented with advanced oxidation processes (AOPs).

AOPs, such as photolysis, electron beam irradiation, plasma technologies, supercritical water oxidation, microwave plasma-based processes, ultrasound cavitation, electrochemical advanced oxidation processes, wet air oxidation, water sonolysis, and photolytic combinations, generate highly reactive and non-selective species, particularly hydroxyl radicals (·OH). These species oxidise organic pollutants and can lead to partial or complete mineralisation into less harmful products, thereby reducing the need for secondary treatment.

Recent research demonstrates the significant potential of non-thermal (cold) plasma technology for degrading antibiotics, dyes, pesticides, and viruses such as SARS-CoV-2, while also disrupting bacterial biofilms.[11–14] Plasma treatment provides high removal efficiency, rapid operation, flexibility, adaptability, and integration potential with other processes, together with sterilisation and disinfection capabilities. Plasma generates reactive oxygen and nitrogen species (ROS/RNS), including ·OH, O_3, H_2O_2, NO, $ONOO^-$, and $O_2^{\bullet-}$, and induces secondary reactive species through interactions with the surrounding chemical environment.[15–17] These chemical effects are complemented by physical effects such as UV radiation, electric fields, and ionizing particles. The combination of short-lived and long-lived species enables both chemical degradation and microbial inactivation.

In wastewater treatment, plasma discharges are classified as liquid-phase, gas-phase, or hybrid gas–liquid systems based on reactor design and plasma distribution. Configurations include dielectric barrier discharge (DBD), corona discharge, plasma jets, plasma needles, gliding arcs, spark discharges, glow discharges, and miniature hollow cathodes. Among emerging plasma reactor designs, a falling film reactors have gained increasing attention for water treatment applications. In this configuration, a thin liquid film flows along a surface while being exposed to plasma generated in the gas phase, enhancing interfacial contact between reactive species and the liquid phase. This design improves mass transfer efficiency, increases the exposure of pollutants to reactive oxygen and nitrogen species, and reduces diffusion limitations compared to bulk liquid systems. As a result, falling film reactors can achieve enhanced degradation rates and improved energy utilisation. Moreover, this configuration is considered promising due to its scalability, relatively simple hydrodynamic control, and potential for continuous operation, making it a strong candidate for integration into non-thermal plasma-based water treatment systems. Fig. 4 illustrates representative plasma configurations and their associated treatment processes.

Despite these advances, knowledge gaps remain regarding degradation pathways, plasma behaviour in complex wastewater matrices containing multiple pharmaceuticals and radical scavengers, and the toxicity of intermediates and by-products. The lack of standardised protocols, reactor configurations, and reporting metrics limits meaningful comparison of degradation efficiency, mineralisation performance, energy consumption, and economic feasibility.

Collectively, these limitations highlight the need for a systematic evaluation of plasma-based technologies to enable meaningful comparison across studies and to identify critical barriers to real-world application.

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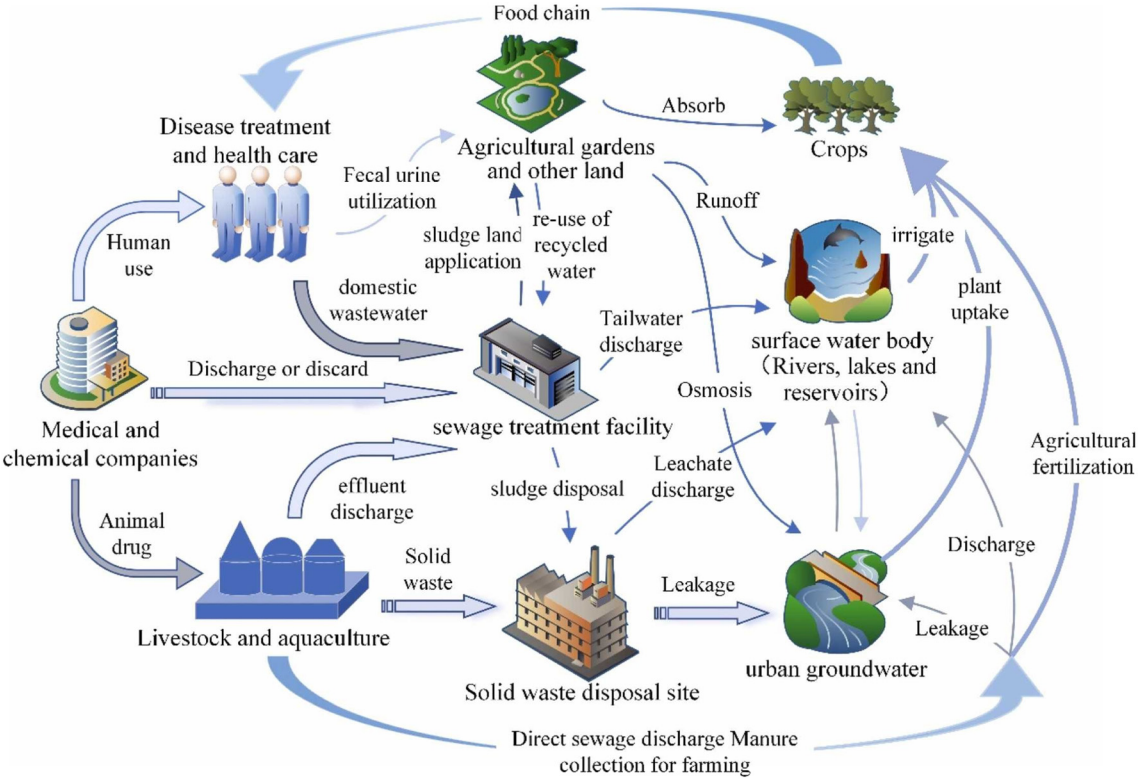


Fig. 1 Pathways of pharmaceutical release into environmental matrices adapted from ref. 3.

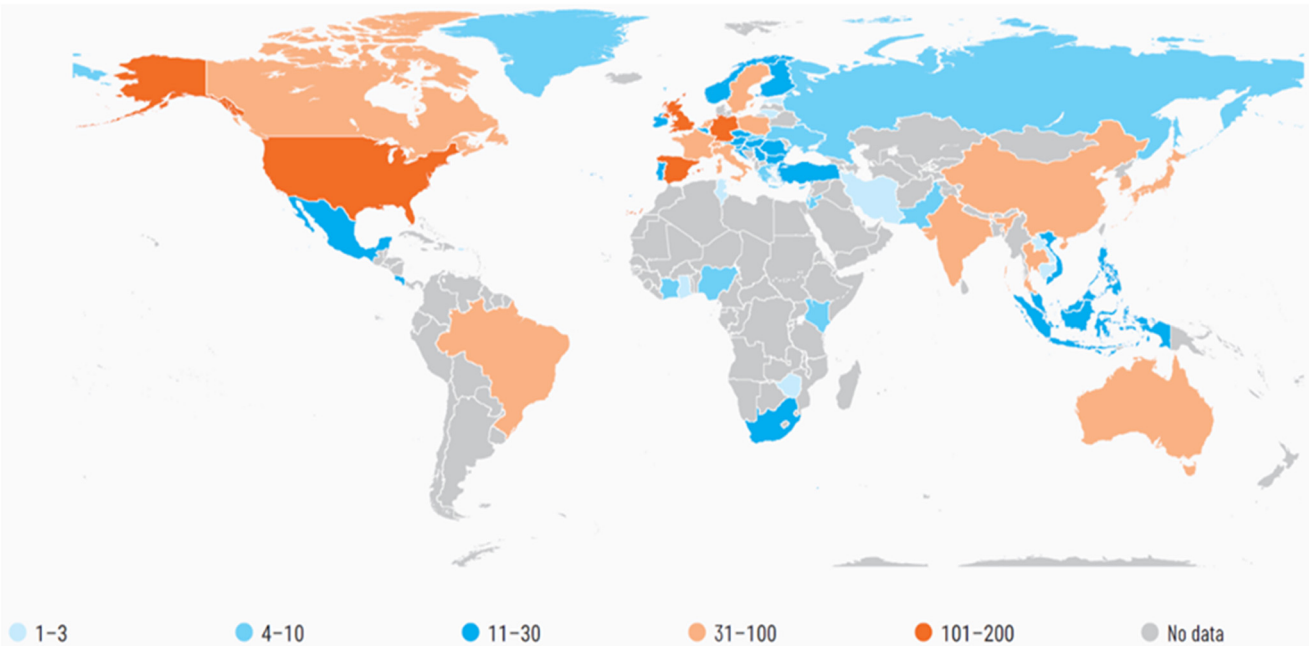


Fig. 2 Drug distribution worldwide in drinking water, tap water, groundwater, and surface water.[5]

1.3 Scope and objectives

Research on plasma-based technologies has expanded substantially over the past decade. Several review articles describe plasma principles, reactor design, and applications. However, most reviews focus on specific compounds or reactor types and do not provide a systematic comparison of plasma configurations and removal efficiencies across studies.[3,10–12,15,18–21] Moreover, temporal research trends are rarely analysed, which limits the ability to identify development patterns and research gaps. Previous reviews

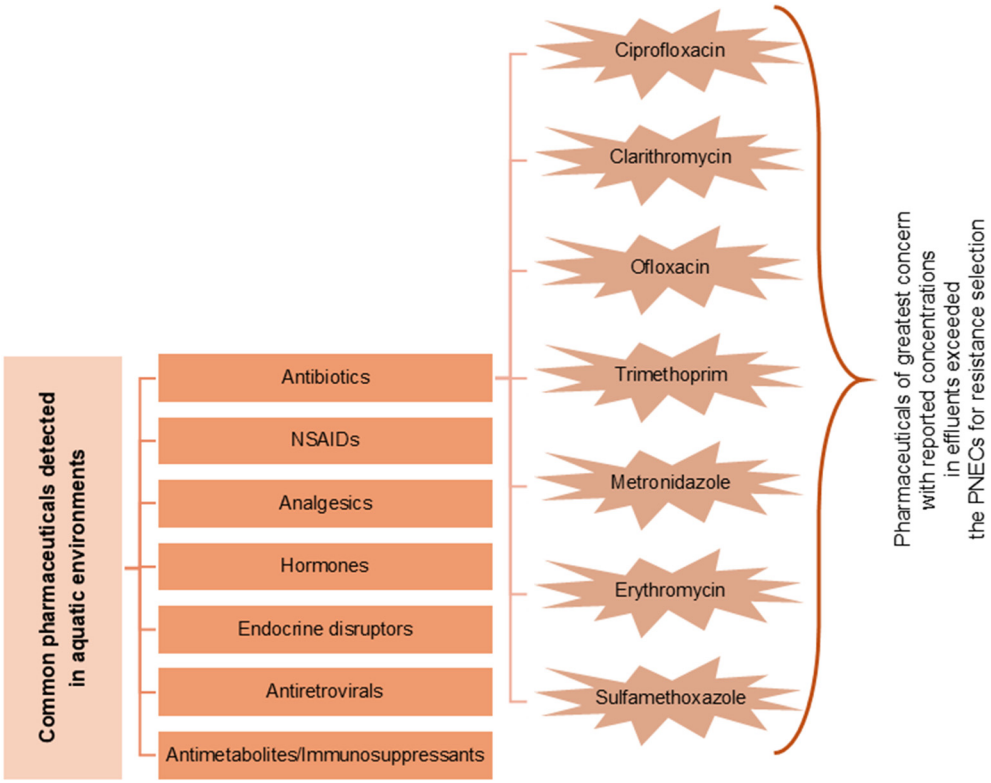


Fig. 3 Common pharmaceuticals detected in aquatic environments (PNEC: predicted no-effect concentrations).

have focused on specific plasma reactors, contaminants, or performance aspects. This study presents the first systematic review integrating plasma type, pharmaceutical class, performance metrics, and global research distribution to provide a comprehensive assessment of research progress and the implementation potential of plasma-based pharmaceutical degradation technologies.

The present review provides a comparison of non-thermal plasma-based technologies developed for the removal of pharmaceutical contaminants from aqueous environments, including both laboratory-scale and real wastewater systems. The analysis is based on pharmaceutical classes and operational conditions reported in the literature. Specifically, the review addresses the following research questions:

1. What are the temporal trends in plasma-based water treatment for pharmaceuticals?

2. Which plasma configurations have been investigated?

3. Which pharmaceutical compounds and classes have been studied?

4. What are the key limitations, research gaps, and opportunities for scale-up and implementation?

2. Methodology

2.1 Search strategy, eligibility, and inclusion

The preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines were followed to ensure a transparent and reproducible literature search. The review comprised four stages: identification, screening, eligibility, and inclusion. Fig. 5 presents the corresponding PRISMA flow diagram.

Eight electronic databases were systematically searched: ScienceDirect, PubMed, Scopus, IEEE Xplore, Wiley Online Library, Springer Link, Taylor & Francis Online, and ProQuest. ProQuest was included to capture grey literature and thereby reduce publication bias. Studies published between January 2000 and August 2025 were identified using combinations of the following keywords: "plasma", "non-thermal plasma", "thermal plasma", "plasma electrolysis", "advanced oxidation processes", "pharmaceutical", "antibiotics", "removal", "degradation", "treatment", "water", "wastewater", and "aqueous". These terms were combined using Boolean operators within the advanced search interface of each database.

All identified records were imported into Mendeley Reference Manager, and duplicates were removed. Snowball sampling was applied by screening the reference lists of selected articles. A two-phase screening process (title and abstract followed by full-text assessment) was conducted according to predefined inclusion and exclusion criteria.

Peer-reviewed original research articles published in English between January 2000 and August 2025 were considered eligible if they investigated plasma-based technologies for the removal or degradation of pharmaceutical compounds in aqueous environments and reported quantitative or qualitative treatment efficiency data.

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Table 1 Impact of pharmaceutical contaminants on the environment and human health[7]

Pharmaceutical class	Impact
β-blockers (vasodilator/cardiovascular drug subclass)	Immobilization in *Daphnia similis* Mortality in green algae Mortality in fish Growth and development problems in algae such as *Synechococcus leopolensis* and *Cyclotella meneghiniana* Mortality in crustacea (*Ceriodaphnia dubia*) Embryonic development problems in *Danio rerio*
Non-steroidal anti-inflammatory drugs (NSAIDs) and analgesics	Cardiovascular abnormalities, hatch and motor behaviour and interruption of oocyte maturation/ovulation in *Danio rerio* Population declines of *Gyps vultures* Prostate gland synthesis and damage to the gills, liver, and kidneys of *Salmo trutta f. fario* Histological alterations of the kidneys and gills, cytological alterations of the liver, kidneys, and gills, and deterioration of ionic regulation in *Oncorhynchus mykiss* Inhibits CYP2M in *Cyprinus carpio* Alteration of oestrogenic activity, response of specific tissue biomarkers, decreased superoxide dismutase and glutathione reductase activities in the gills, and increased catalase activity and lipid peroxidation levels in the digestive gland in *Mytilus galloprovincialis* Change in the breeding pattern of *Oryzias latipes* Reduce the shoot and root lengths; fresh and dry weights; leaf area, and chlorophyll a and b; carotenoid; total chlorophyll; mineral (K and Mg); glutathione reductase; and soluble protein contents of *Vigna unguiculata* Algae and aquatic plants are severely affected Block the electron chain of photosystems II and increase oxidative stress (photosynthesis inhibitors) Prolonged exposure to low concentrations can lead to developing resistance over several generations
Antibiotics	*Hydra attenuata* show relatively high tolerance to acute toxicity Crustaceans such as *Artemia salina*, *Daphnia magna*, and *Ceriodaphnia dubia* show relatively low acute toxicity Invertebrates such as *Hydra attenuata* and crustaceans such as *Artemia salina*, *Daphnia magna*, and *Ceriodaphnia dubia* show relatively low acute toxicity in the presence of antibiotics
Endocrine disruptors	Block or imitate the natural hormones responsible for the functioning of some organs in both humans and animals Alter the reproductive system Alzheimer's disease Thyroid problems Obesity and/or cancer Affected the reproductive system Levels of vitellogenin and hatchability Cytotoxic, genotoxic, mutagenic, and teratogenic effects in any eukaryotic organism Groups at greatest risk are children, pregnant women, and the elderly Caused histopathological changes in the liver and kidney and impaired the integrity of their DNA, introducing massive changes in the entire transcriptome in *Danio rerio*
Antimetabolites and immunosuppressants	Resistant strains of HIV can be created in the body through exposure to water contaminated with these drugs Anaemia Nausea Hypersensitivity Nephrotoxicity and renal failure Rash

Non-English publications, inaccessible full texts, reviews, conference abstracts, editorials, book chapters, and studies lacking relevant performance data were excluded.

2.2 Data extraction and synthesis

A total of 3519 records were identified, of which 2115 were retained after the initial screening. Subsequently, 556 articles underwent full-text assessment. Following application of the eligibility criteria and risk-of-bias evaluation, 62 studies were included in the final analysis.

The following data were extracted: (1) first author and year of publication; (2) pharmaceutical compound; (3) plasma type; (4) reported treatment performance (removal, degradation, or mineralisation, as defined by the respective authors); and (5) country of the corresponding author's affiliation. The dataset comprised studies conducted in both synthetic water matrices spiked with pharmaceuticals and real wastewater samples. Table 2 summarizes the main characteristics of the included studies. Bibliometric analysis was conducted using VOSviewer (version 1.6.20) to examine co-occurrence relationships among the included studies. This

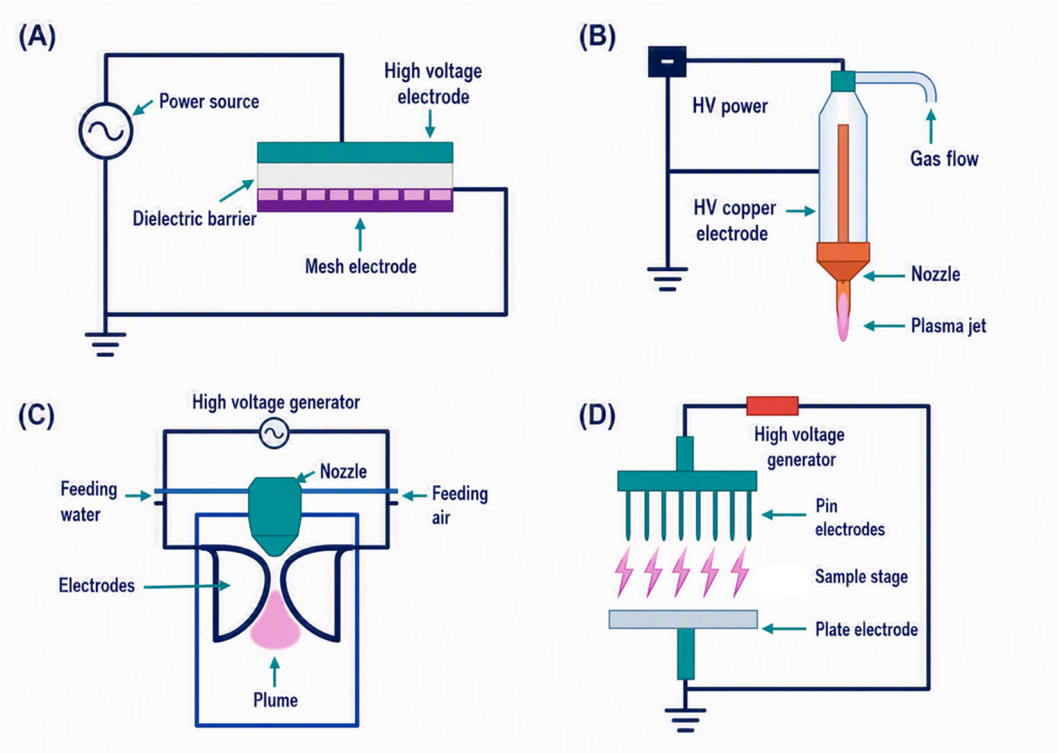


Fig. 4 Plasma configurations used in wastewater treatment: (A) dielectric barrier discharge, (B) plasma jet, (C) gliding arc and (D) corona plasma reactor, adapted from ref. 9.

approach offers a perspective for identifying research hotspots and development trends.

2.3 Risk of bias assessment

Internal and external validity were evaluated through full-text assessment using predefined criteria addressing selection, performance, detection, attrition, and reporting bias. Each criterion was scored on a scale from 0 to 2 according to the degree of compliance, and the total score was normalized to a 0–100 scale. Studies classified as having a high risk of bias (score <33) were excluded from the data extraction phase.

3. Results and discussion

3.1 From molecular degradation to risk reduction: reframing plasma performance

Across the 62 studies analysed, non-thermal plasma technologies consistently achieved rapid degradation of parent pharmaceutical compounds, frequently exceeding 80–95% removal under optimized laboratory conditions.[3] However, chromatographic disappearance does not inherently equate with environmental safety. From a public health perspective, treatment performance must be evaluated in terms of biological activity suppression, toxicity evolution, and reduction of long-term exposure risk, rather than solely percentage degradation.

Pharmaceutical contamination in aquatic systems represents a chronic, low-dose exposure issue affecting ecosystems and potentially human populations through drinking water abstraction and food-chain transfer. Therefore, plasma efficacy should be interpreted as a function of its ability to attenuate biological effects, including antimicrobial activity, endocrine disruption potential, and cytotoxicity, rather than being assessed solely as a chemical transformation process.[6] This broader perspective is essential for understanding the full implications of plasma treatment as reflected in Table 2, which summarizes treatment efficiencies and the biological impacts observed across studies.

3.2 Thematic analysis

Full counting methodology was employed to conduct a co-occurrence analysis of keywords based on bibliographic data. The minimum occurrence threshold for keywords was set to 10, resulting in a total of 878 keywords, of which 34 met the threshold. The results presented in Table 3 (top 10 keywords) demonstrate the main research focuses and trends in plasma-based technologies for pharmaceutical removal over the past 15 years.

Five principal keywords were identified: “degradation”, “article”, “plasma applications”, “electric discharges”, and “plasma”, which highlight the central research themes on the topic. The generic term “article” was excluded from interpretation due to its limited thematic value.

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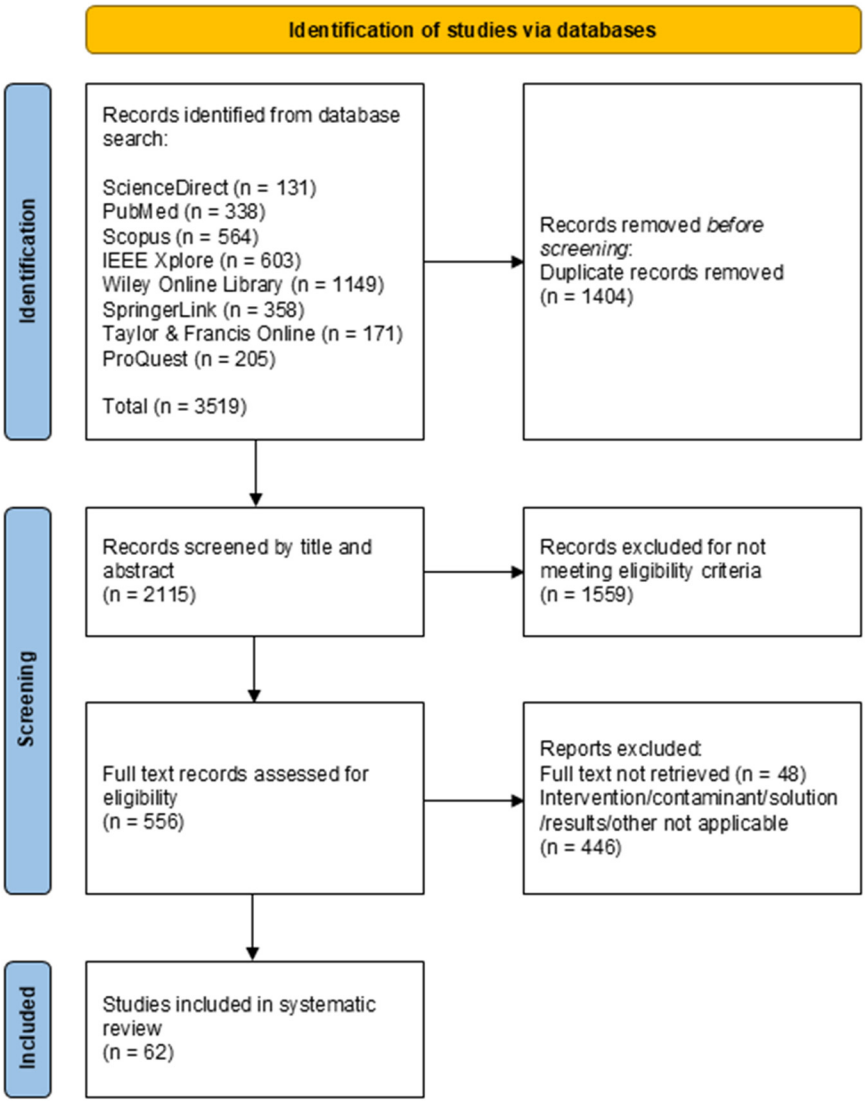


Fig. 5 PRISMA flow chart outlining the search and selection strategy.

3.3 Spatial landscape and collaboration patterns

In total, the selected literature appraised in this review encompasses 62 studies from 22 countries spanning six continents (Asia, Europe, North America, South America, Africa, and Oceania) (Fig. 6).

China leads the research efforts, contributing 27.4% of the total dataset followed by Romania (9.7%) and India (8.1%) demonstrating contributions to this critical area of research. Other countries, including Finland, France, Germany, Italy, South Korea, the United States, Belgium, the Netherlands, and the United Kingdom, each contributed between 3.2% and 4.8%, underscoring the broad international interest.

A notable temporal-geographical correlation is evident in the evolution of research activity. Early studies (2009–2013) were primarily Europe-based; the progression phase (2014–2019) reflected balanced contributions between Europe and Asia, whereas the most recent period (2020–2024) demonstrates a distinct shift toward Asia, accompanied by increasing output from other countries worldwide.

3.4 Distribution of pharmaceutical classes investigated

Across the 62 studies included in this review (Table 2, Fig. 7), 21 distinct pharmaceutical classes were investigated. The distribution of compounds reflects both their environmental prevalence in wastewater matrices and the evolving research priorities within AOP studies.

Antibiotics represent the largest category, accounting for approximately 33% of all investigated compounds. Frequently studied representatives include sulfamethoxazole, sulfamethizole, sulfadiazine, tetracyclines, fluoroquinolones, and β-lactams. Their predominance is consistent with growing global concern regarding antimicrobial resistance (AMR), environmental persistence, and the potential for sub-inhibitory concentrations to exert selective pressure in aquatic ecosystems.

Table 2 Summary of studies included in the systematic review

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
Antibiotics	Sulfamethoxazole	Dielectric barrier discharge (DBD) plasma	Complete removal (~100% at 10 μM) in <25 min; degradation efficiency enhanced at lower concentrations and higher pH Exhaustive mineralisation (~100%) in 6 hours Energy efficiency of 6.4 g kWh^{-1} at 50% conversion	Italy	22
	Sulfamethoxazole	DBD plasma bubbling reactor	Removal reaches below detection limit (~100%) after 7 and 30 min for low and moderate concentrations, with higher efficiency at lower initial concentrations Fast and efficient removal achieving $Y_{50\%}$ = 8.12 g kWh^{-1}	United Kingdom	23
	Sulfamethoxazole	Double cylindrical DBD (DCDBD) reactor	Complete mineralisation and degradation (~100% at 40 mg L^{-1}) were achieved after 30 min at rate constants of 3.79 × 10^{-2} min^{-1} The energy yield G_{50} required for the degradation of 50% SMX reached 34.64 g kWh^{-1}	Republic of South Africa	24
	Sulfamethoxazole	DBD plasma coupled with calcium peroxide (CaO_2)	96% degradation at 20 mg L^{-1} achieved within 20 min with rate constant k = 0.153 min^{-1} 36.7% mineralisation after 20 min G_{50} = 2.75 g kWh^{-1}	China	25
	Sulfamethoxazole	Pulsed corona discharge plasma in oxygen coupled with ozonation	Complete removal (~100%) in 10–40 min (0.1–0.5 mM) Partial mineralisation (25–28% for carbon, 34% for nitrogen, and 52% for sulfur at 0.5 mM in 60 min) Higher concentrations slowed degradation kinetics and limited mineralisation efficiency 20.1–42 g kWh^{-1} at 90% removal	Romania	26
	Sulfamethoxazole	DBD plasma jet	99.5% after 5 min at 20 mg L^{-1} 90.0% mineralisation in 20 min Higher concentrations slowed degradation Up to 2.79 g kWh^{-1} energy yield	China	27

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Table 2 *(continued)*

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
	Sulfamethizole	Pulsed corona discharge	99% removal: 24 min (500 pps), 40 min (200 pps), 100 min (50 pps) Highest $\varepsilon_{1/2}$ (≈120 g kWh^{-1}) was observed at 50 pps	Finland	28
	Sulfadiazine	Water falling film DBD	98% degradation in 30 min with 25% mineralisation	China	29
	Sulfadiazine	Wetted-wall corona discharge reactor	Complete removal (~100%) at 10 mg L^{-1} in 30 min (100 W), with 23% mineralisation (can be enhanced to two-fold with Fe^{2+} or CCl_4) Higher initial concentrations slowed kinetics and reduced mineralisation efficiency	China	30
	Sulfathiazole, sulfamethazine, sulfamethoxazole	DBD plasma	Complete degradation (~100%) with O_2 plasma: sulfamethazine (15 min), sulfathiazole (30 min), sulfamethoxazole (60 min) Mineralisation: ≤40% TOC after 60 min Energy efficiency (60% removal): 30.8–41.3 J mg^{-1} (oxygen) *vs.* 53.1–80.2 J mg^{-1} (air)	South Korea	31
	Cefixime	Non-thermal plasma (NTP) bubble column reactor	99.8% with O_2 plasma in 30 min, 94.8% with air plasma Mineralisation: 73.1% in 30 min Energy efficiency: Up to 1.5 g kWh^{-1} (10-hole reactor, 30 min) Influences: lower concentration & higher pH improved efficiency	Australia	32
	Ampicillin	Floating electrode dielectric barrier discharge (FE-DBD) (non-thermal)	Complete degradation (~100%) in 3–5 min at 20 mM	USA	33
	Amoxicillin, ciprofloxacin, tetracycline, sulfamethoxazole	Cold atmospheric plasma (CAP)	≥90% for all antibiotics in 5 min, 100% removal of ampicillin and sulfamethoxazole in 10 min 22–35% mineralisation after 30 min (highest = sulfamethoxazole, 34.6%) 2.8 g kWh^{-1} (sulfamethoxazole, G_{50})	United Kingdom	34
	Amoxicillin, oxacillin, ampicillin	DBD	Removal: amoxicillin 10 min (~100%), oxacillin 30 min and ampicillin 30 min (≥90%) Mineralisation: 22.5–29% after 120 min Energy efficiency: 27 g kWh^{-1} (oxacillin), 105 g kWh^{-1} (amoxicillin), 29 g kWh^{-1} (ampicillin)	Romania	35

Table 2 *(continued)*

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
	Amoxicillin, cefuroxime, ofloxacin, ciprofloxacin	Pulsed corona discharge	Removal (15 min): ofloxacin 72.13%, amoxicillin 75.80%, cefuroxime 99.20%, ciprofloxacin 99.60%	Vietnam	36
	Norfloxacin	DBD coupled with H_2O_2/Fe^{2+}	Removal: >98% in 0.5 min (DBD + H_2O_2 + Fe^{2+}) Mineralisation: up to 72.3% in 15 min (DBD/Fe^{2+})	China	37
	Tetracycline	Pulsed DBD	Removal: 92.3% at 50 mg L^{-1} (30 min) and mineralisation up to 65.01% Higher concentrations slowed down degradation efficiency and kinetic rate Energy efficiency: 20.24 g kWh^{-1} (at 50 mg L^{-1})	China	38
	Tetracycline	Pulsed corona discharge	82.64% removal in 60 min (50 mg L^{-1}) Energy yield: up to 1.05 × 10^{-2} g kWh^{-1}	China	39
	Tetracycline	Corona discharge plasma coupled with nanoscale TiO_2 catalysis	Removal: 98.7% (25 mg L^{-1}, 24 min) Mineralisation: up to 53.4% (1.5 g L^{-1} TiO_2, 24 min)	China	40
	Tetracycline	Gliding arc discharge	Removal 94.95% and mineralisation 81.3% (5 mg L^{-1}, 30 min, O_2 plasma)	South Korea	41
	Metronidazole	Glow plasma discharge (GPD) coupled with hydrodynamic cavitation (HC-GPD)	90% degradation after 15 min at 300 μmol L^{-1}	Brazil	42
	Ciprofloxacin	Submerged thermal plasma generated by a DC non-transferred arc hollow cathode plasma torch	Removal: 99% (10 mg L^{-1}, 20 min) Mineralisation: 60% TOC removal (25 mg L^{-1}, 20 min) Energy efficiency: 176.98 mg kWh^{-1} (25 mg L^{-1}, 5 min)	India	43
	Ciprofloxacin	Gas–liquid discharge non-thermal plasma using a needle-type atmospheric discharge reactor	Removal: 93.4% in 24 min (10 mg L^{-1}) Mineralisation: 47.4% in 24 min Energy efficiency: 7.3 mg kWh^{-1}	China	44
	Ofloxacin and ciprofloxacin	DBD	Removal: 92% ofloxacin, 89% ciprofloxacin in 25 min (10 mg L^{-1})	Ireland	45
	Levofloxacin	DBD coupled with Ag_3PO_4/activated carbon fibers (ACFs) as catalyst	Removal: 93% in 18 min (20 mg L^{-1}, with catalyst) Mineralisation: 46% with catalyst Energy efficiency: up to 0.866 g kWh^{-1}	China	46

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Table 2 *(continued)*

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
	Pefloxacin	DBD	Removal: Up to 97.7% in 25 min (10 mg L^{-1}) Mineralisation: 46.9% in 25 min Energy efficiency: Up to 39.6 g kWh^{-1} (120 mg L^{-1})	China	47
	Clindamycin	Non-thermal plasma (NTP)	Removal: 100% in 10–15 min Mineralisation: 50% in 15 min	Iran	48
	Oxytetracycline, sulfadiazine, levofloxacin	Pin-to-plate DBD plasma system combined with vacuum ultraviolet and ultraviolet C	Oxytetracycline: removal: 93.2% in 2.5 min (10 mg L^{-1}) Mineralisation: 0.47 mg C min^{-1} Energy efficiency: reported as G_{50} values (2 g kWh^{-1})	China	49
	Lincomycin, ciprofloxacin, enrofloxacin, chlortetracycline, oxytetracycline, sulfathiazole, sulfamethoxazole, sulfamethazine, and trimethoprim	DBD	Most efficient degradation: sulfathiazole (60% at 0.26 kJ mg^{-1}; 90% at 0.39 kJ mg^{-1}) Least efficient degradation: ciprofloxacin (60% at 1.49 kJ mg^{-1}; 90% at 2.06 kJ mg^{-1})	South Korea	50
ACE inhibitors	Enalapril	DBD	>99% removal in 120 min (50 mg L^{-1}) 40% total organic carbon (TOC), 50% chemical oxygen demand (COD) in distilled water after 120 min	Romania	51
	Enalapril, enalaprilat, diketopiperazine	DBD	Removal: enalaprilat: 100% in 60 min (50 mg L^{-1}). Enalapril: 99.4% in 120 min. Diketopiperazine: ~50% in 120 min Mineralisation: 40% TOC removal in 120 min Energy efficiency: enalaprilat: up to 34.6 g kWh^{-1} (50% removal), 20.66 g kWh^{-1} (90%). Enalapril: 13.64 g kWh^{-1} (50%), 4.33 g kWh^{-1} (90%). Diketopiperazine: 3.04 g kWh^{-1} (50%)	Romania	52
Angiotensin II receptor blockers (ARBs)	Valsartan	Non-equilibrium atmospheric pressure plasma (NEAPP) jet	Removal: 49% in 10 min (NEAPP + ZnO nanoparticles) Mineralisation: 5.43% TOC (plasma alone); best with ZnO but no % reported	India	53
	Telmisartan + hydrochlorothiazide (Telma-H)	Non-thermal atmospheric pressure plasma jet	Removal: 63% in 20 min	India	54

Table 2 *(continued)*

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
Diuretics	Furosemide	Electrical discharge (ED) cold plasma, hybrid with hydrodynamic cavitation	100% in 10 min (50 mg L^{-1}) Energy efficiency: 82–350 mg kWh^{-1} (highest at 50 mg L^{-1})	Italy	55
Vasodilators	Pentoxifylline	DBD	Removal: up to 92.5% in 60 min (100 mg L^{-1}) 19–20 g kWh^{-1} at 90% removal for 100–150 mg L^{-1}	Romania	56
Hormones	17β-Estradiol (E2)	DBD + Pt–TiO_2 photocatalyst	DBD + Pt–TiO_2: 98.9% in 30 min with energy efficiency of 468.1×10^{-6} g kWh^{-1}	China	57
	17α-Ethinylestradiol	DBD with a falling water film on activated carbon textile	Removal: >85% (200 μg L^{-1} spiked) under optimized cascade ozonation + DBD plasma conditions, with EE/O = 2.3–5.3 kWh m^{-3}	Belgium	58
	1,7-α-Ethinylestradiol	Plasma-ozonation using a pulsed DBD plasma reactor combined with an ozonation chamber	>99.8% in 10 min (EE/O): 4.48 kWh m^{-3}	Belgium	59
Contrast agents/diagnostic	Iopromide	DBD	99% removal within 10 min	China	60
Anticonvulsants	Carbamazepine	*Ex situ* and *in situ* DBD	*Ex situ* superior: 100% 3 to 60 min, with 48.2% total organic carbon (TOC) removal (mineralisation)	China	61
	Carbamazepine	DBD	>90% removal in pure water with an energy yield of 0.19–0.45 g kWh^{-1}	France	62
	Carbamazepine	Liquid-phase discharge plasma	Degradation: 99% in 5 min at 225 W Mineralisation: CBZ and intermediates fully degraded/mineralized within 5 min (no detectable LC-MS signals) Energy yield: up to 0.11 g kWh^{-1} at 225 W	China	63
Analgesics (non-opioid)	Paracetamol	DBD coupled with heterogeneous Fenton-like catalyst	Complete removal (~100%) after 60 min (plasma alone) Mineralisation: up to 54% TOC removal in 60 min with plasma–catalyst coupling Energy yield: 2.9–4.4 g kWh^{-1} for plasma alone; improved by 160–200% with plasma–catalyst coupling	France	64
	Paracetamol	DBD	Removal: 100% of 10 mg L^{-1} within 5 min; up to 99% at 25 mg L^{-1} in 30 min Mineralisation: TOC removal 46.3% after 20 min	China	65

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Table 2 *(continued)*

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
	Paracetamol	DBD	81% degradation after 60 min	France	66
Antimetabolites/immunosuppressants	Methotrexate	Non-thermal arc pencil plasma jet (NT-PPJ)	Degradation: (~100%) within 9 min (first-order, $k = 0.38$ min^{-1}) Mineralisation: 84.54% TOC removal after 9 min	India	67
NSAIDs (non-steroidal anti-inflammatory drugs)	Diclofenac	Non-thermal atmospheric pressure plasma jet (APPJ)	Removal: 98% in 20 min Mineralisation: 43% TOC removal (20 min) Energy efficiency: $G_{50} = 0.45$ g kWh^{-1}	Serbia	68
	Diclofenac	Pulsed corona discharge	Removal: (~100%) after 15 min Mineralisation: 50% TOC removal after 30 min	Romania	69
Multiple groups	Carbamazepine, iopromide, phenol	Non-thermal positive DBD, corona above thin water film on rotating drum	Phenol degraded fastest (complete in 15 min) Carbamazepine degraded well (>99% in 90 min) Iopromide was most recalcitrant (max 67–75% in mixtures, 19–40% in landfill leachate)	Germany	70
	Carbamazepine, iopromide	Non-thermal positive DBD, corona above thin water film	Carbamazepine: up to 98% removal in 30 min; 97–99% with optimized atmosphere Iopromide: up to 99% removal in 30 min; complete loss of estrogenic activity after 15 min	Germany	71
	Paracetamol, β-oestradiol, indomethacin, ibuprofen	Pulsed corona discharge	Most efficient degradation: indomethacin (complete (~100%) at 0.5–1 kWh m^{-3}) Mineralisation: highest for indomethacin (35%), low for paracetamol (11%) and ibuprofen (26%) Energy efficiency: indomethacin highest (158–172 g kWh^{-1} in oxygen)	Finland	72
	Paracetamol, atenolol, caffeine, carbamazepine, diclofenac, furosemide, hydrochlorothiazid, ibuprofen, metoprolol, naproxen, paracetamol, propranolol, sulfamethoxazole, venlafaxine	Thermal plasma (hot arc)	Most efficient degradation: 100% removal within 5 min for paracetamol, diclofenac, ibuprofen, naproxen, propranolol, venlafaxine Moderate degradation: 60–90% removal for carbamazepine, atenolol, metoprolol, sulfamethoxazole Lowest degradation: ≤70% for caffeine, furosemide, hydrochlorothiazide Mineralisation: 38% TOC reduction (mixture) Energy efficiency: 0.12–0.35 g kWh^{-1}	Netherlands	73

Table 2 *(continued)*

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
	Carbamazepine, diatrizoate, diazepam, diclofenac, ibuprofen, 17α-ethinylestradiol, trimethoprim	Pulsed corona discharge	~100% removal (below detection) in 5–15 min for carbamazepine, diclofenac, ibuprofen, 17α-ethinylestradiol, trimethoprim Diazepam ~90% in 30 min Diatrizoate least degraded, 40–50% in 30 min Mineralisation: 35–40% TOC reduction after 30 min Energy efficiency: 0.08–0.12 g kWh^{-1}	Germany	74
	Caffeine, paracetamol, methylprednisolon, progesterone, bisoprolol, carbamazepine, citalopram, diclofenac, fluoxetine, furosemide, hydrochlorothiazid, ketoprofen, metoprolol, metronidazole, naproxen, propranolol, salbutamol, sotalol, trimethoprim, warfarin, ibuprofen	Pulsed corona discharge	All fully removed (100%) at 0.5–1.0 kWh m^{-3} except: caffeine (resistant, only ~19% removed but biodegradable elsewhere), metronidazole (only 36% removed in hospital wastewater, but fully removed in Rinnekoti effluent), ibuprofen (partly removed, influenced by metabolite reformation), progesterone and methylprednisolone (not present initially, formed during oxidation)	Finland	75
	Paracetamol, atenolol, 17α-ethynyl estradiol, ibuprofen, naproxen, sulfamethoxazole	DBD	All six degraded with first-order rate constants between 4.95×10^{-4} and 1.46×10^{-3} s^{-1} in plasma Plasma treatment was resilient to urine matrix effects but had lower energy efficiency (12–237 kWh m^{-3}/order) compared to UV/H_2O_2	USA	76
	Diclofenac, sulfamethoxazole, trimethoprim, carbamazepine, caffeine	Cold atmospheric plasma jet	Most efficient removal: trimethoprim (98%), followed by diclofenac (91%), then sulfamethoxazole (73%) Poor removal: carbamazepine (1%), caffeine (0%)	Poland	77
	Valsartan, sulfamethoxazole, trimethoprim, naproxen, diclofenac, tramadol, propyphenazone, carbamazepine, 17β-estradiol	Sub-atmospheric-pressure non-thermal plasma ignited in supercavitation bubble coupled with rotational generator of hydrodynamic cavitation (RGHC)	99% removal (17β-estradiol), 89% (diclofenac), 33–65% (other compounds) Energy yield: 1–26 mg kWh^{-1} (best: 17β-estradiol and diclofenac at 9–26 mg kWh^{-1})	Slovenia	78
	Diclofenac, ibuprofen, naproxen, hydrochlorothiazid, carbamazepine, ciprofloxacin, metronidazole	Non-thermal arc plasma (flashover discharge) in a hyperbolic vortex reactor	Removal: diclofenac (≥99.3%), ibuprofen and naproxen >70%, hydrochlorothiazide 70%, carbamazepine 60%, ciprofloxacin 50%, metronidazole 35%	Netherlands	79

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Table 2 *(continued)*

Pharmaceutical class	Compound	Plasma type	Treatment performance	Author affiliation country	Ref.
	Metformin, atenolol, paracetamol, ranitidine	Pulsed corona discharge	Removal: metformin 94%, atenolol 86%, paracetamol 84%, ranitidine 93% Mineralisation: 38–55%, highest for metformin and ranitidine Energy efficiency: 0.84–1.52 g kWh^{-1}	India	80
	Carbamazepine, trimethoprim, meprobamate, primidone, dilantin, atenolol	Nonthermal plasma (corona discharge)	Carbamazepine and trimethoprim degraded most rapidly in all experiments; moderately recalcitrant compounds are atenolol, primidone, dilantin; recalcitrant is meprobamate Energy efficiency range: <0.3 to 14 kWh m^{-3}-log, depending on compound and water matrix (best for carbamazepine and trimethoprim, poorest for meprobamate)	USA	81
	Methylene blue, phenol, caffeine, paracetamol, ceftriaxone	DBD	Degradation: ceftriaxone complete (100%) at 5 min, paracetamol complete at 15 min, methylene blue complete in 25 min, phenol complete at 20 min, caffeine complete at 30 min Most energy-efficient: phenol (1.0 g kWh^{-1}), least energy-efficient: ceftriaxone (0.17 g kWh^{-1})	Italy	82
	Diclofenac, carbamazepine, sulfamethoxazole	Gas-phase pulsed corona discharge plasma	Degradation: diclofenac (90%), sulfamethoxazole (80%), carbamazepine (60%) in 10 min Mineralisation (TOC): diclofenac 40% > sulfamethoxazole 30% > carbamazepine 20% 2.5 g kWh^{-1} for diclofenac, 1.8 g kWh^{-1} for sulfamethoxazole, and 1.2 g kWh^{-1} for carbamazepine	Austria	83

Anticonvulsants constitute the second most represented class (11%), primarily driven by carbamazepine, a well-documented recalcitrant compound frequently detected in surface waters and wastewater effluents. Non-steroidal anti-inflammatory drugs and non-opioid analgesics each account for approximately 9% of the investigated compounds, reflecting their high consumption rates and incomplete removal in conventional wastewater treatment systems.

Hormones (7%), beta-blockers (4%), and contrast agents (4%) represent additional clinically relevant categories. The inclusion of endocrine-active compounds and diagnostic agents demonstrates increasing recognition that plasma treatment must address not only concentration reduction but also biological activity attenuation at environmentally relevant levels.

Overall, the broad spectrum of pharmaceutical classes investigated highlights the expanding scope of plasma-based oxidation research. However, the uneven distribution of compound classes also reveals research concentration around antibiotics and a limited exploration of emerging therapeutic categories, suggesting areas for future investigation.

Table 3 Most highly co-occurring keywords

Ranking	Keyword	Cluster	Occurrences	Links	Total link strength
Top 1	Degradation	2	37	33	327
Top 2	Article	1	23	33	264
Top 3	Plasma applications	2	21	33	188
Top 4	Electric discharges	2	20	32	146
Top 5	Plasma	1	18	33	219
Top 6	Nonthermal plasma	3	18	33	185
Top 7	Oxidation	1	16	33	173
Top 8	Dielectric devices	2	16	32	153
Top 9	Dielectric barrier discharge	2	15	32	164
Top 10	Antibiotics	2	15	33	147

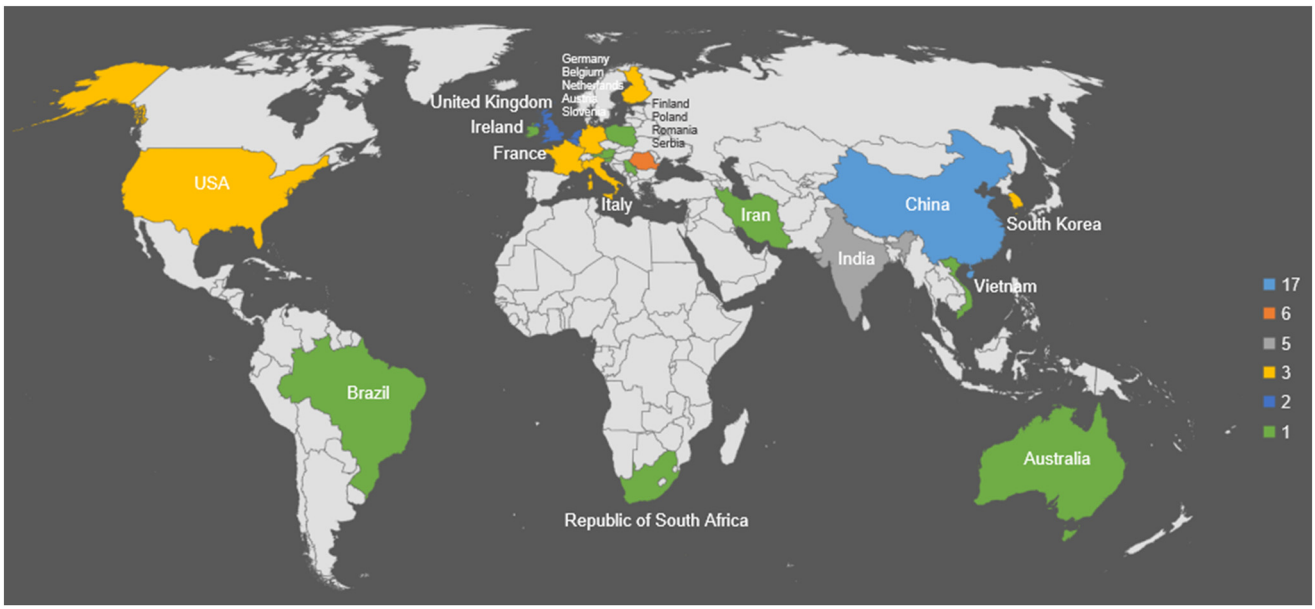


Fig. 6 Country-wise distribution of research publications.

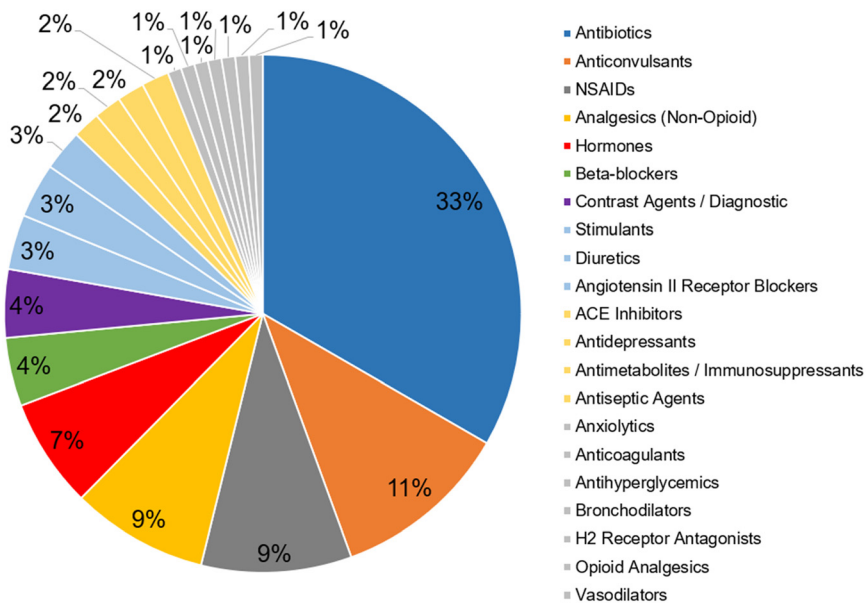


Fig. 7 Distribution of pharmaceutical classes investigated in the reviewed studies.

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3.5 Mechanistic basis of plasma-induced pharmaceutical oxidation

Non-thermal plasma systems operate as highly non-equilibrium reactors capable of generating a complex mixture of reactive oxygen and nitrogen species (ROS/RNS) *in situ*. These include hydroxyl radicals (·OH), atomic oxygen (O·), ozone (O_3), hydrogen peroxide (H_2O_2), superoxide ($O_2^{\bullet-}$), nitric oxide (NO·), nitrite (NO_2^-), and nitrate (NO_3^-), which collectively govern the oxidation of pharmaceutical contaminants in aqueous environments.[16]

The formation of these species is initiated in the gas phase through electron–impact reactions driven by energetic electrons generated within the plasma discharge. Electron collisions with O_2, H_2O, and N_2 molecules induce excitation, ionisation, and dissociation processes. In particular, water vapour dissociation produces hydroxyl radicals (·OH) and hydrogen atoms, while oxygen dissociation yields atomic oxygen (O·), which subsequently contributes to ozone (O_3) formation through multi-step reactions. These reactions establish a strongly oxidative gas-phase environment that serves as the primary source of reactive species.

At the gas–liquid interface, a fraction of these reactive species is transferred into the aqueous phase, where they undergo secondary chemical reactions. Long-lived oxidants such as hydrogen peroxide (H_2O_2), nitrite (NO_2^-), and nitrate (NO_3^-) are formed through dissolution and redox reactions. In plasma-in-liquid systems, additional short-lived radicals are generated directly within the liquid phase *via* hydrated electron (e_{aq}^-) reactions and localised electric field effects, significantly enhancing oxidative activity. The mechanistic coupling between electron–impact plasma chemistry, gas–liquid interfacial transfer, and aqueous-phase radical reactions underpins the broad oxidative capability of non-thermal plasma systems, enabling simultaneous generation of multiple reactive species that act synergistically across both short-lived and long-lived oxidation pathways.[18]

The degradation of pharmaceuticals is governed by a coupled gas-phase–liquid-phase reaction network in which short-lived radicals (·OH, $O_2^{\bullet-}$) and long-lived oxidants (O_3, H_2O_2, NO_x-derived species) act synergistically. Short-lived species drive rapid and non-selective oxidation of parent compounds, whereas long-lived oxidants sustain secondary reactions in the bulk solution.

These processes involve hydroxylation, electron abstraction, dealkylation, decarboxylation, and aromatic ring opening, leading to partially oxidised intermediates. Despite efficient parent compound degradation, total organic carbon (TOC) removal typically remains moderate (20–60%) under standard conditions, indicating incomplete mineralisation (Fig. 8).[25–26,84]

Enhanced mineralisation efficiencies (>70–80%) are achieved only under intensified conditions such as high energy density operation, plasma-in-liquid systems, oxygen-enriched atmospheres, or coupling with catalytic processes including Fenton-like reactions or photocatalysis.[11] This highlights that plasma performance depends not only on radical generation but also on reactor design, interfacial transport, and energy input.

3.6 Reactor configuration and plasma–liquid interaction

As noted earlier, plasma-based systems demonstrate a diverse range of configurations. The process-based distribution of research using different plasma types is summarized in Fig. 9 and Table 4.

A marked temporal evolution is observed in plasma research trends, reflecting changes in reactor development

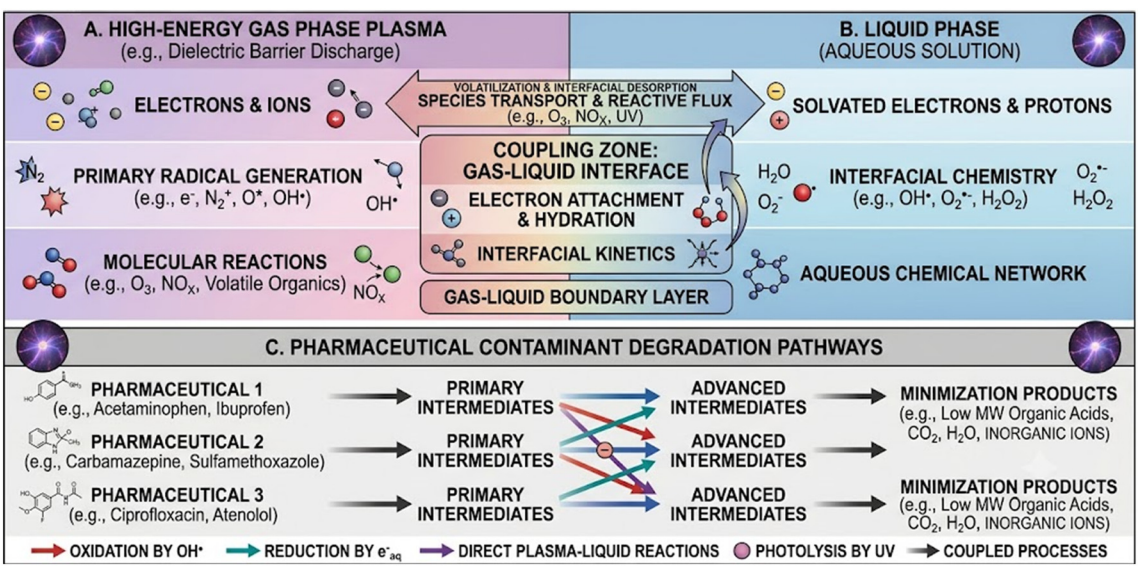


Fig. 8 Multi-layered chemical reaction pathways in gas–liquid plasma networks. Conceptual overview of the coupled gas-phase and liquid-phase reaction networks governing the advanced oxidation and mineralisation of pharmaceutical contaminants.

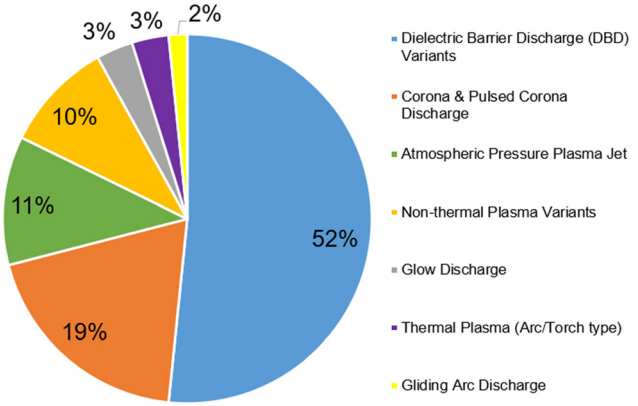


Fig. 9 Process-based distribution of research publications.

and application focus (Fig. 10). Early studies (2009–2013) were dominated by dielectric barrier discharge (DBD) systems and corona discharges. During the intermediate phase (2014–2019), atmospheric pressure plasma jets and hybrid configurations emerged. In the most recent period (2020–2024), research activity has diversified toward novel and hybrid plasma systems, although DBD and corona discharges remain widely used.

Substantial heterogeneity exists in plasma configurations, including DBD, corona discharge, atmospheric plasma jets, gliding arc systems, and plasma-in-liquid designs. This variability has important mechanistic implications and strongly influences reactive species distribution and interfacial transport processes.[46] Surface discharge systems primarily generate long-lived oxidants (*e.g.*, ozone and hydrogen peroxide) that diffuse into the aqueous phase, resulting in efficient parent compound oxidation but often limited mineralisation due to mass transfer constraints. In contrast, plasma-in-liquid systems generate short-lived radicals directly within the aqueous bulk, enhancing bond cleavage and accelerating oxidation depth.[27] However, these systems require higher energy input and present challenges related to electrode erosion, operational stability, and scalability. Notably, cross-study comparisons are limited by inconsistent energy normalisation metrics.[18]

In recent years, hybrid configurations combining non-thermal plasma with conventional advanced oxidation processes (AOPs) have gained increasing attention due to synergistic effects in pollutant degradation. For example, plasma–H_2O_2 and plasma–Fenton systems enhance hydroxyl radical production, improving mineralisation efficiency compared to standalone plasma treatment.[47] Similarly, plasma–UV and plasma–photocatalysis systems (*e.g.*, TiO_2-based) promote electron–hole generation and sustain reactive species formation under reduced energy input.[48] Plasma–ozonation hybrids further benefit from *in situ* ozone activation and accelerated formation of secondary reactive oxygen species, enhancing oxidation pathways.[49] Overall, these hybrid systems can mitigate limitations of single plasma processes, particularly in terms of energy efficiency and treatment completeness, although reactor integration and process optimisation remain key challenges.

A comparison of the energy efficiencies and scaling challenges between surface discharge and plasma-in-liquid systems is summarised in Table 5, which offers a direct comparison between surface DBD and plasma-in-liquid systems, further highlighting differences in radical generation, mass transfer limitations, energy efficiency, and scalability.[34]

3.7 Water matrix effects and environmental realism

A critical limitation across the literature is the predominance of experiments conducted in deionized or simplified synthetic matrices. Real wastewater contains bicarbonate, carbonate, chloride, natural organic matter (NOM), metals, and mixed contaminant loads that compete for reactive species. Bicarbonate and carbonate scavenge hydroxyl radicals, forming less reactive carbonate radicals. Chloride ions can produce reactive chlorine species, potentially generating chlorinated intermediates. Natural organic matter reduces oxidant availability and alters degradation kinetics.[4] Studies evaluating hospital or municipal effluents consistently report lower degradation efficiencies and reduced energy yields compared to synthetic systems.[25] Consequently, laboratory results likely overestimate real-world performance.[76]

From a public health standpoint, validation of plasma-based systems in more complex, real-world matrices is essential to accurately assess their environmental relevance, treatment effectiveness, and capacity to reduce contaminant-related exposure risks.[5]

3.8 Transformation products and toxicity evolution

Although most studies document parent compound removal using chromatographic techniques, relatively few conduct

Table 4 Process-based distribution of research publications on non-thermal plasma systems for pharmaceutical degradation (n = 62)

Plasma type	Studies	Number of studies (n = 62)
Dielectric barrier discharge (DBD) variants	22–26, 29, 31, 33, 35, 37, 38, 45–47, 49–52, 56–62, 64–66, 70, 71, 76, 82	32
Corona & pulsed corona discharge	28, 30, 36, 39, 40, 69, 72, 74, 75, 80, 81, 83	12
Atmospheric pressure plasma jet	27, 34, 53, 54, 67, 68, 77	7
Non-thermal plasma variants	32, 44, 48, 55, 78, 79	6
Glow discharge	42, 63	2
Thermal plasma (arc/torch type)	43, 73	2
Gliding arc discharge	41	1

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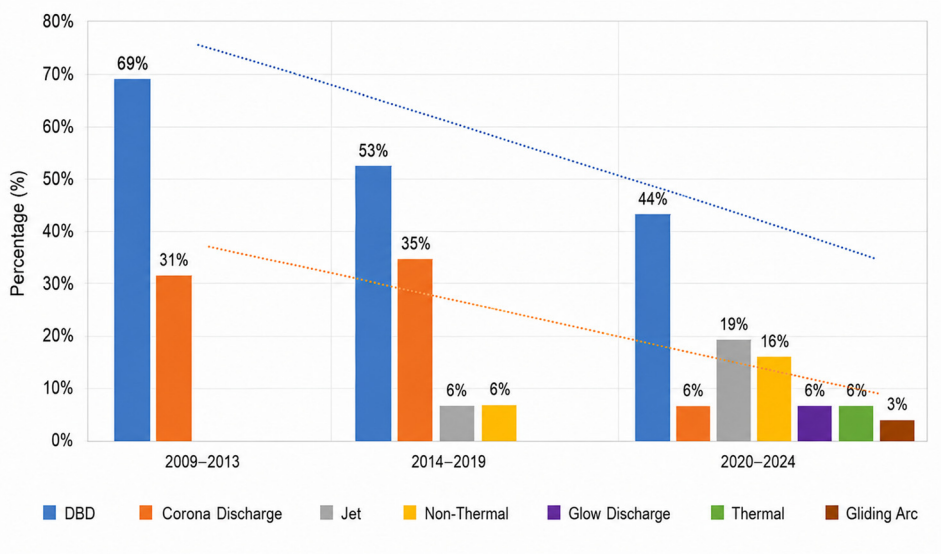


Fig. 10 Process-based distribution of research publications over time.

comprehensive identification of transformation products using high-resolution mass spectrometry, whereas even fewer assess toxicity evolution during treatment.[19] Plasma oxidation produces hydroxylated derivatives, ring-opened intermediates, aldehydes, organic acids, and nitrogen-containing fragments. These intermediates may exhibit altered polarity, mobility, or biological activity.[3] Total organic carbon reduction alone cannot serve as a proxy for detoxification. Risk-relevant evaluation should include:

- Acute and chronic ecotoxicity assays
- Bioassay-guided toxicity tracking
- Endocrine receptor activity testing
- Genotoxicity and mutagenicity screening

Without such integration, chemical removal data remain insufficient to confirm environmental and public health protection. Fig. 11 illustrates a conceptual risk pathway linking plasma oxidation to biological effects and public health implications, underscoring the necessity for toxicity testing alongside chemical removal.[10]

3.9 Antibiotics and antimicrobial resistance mitigation

Antibiotics constitute the most frequently investigated class in plasma studies. Environmental antibiotic residues contribute to selective pressure on microbial communities, promoting the propagation of resistance genes. Even sub-inhibitory concentrations may drive horizontal gene transfer.[11,36] Although plasma treatment generally reduces antibiotic concentrations rapidly, few studies assess residual antimicrobial activity or resistance gene dynamics. Structural modification of antibiotics does not necessarily eliminate pharmacological activity.

Table 5 Summary of plasma configurations and their characteristics[13]

Feature	Surface DBD	Plasma-in-liquid
Radical source	Gas phase	Direct liquid
Dominant oxidant	O_3	·OH, solvated electrons
Mass transfer limitation	Yes	Reduced
Energy density	Moderate	High
Mineralisation potential	Moderate	Higher
Scalability	Easier	More complex

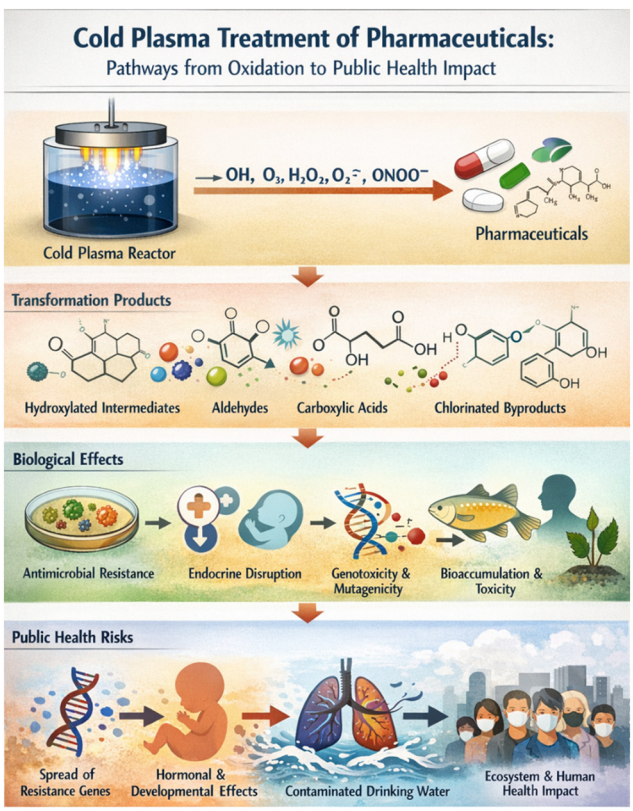


Fig. 11 Schematic risk pathway linking plasma oxidation to biological effects and public health implications.

Given that antimicrobial resistance is identified by the World Health Organization as a major global health threat, plasma systems should be evaluated for the following:

- Reduction in minimum inhibitory concentration (MIC) activity
- Suppression of resistance gene abundance
- Impact on microbial community structure

Such microbiological validation is essential to confirm that plasma treatment contributes meaningfully to AMR mitigation rather than merely altering chemical structure.[11]

3.10 Endocrine disruptors and low-dose biological effects

Hormonal pharmaceuticals exert biological effects at ng L^{-1} concentrations. For endocrine-active compounds, elimination of receptor-binding activity is more relevant than complete mineralisation.

Partial oxidation products may retain affinity for oestrogen or androgen receptors. Therefore, plasma treatment performance for endocrine disruptors should be evaluated using *in vitro* receptor assays and integrated bioanalytical tools rather than relying solely on concentration decline. Failure to assess endocrine activity risks underestimating ecological and developmental consequences of residual transformation products.

3.11 Cytotoxic compounds and genotoxic risk

Cytotoxic and antimetabolite drugs present unique challenges due to inherent genotoxicity. Oxidative fragmentation may reduce concentration but generate reactive intermediates capable of DNA interaction.[53,54] Few reviewed studies incorporate genotoxicity assays or DNA damage biomarkers. Given the mutagenic potential of some pharmaceutical classes, precautionary evaluation frameworks should integrate genotoxicity screening to ensure that plasma treatment does not inadvertently generate genotoxic intermediates.

3.12 Scalability, sustainability, and energy efficiency challenges

Energy consumption remains the principal barrier to large-scale implementation. Reported performance metrics vary widely, limiting direct comparison among studies.[20,59] Moreover, deep mineralisation typically requires substantially higher energy input than initial molecular transformation.[29] In addition, the predominance of laboratory-scale studies and the limited number of pilot-scale investigations continue to restrict assessment of operational feasibility under realistic treatment conditions. Therefore, further validation in real wastewater systems, together with techno-economic evaluation, is necessary to support large-scale deployment.

Key conclusions on plasma-based technologies for pharmaceutical removal are presented in Table 6.

Energy demand is not solely a technical parameter but also a sustainability and equity consideration. Regions disproportionately affected by pharmaceutical pollution and antimicrobial resistance may lack infrastructure to support energy-intensive technologies.[8] Aligning plasma technology with sustainable deployment models is essential to translate laboratory success into environmental and global public health outcomes, highlighting the need for energy-efficient systems.

3.13 Strategic outlook: toward interdisciplinary validation

Non-thermal plasma represents a versatile advanced oxidation platform capable of rapid pharmaceutical transformation and simultaneous disinfection.[8,13] However, its transition from promising laboratory technology to credible environmental health intervention requires interdisciplinary validation integrating advanced analytical chemistry, toxicology, microbiology and environmental engineering

Future research should emphasise real effluent testing, transformation product profiling, antimicrobial resistance assessment, endocrine activity evaluation, and pilot-scale studies under energy-optimized conditions.[77] To consolidate these recommendations, Table 7 summarises the key future perspectives and strategic priorities for plasma-based pharmaceutical removal.

Collectively, the evidence indicates that non-thermal plasma technologies provide high oxidative capability for pharmaceutical degradation. Yet chemical disappearance alone does not ensure environmental safety or public health protection. Treatment efficacy must be defined by elimination of biological activity, mitigation of antimicrobial resistance pressure, prevention of endocrine disruption, suppression of genotoxic intermediate formation, and sustainable energy deployment. Bridging these dimensions will determine whether plasma-based systems evolve from experimental oxidation tools into robust, scalable solutions for pharmaceutical pollution control in the context of global environmental health.

Table 6 Key conclusions on plasma-based technologies for pharmaceutical removal from aqueous environments

Rank	Conclusion/finding
1	Plasma technologies effectively degrade a wide spectrum of pharmaceuticals and organic pollutants in water
2	Hydroxyl radicals, ozone, and other reactive oxygen and nitrogen species are the primary agents responsible for oxidation and mineralisation
3	Reactor design, discharge type, operational parameters, and gas composition critically affect removal or degradation efficiency and energy yield
4	Combination with catalysts or other advanced oxidation processes enhances performance and mineralisation
5	High pollutant removal does not always correspond to complete mineralisation; intermediate and transformation products often persist

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Table 7 Key future perspectives on plasma-based technologies for pharmaceutical removal from aqueous environments

Rank	Future perspectives/recommendations
1	Optimise energy efficiency and reduce power consumption through improved reactor design, discharge control, and renewable power integration
2	Conduct scaling-up and pilot-scale studies to bridge the gap between laboratory success and industrial application
3	Establish standardised protocols for performance reporting
4	Expand studies to real wastewater and multi-pollutant matrices
5	Investigate degradation pathways and transformation product toxicity using advanced analytical methods

4. Conclusion

This systematic review critically evaluated recent advances in non-thermal plasma technologies for the removal of pharmaceutical contaminants from aqueous environments, with a focus on reactor configurations, degradation performance, and implementation challenges. The analysis of 62 peer-reviewed studies demonstrates that non-thermal plasma systems, particularly dielectric barrier discharge and corona-based configurations, are highly effective in achieving rapid degradation of a wide range of pharmaceutical compounds, frequently exceeding 90% removal, with complete degradation reported under optimised laboratory conditions.

The review highlights the emerging role of advanced reactor designs such as falling film systems and plasma-in-liquid configurations, which enhance gas-liquid interfacial interactions, improve reactive species utilisation, and offer promising pathways toward improved degradation efficiency and process intensification.

Despite these promising results, significant challenges remain. Most studies are limited to synthetic wastewater matrices and laboratory-scale systems, with insufficient evaluation in real environmental conditions. Furthermore, incomplete mineralisation, formation of transformation products, and variability in energy efficiency reporting limit direct comparison between studies and hinder techno-economic assessment.

From a technological perspective, energy consumption and the absence of standardised performance metrics remain the principal barriers to large-scale deployment, as discussed in detail in section 3.12. Progress in these areas will require coordinated effort across reactor engineering, analytical standardisation, and sustainable energy integration.

From a knowledge perspective, this review emphasises that plasma treatment performance should not be evaluated solely based on parent compound degradation, but rather through a broader lens that includes mineralisation efficiency, toxicity reduction, antimicrobial resistance mitigation, and attenuation of endocrine-disrupting activity.

Future research should focus on (i) scale-up and pilot-scale demonstrations, (ii) application in complex full-scale wastewater matrices, (iii) detailed transformation product and toxicity assessment, and (iv) development of energy-efficient and hybrid plasma-based treatment systems.

Overall, non-thermal plasma represents a promising and versatile advanced oxidation platform for pharmaceutical wastewater treatment. However, its transition from laboratory research to full-scale application will depend on addressing key challenges related to energy efficiency, reactor scalability, and environmental safety validation. Addressing these interconnected challenges will be essential for establishing non-thermal plasma as a credible, scalable solution within integrated water treatment frameworks.

Author contributions

Conceptualization, Alevtina Kodresko and Heba Ghazal; writing – original draft preparation, Alevtina Kodresko, Ayman Khalil; writing – review and editing, Alevtina Kodresko, Heba Ghazal and Ayman Khalil; visualisation, Alevtina Kodresko and Heba Ghazal. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

1 O. Z. Wada and D. B. Olawade, Recent Occurrence of Pharmaceuticals in Freshwater, Emerging Treatment Technologies, and Future Considerations: A Review, *Chemosphere*, 2025, **374**, 144153, DOI: 10.1016/J.CHEMOSPHERE.2025.144153.

2 *Pharmaceutical Market Size & Outlook*, 2030, https://www.grandviewresearch.com/horizon/outlook/pharmaceuticals-market-size/global, (accessed 2025-10-04).

3 Y. Wang, J. Song, R. Zhu, M. Peng, J. Long and T. Bao, Degradation of Pharmaceutical Contaminants in Wastewater by Non-Thermal Plasma Technology: A Comprehensive Review, *J. Environ. Chem. Eng.*, 2025, **13**(3), 116150, DOI: 10.1016/J.JECE.2025.116150.

4 M. Patel, R. Kumar, K. Kishor, T. Mlsna, C. U. Pittman and D. Mohan, Pharmaceuticals of Emerging Concern in Aquatic Systems: Chemistry, Occurrence, Effects, and Removal Methods, *Chem. Rev.*, 2019, **119**(6), 3510–3673, DOI: 10.1021/ACS.CHEMREV.8B00299/ASSET/IMAGES/MEDIUM/CR-2018-00299Y_M010.GIF.

5 H. Aib, M. S. Parvez and H. M. Czédli, Pharmaceuticals and Microplastics in Aquatic Environments: A Comprehensive Review of Pathways and Distribution, Toxicological and Ecological Effects, *Int. J. Environ. Res. Public Health*, 2025, **22**(5), 799, DOI: 10.3390/IJERPH22050799.

6 G. Frascaroli, D. Reid, C. Hunter, J. Roberts, K. Helwig, J. Spencer and A. Escudero, Pharmaceuticals in Wastewater Treatment Plants: A Systematic Review on the Substances of Greatest Concern Responsible for the Development of Antimicrobial Resistance, *Appl. Sci.*, 2021, **11**(15), 6670, DOI: 10.3390/APP11156670/S1.

7 M. Ortúzar, M. Esterhuizen, D. R. Olicón-Hernández, J. González-López and E. Aranda, Pharmaceutical Pollution in Aquatic Environments: A Concise Review of Environmental Impacts and Bioremediation Systems, *Front. Microbiol.*, 2022, **13**, 869332, DOI: 10.3389/FMICB.2022.869332/XML.

8 K. Kyere-Yeboah, I. K. Bique and X. C. Qiao, Advances of Non-Thermal Plasma Discharge Technology in Degrading Recalcitrant Wastewater Pollutants. A Comprehensive Review, *Chemosphere*, 2023, **320**, 138061, DOI: 10.1016/j.chemosphere.2023.138061.

9 Y. Yin, H. Xu, Y. Zhu, J. Zhuang, R. Ma, D. Cui, Z. Jiao, Y. Yin, H. Xu, Y. Zhu, J. Zhuang, R. Ma, D. Cui and Z. Jiao, Recent Progress in Applications of Atmospheric Pressure Plasma for Water Organic Contaminants' Degradation, *Appl. Sci.*, 2023, **13**(23), 12631, DOI: 10.3390/APP132312631.

10 K. H. Hama Aziz, F. S. Mustafa, M. A. H. Karim and S. Hama, Pharmaceutical Pollution in the Aquatic Environment: Advanced Oxidation Processes as Efficient Treatment Approaches: A Review, *Mater. Adv.*, 2025, **6**(11), 3433–3454, DOI: 10.1039/D4MA01122H.

11 J.-A. Maybin, L. McClenaghan, B. Gilmore and T. Thompson, Cold Plasma for Enhanced Water Purification, *Sustainable Microbiol.*, 2024, **1**(1), 32, DOI: 10.1093/SUMBIO/QVAE032.

12 E. S. Massima Mouele, J. O. Tijani, K. O. Badmus, O. Pereao, O. Babajide, C. Zhang, T. Shao, E. Sosnin, V. Tarasenko, O. O. Fatoba, K. Laatikainen and L. F. Petrik, Removal of Pharmaceutical Residues from Water and Wastewater Using Dielectric Barrier Discharge Methods—A Review, *Int. J. Environ. Res. Public Health*, 2021, **18**(4), 1683, DOI: 10.3390/IJERPH18041683.

13 J. E. Foster, Plasma-Based Water Purification: Challenges and Prospects for the Future, *Phys. Plasmas*, 2017, **24**(5), 55501, DOI: 10.1063/1.4977921/15994295/055501_1_ACCEPTED_MANUSCRIPT.PDF.

14 R. C. Sanito, S. J. You and Y. F. Wang, Degradation of Contaminants in Plasma Technology: An Overview, *J. Hazard. Mater.*, 2022, **424**, 127390, DOI: 10.1016/J.JHAZMAT.2021.127390.

15 A. Kumar, N. Škoro, W. Gernjak and N. Puač, Cold Atmospheric Plasma Technology for Removal of Organic Micropollutants from Wastewater—a Review, *Eur. Phys. J. D*, 2021, **75**(11), 1–26, DOI: 10.1140/EPJD/S10053-021-00283-5.

16 P. Gururani, P. Bhatnagar, B. Bisht, V. Kumar, N. C. Joshi, M. S. Tomar and B. Pathak, Cold Plasma Technology: Advanced and Sustainable Approach for Wastewater Treatment, *Environ. Sci. Pollut. Res.*, 2021, **28**(46), 65062–65082, DOI: 10.1007/S11356-021-16741-X/FIGURES/3.

17 K. H. Hama Aziz, F. S. Mustafa, K. M. Omer and I. Shafiq, Recent Advances in Water Falling Film Reactor Designs for the Removal of Organic Pollutants by Advanced Oxidation Processes: A Review, *Water Resour. Ind.*, 2023, **30**, 100227, DOI: 10.1016/J.WRI.2023.100227.

18 H. Zeghioud, P. Nguyen-Tri, L. Khezami, A. Amrane and A. A. Assadi, Review on Discharge Plasma for Water Treatment: Mechanism, Reactor Geometries, Active Species and Combined Processes, *J. Water Process Eng.*, 2020, **38**, 101664, DOI: 10.1016/J.JWPE.2020.101664.

19 N. Takeuchi and K. Yasuoka, Review of Plasma-Based Water Treatment Technologies for the Decomposition of Persistent Organic Compounds, *Jpn. J. Appl. Phys.*, 2020, **60**(SA), SA0801, DOI: 10.35848/1347-4065/ABB75D.

20 M. Ansari, G. Moussavi, M. H. Ehrampoosh and S. Giannakis, A Systematic Review of Non-Thermal Plasma (NTP) Technologies for Synthetic Organic Pollutants (SOPs) Removal from Water: Recent Advances in Energy Yield Aspects as Their Key Limiting Factor, *J. Water Process Eng.*, 2023, **51**, 103371, DOI: 10.1016/J.JWPE.2022.103371.

21 M. Magureanu, F. Bilea, C. Bradu and D. Hong, A Review on Non-Thermal Plasma Treatment of Water Contaminated with Antibiotics, *J. Hazard. Mater.*, 2021, **417**, 125481, DOI: 10.1016/J.JHAZMAT.2021.125481.

22 A. Giardina, G. Lofrano, G. Libralato, A. Siciliano, E. Marotta and C. Paradisi, Air Non-Thermal Plasma, a Green Approach for the Treatment of Contaminated Water: The Case of Sulfamethoxazole, *Front. Environ. Chem.*, 2024, **5**, 1416702, DOI: 10.3389/FENVC.2024.1416702/BIBTEX.

23 X. Tang, A. D. N. Ferraz Junior, K. Karu, L. C. Campos and M. Kim, Atmospheric Pressure Dielectric Barrier Discharge Plasma for In-Situ Water Treatment Using a Bubbling Reactor, *J. Environ. Manage.*, 2024, **370**, 122574, DOI: 10.1016/J.JENVMAN.2024.122574.

24 E. S. Massima Mouele, T. Z. Myint Myo, H. H. Kyaw, J. O. Tijani, M. Dinu, A. C. Parau, I. Pana, Y. El Ouardi, J. Al-Sabahi, M. Al-Belushi, E. Sosnin, V. Tarasenko, C. Zhang, T. Shao, T. V. Iordache, S. Teodor, K. Laatikainen, A. Vladescu, M. Al-Abri, A. Sarbu, M. Braic, V. Braic, S. Dobretsov and L. F. Petrik, Degradation of Sulfamethoxazole by Double Cylindrical Dielectric Barrier Discharge System Combined with Ti/C-N-TiO2 Supported Nanocatalyst, *J. Hazard. Mater. Adv.*, 2022, **5**, 100051, DOI: 10.1016/J.HAZADV.2022.100051.

25 A. Zhang, Y. Zhou, Y. Li, Y. Liu, X. Li, G. Xue, A. C. Miruka, M. Zheng and Y. Liu, Motivation of Reactive Oxygen and Nitrogen Species by a Novel Non-Thermal Plasma Coupled with Calcium Peroxide System for Synergistic Removal of Sulfamethoxazole in Waste Activated Sludge, *Water Res.*, 2022, **212**, 118128, DOI: 10.1016/J.WATRES.2022.118128.

26 F. Bilea, C. Bradu, M. Cicirma, A. V. Medvedovici and M. Magureanu, Plasma Treatment of Sulfamethoxazole Contaminated Water: Intermediate Products, Toxicity Assessment and Potential Agricultural Reuse, *Sci. Total Environ.*, 2024, **909**, 168524, DOI: 10.1016/J.SCITOTENV.2023.168524.

This journal is © The Royal Society of Chemistry 2026

27 S. Hu, W. Yan, J. Yu, B. Zhu, Y. Lan, W. Xi, Z. Xu, W. Han and C. Cheng, Degradation of Sulfamethoxazole in Water by Dielectric Barrier Discharge Plasma Jet: Influencing Parameters, Degradation Pathway, Toxicity Evaluation, *Plasma Sci. Technol.*, 2023, **25**(3), 035510, DOI: 10.1088/2058-6272/AC9D85.

28 A. Sokolov and M. Louhi-Kultanen, Behaviour of Aqueous Sulfamethizole Solution and Temperature Effects in Cold Plasma Oxidation Treatment, *Sci. Rep.*, 2018, **8**(1), 1–10, DOI: 10.1038/s41598-018-27061-5.

29 S. P. Rong, Y. B. Sun and Z. H. Zhao, Degradation of Sulfadiazine Antibiotics by Water Falling Film Dielectric Barrier Discharge, *Chin. Chem. Lett.*, 2014, **25**(1), 187–192, DOI: 10.1016/J.CCLET.2013.11.003.

30 S. Rong and Y. Sun, Wetted-Wall Corona Discharge Induced Degradation of Sulfadiazine Antibiotics in Aqueous Solution, *J. Chem. Technol. Biotechnol.*, 2013, **89**(9), 1351–1359, DOI: 10.1002/JCTB.4211.

31 K. S. Kim, S. K. Kam and Y. S. Mok, Elucidation of the Degradation Pathways of Sulfonamide Antibiotics in a Dielectric Barrier Discharge Plasma System, *Chem. Eng. J.*, 2015, **271**, 31–42, DOI: 10.1016/J.CEJ.2015.02.073.

32 T. Zhang, R. Zhou, P. Wang, A. Mai-Prochnow, R. McConchie, W. Li, R. Zhou, E. W. Thompson, K. (Ken) Ostrikov and P. J. Cullen, Degradation of Cefixime Antibiotic in Water by Atmospheric Plasma Bubbles: Performance, Degradation Pathways and Toxicity Evaluation, *Chem. Eng. J.*, 2021, **421**, 127730, DOI: 10.1016/J.CEJ.2020.127730.

33 J. B. Smith, I. Adams and H.-F. Ji, Mechanism of Ampicillin Degradation by Non-Thermal Plasma Treatment with FE-DBD, *Plasma*, 2018, **1**(1), 1–11, DOI: 10.3390/PLASMA1010001.

34 E. Wielogorska, P. B. Flynn, J. Meneely, T. P. Thompson, W. G. Graham, B. F. Gilmore and C. T. Elliott, Assessment of Cold Atmospheric Pressure Plasma (CAPP) Treatment for Degradation of Antibiotic Residues in Water, *Antibiotics*, 2023, **12**(7), 1115, DOI: 10.3390/ANTIBIOTICS12071115/S1.

35 M. Magureanu, D. Piroi, N. B. Mandache, V. David, A. Medvedovici, C. Bradu and V. I. Parvulescu, Degradation of Antibiotics in Water by Non-Thermal Plasma Treatment, *Water Res.*, 2011, **45**(11), 3407–3416, DOI: 10.1016/J.WATRES.2011.03.057.

36 P. T. T. Nguyen, H. T. Nguyen, U. N. P. Tran and H. Manh Bui, Removal of Antibiotics from Real Hospital Wastewater by Cold Plasma Technique, *J. Chem.*, 2021, **2021**(1), 9981738, DOI: 10.1155/2021/9981738.

37 Z. Xu, X. Xue, S. Hu, Y. Li, J. Shen, Y. Lan, R. Zhou, F. Yang and C. Cheng, Degradation Effect and Mechanism of Gas-Liquid Phase Dielectric Barrier Discharge on Norfloxacin Combined with H2O2 or Fe2+, *Sep. Purif. Technol.*, 2020, **230**, 115862, DOI: 10.1016/J.SEPPUR.2019.115862.

38 C. Hao, Z. Yan, K. Liu and J. Qiu, Degradation of Pharmaceutical Contaminant Tetracycline in Aqueous Solution by Coaxial-Type DBD Plasma Reactor, *IEEE Trans. Plasma Sci.*, 2020, **48**(2), 471–481, DOI: 10.1109/TPS.2020.2964612.

39 C. Wang, G. Qu, T. Wang, F. Deng and D. Liang, Removal of Tetracycline Antibiotics from Wastewater by Pulsed Corona Discharge Plasma Coupled with Natural Soil Particles, *Chem. Eng. J.*, 2018, **346**, 159–170, DOI: 10.1016/J.CEJ.2018.03.149.

40 D. He, Y. Sun, L. Xin and J. Feng, Aqueous Tetracycline Degradation by Non-Thermal Plasma Combined with Nano-TiO_2, *Chem. Eng. J.*, 2014, **258**, 18–25, DOI: 10.1016/J.CEJ.2014.07.089.

41 A. Ouzar and I. K. Kim, Tetracycline Degradation by Nonthermal Plasma: Removal Efficiency, Degradation Pathway, and Toxicity Evaluation, *Water Sci. Technol.*, 2022, **86**(11), 2794–2807, DOI: 10.2166/WST.2022.339.

42 T. C. Pereira, E. M. M. Flores, A. V. Abramova, F. Verdini, E. Calcio Gaudino, F. Bucciol and G. Cravotto, Simultaneous Hydrodynamic Cavitation and Glow Plasma Discharge for the Degradation of Metronidazole in Drinking Water, *Ultrason. Sonochem.*, 2023, **95**, 106388, DOI: 10.1016/J.ULTSONCH.2023.106388.

43 N. Nandy, A. Pasupathi, Y. Subramaniam and S. Nachimuthu, Eliminating Ciprofloxacin Antibiotic Contamination from Water with a Novel Submerged Thermal Plasma Technology, *Chemosphere*, 2023, **326**, 138470, DOI: 10.1016/J.CHEMOSPHERE.2023.138470.

44 S. Hu, X. Liu, Z. Xu, J. Wang, Y. Li, J. Shen, Y. Lan and C. Cheng, Degradation and Mineralisation of Ciprofloxacin by Gas–Liquid Discharge Non-Thermal Plasma, *Plasma Sci. Technol.*, 2018, **21**(1), 015501, DOI: 10.1088/2058-6272/AADE82.

45 C. Sarangapani, D. Ziuzina, P. Behan, D. Boehm, B. F. Gilmore, P. J. Cullen and P. Bourke, Degradation Kinetics of Cold Plasma-Treated Antibiotics and Their Antimicrobial Activity, *Sci. Rep.*, 2019, **9**(1), 1–15, DOI: 10.1038/s41598-019-40352-9.

46 S. Gong, Y. Sun, K. Zheng, G. Jiang, L. Li and J. Feng, Degradation of Levofloxacin in Aqueous Solution by Non-Thermal Plasma Combined with Ag3PO4/Activated Carbon Fibers: Mechanism and Degradation Pathways, *Sep. Purif. Technol.*, 2020, **250**, 117264, DOI: 10.1016/J.SEPPUR.2020.117264.

47 X. Hu and B. Wang, Removal of Pefloxacin from Wastewater by Dielectric Barrier Discharge Plasma: Mechanism and Degradation Pathways, *J. Environ. Chem. Eng.*, 2021, **9**(4), 105720, DOI: 10.1016/J.JECE.2021.105720.

48 A. Akbarzadeh, H. R. Ghomi, M. Rafiee, O. Hosseini and M. Jahangiri-Rad, Clindamycin Removal from Aqueous Solution by Non-Thermal Air Plasma Treatment: Performance, Degradation Pathway and Ensuing Antimicrobial Activity, *Water Sci. Technol.*, 2022, **86**(10), 2593–2610, DOI: 10.2166/WST.2022.325.

49 J. Lou, J. An, X. Wang, X. Yang, G. Lu, L. Wang and Z. Zhao, Enhanced Degradation of Oxytetracycline in Aqueous Solution by DBD Plasma-Coupled Vacuum Ultraviolet/Ultraviolet (VUV/UVC) System, *Chemosphere*, 2023, **335**, 139021, DOI: 10.1016/J.CHEMOSPHERE.2023.139021.

50 K. S. Kim, C. S. Yang and Y. S. Mok, Degradation of Veterinary Antibiotics by Dielectric Barrier

Discharge Plasma, *Chem. Eng. J.*, 2013, **219**, 19–27, DOI: 10.1016/J.CEJ.2012.12.079.

51 M. Magureanu, D. Piroi, N. B. Mandache, C. Bradu, A. Medvedovici and V. I. Parvulescu, Degradation of Pharmaceutical Compounds in Aqueous Solution Using Non-Thermal Plasma, *Proceedings of the International Conference on Optimisation of Electrical and Electronic Equipment*, OPTIM, 2012, pp. 1375–1379, DOI: 10.1109/OPTIM.2012.6231955.

52 M. Magureanu, D. Dobrin, N. B. Mandache, C. Bradu, A. Medvedovici and V. I. Parvulescu, The Mechanism of Plasma Destruction of Enalapril and Related Metabolites in Water, *Plasma Processes Polym.*, 2013, **10**(5), 459–468, DOI: 10.1002/PPAP.201200146.

53 A. Raji, K. N. Pandiyaraj, D. Vasu, M. C. Ramkumar, R. R. Deshmukh and V. Kandavelu, Non-Equilibrium Atmospheric Pressure Plasma Assisted Degradation of the Pharmaceutical Drug Valsartan: Influence of Catalyst and Degradation Environment, *RSC Adv.*, 2020, **10**(59), 35709–35717, DOI: 10.1039/D0RA05608A.

54 D. Vasu, A. Raji, K. N. Pandiyaraj, P. V. A. Padmanabhan and V. Kandhavelu, Degradation of Telmisartan (TELMA-H) Compounds in Aqueous Solution Using Non-Thermal Atmospheric Pressure Plasma Jet, *Front. Adv. Mater. Res.*, 2019, **1**(1), 46–52, DOI: 10.34256/famr1919.

55 F. Verdini, A. Abramova, L. Boffa, E. Calcio Gaudino and G. Cravotto, The Unveiling of a Dynamic Duo: Hydrodynamic Cavitation and Cold Plasma for the Degradation of Furosemide in Wastewater, *Sci. Rep.*, 2024, **14**(1), 1–11, DOI: 10.1038/s41598-024-57038-6.

56 M. Magureanu, D. Piroi, N. B. Mandache, V. David, A. Medvedovici and V. I. Parvulescu, Degradation of Pharmaceutical Compound Pentoxifylline in Water by Non-Thermal Plasma Treatment, *Water Res.*, 2010, **44**(11), 3445–3453, DOI: 10.1016/J.WATRES.2010.03.020.

57 Y. Chen, L. Sun, Z. Yu, L. Wang, G. Xiang and S. Wan, Synergistic Degradation Performance and Mechanism of 17β-Estradiol by Dielectric Barrier Discharge Non-Thermal Plasma Combined with Pt–TiO2, *Sep. Purif. Technol.*, 2015, **152**, 46–54, DOI: 10.1016/J.SEPPUR.2015.07.061.

58 C. Chen, C. Ma, Y. Yang, X. Yang, K. Demeestere, A. Nikiforov and S. Van Hulle, Degradation of Micropollutants in Secondary Wastewater Effluent Using Nonthermal Plasma-Based AOPs: The Roles of Free Radicals and Molecular Oxidants, *Water Res.*, 2023, **235**, 119881, DOI: 10.1016/J.WATRES.2023.119881.

59 N. Wardenier, Z. Liu, A. Nikiforov, S. W. H. Van Hulle and C. Leys, Micropollutant Elimination by O3, UV and Plasma-Based AOPs: An Evaluation of Treatment and Energy Costs, *Chemosphere*, 2019, **234**, 715–724, DOI: 10.1016/J.CHEMOSPHERE.2019.06.033.

60 Y. Liu, Y. Sun, J. Hu, J. He, S. Mei, G. Xue and S. Ognier, Removal of Iopromide from an Aqueous Solution Using Dielectric Barrier Discharge, *J. Chem. Technol. Biotechnol.*, 2012, **88**(3), 468–473, DOI: 10.1002/JCTB.3851.

61 Y. Liu, S. Mei, D. Iya-Sou, S. Cavadias and S. Ognier, Carbamazepine Removal from Water by Dielectric Barrier Discharge: Comparison of Ex Situ and In Situ Discharge on Water, *Chem. Eng. Process.: Process Intesif.*, 2012, **56**, 10–18, DOI: 10.1016/J.CEP.2012.03.003.

62 M. P. Rayaroth, O. Aubry, H. Rabat, E. Marilleau, Y. Gru, D. Hong and P. Brault, Degradation and Transformation of Carbamazepine in Aqueous Medium under Non-Thermal Plasma Oxidation Process, *Chemosphere*, 2024, **352**, 141449, DOI: 10.1016/J.CHEMOSPHERE.2024.141449.

63 S. Gao, F. Lu, A. A. Abid, X. Yang and Z. Wu, Fast Degradation of Carbamazepine in Water by Electric Discharge Plasma, *Front. Environ. Sci.*, 2023, **11**, 1242405, DOI: 10.3389/FENVS.2023.1242405/BIBTEX.

64 N. Korichi, O. Aubry, H. Rabat, B. Cagnon and D. Hong, Paracetamol Degradation by Catalyst Enhanced Non-Thermal Plasma Process for a Drastic Increase in the Mineralisation Rate, *Catalysts*, 2020, **10**(9), 959, DOI: 10.3390/CATAL10090959.

65 X. Y. Pan and X. C. Qiao, Influences of Nitrite on Paracetamol Degradation in Dielectric Barrier Discharge Reactor, *Ecotoxicol. Environ. Saf.*, 2019, **180**, 610–615, DOI: 10.1016/j.ecoenv.2019.04.037.

66 Y. Baloul, H. Rabat, D. Hong, S. Chuon and O. Aubry, Preliminary Study of a Non-Thermal Plasma for the Degradation of the Paracetamol Residue in Water, *Int. J. Plasma Environ. Sci. Technol.*, 2016, **10**, 102–107.

67 V. Rathore, S. Patel, A. Pandey, J. Savjani, S. Butani, H. Dave and S. K. Nema, Methotrexate Degradation in Artificial Wastewater Using Non-Thermal Pencil Plasma Jet, *Environ. Sci. Pollut. Res.*, 2023, **1**, 1–10, DOI: 10.1007/S11356-023-28502-Z/FIGURES/6.

68 A. Kumar, N. Škoro, W. Gernjak, O. Jovanović, A. Petrović, S. Živković, E. C. Lumbaque, M. J. Farré and N. Puač, Degradation of Diclofenac and 4-Chlorobenzoic Acid in Aqueous Solution by Cold Atmospheric Plasma Source, *Sci. Total Environ.*, 2023, **864**, 161194, DOI: 10.1016/J.SCITOTENV.2022.161194.

69 D. Dobrin, C. Bradu, M. Magureanu, N. B. Mandache and V. I. Parvulescu, Degradation of Diclofenac in Water Using a Pulsed Corona Discharge, *Chem. Eng. J.*, 2013, **234**, 389–396, DOI: 10.1016/J.CEJ.2013.08.114.

70 H. Krause, B. Schweiger, E. Prinz, J. Kim and U. Steinfeld, Degradation of Persistent Pharmaceuticals in Aqueous Solutions by a Positive Dielectric Barrier Discharge Treatment, *J. Electrost.*, 2011, **69**(4), 333–338, DOI: 10.1016/J.ELSTAT.2011.04.011.

71 H. Krause, B. Schweiger, J. Schuhmacher, S. Scholl and U. Steinfeld, Degradation of the Endocrine Disrupting Chemicals (EDCs) Carbamazepine, Clofibric Acid, and Iopromide by Corona Discharge over Water, *Chemosphere*, 2009, **75**(2), 163–168, DOI: 10.1016/J.CHEMOSPHERE.2008.12.020.

72 I. Panorel, S. Preis, I. Kornev, H. Hatakka and M. Louhi-Kultanen, Oxidation of Aqueous Pharmaceuticals by Pulsed Corona Discharge, *Environ. Technol.*, 2012, **34**(7), 923–930, DOI: 10.1080/09593330.2012.722691.

73 M. H. F. Graumans, W. F. L. M. Hoeben, M. F. P. van Dael, R. B. M. Anzion, F. G. M. Russel and P. T. J. Scheepers, Thermal Plasma Activation and UV/H2O2 Oxidative

 This journal is © The Royal Society of Chemistry 2026

Degradation of Pharmaceutical Residues, *Environ. Res.*, 2021, **195**, 110884, DOI: 10.1016/J.ENVRES.2021.110884.

74 R. Banaschik, P. Lukes, H. Jablonowski, M. U. Hammer, K. D. Weltmann and J. F. Kolb, Potential of Pulsed Corona Discharges Generated in Water for the Degradation of Persistent Pharmaceutical Residues, *Water Res.*, 2015, **84**, 127–135, DOI: 10.1016/J.WATRES.2015.07.018.

75 P. Ajo, S. Preis, T. Vornamo, M. Mänttäri, M. Kallioinen and M. Louhi-Kultanen, Hospital Wastewater Treatment with Pilot-Scale Pulsed Corona Discharge for Removal of Pharmaceutical Residues, *J. Environ. Chem. Eng.*, 2018, **6**(2), 1569–1577, DOI: 10.1016/J.JECE.2018.02.007.

76 E. E. Rodriguez, W. A. Tarpeh, K. R. Wigginton and N. G. Love, Application of Plasma for the Removal of Pharmaceuticals in Synthetic Urine, *Environ. Sci.*, 2022, **8**(3), 523–533, DOI: 10.1039/D1EW00863C.

77 A. Wypart-Pawul, E. Neczaj, A. Grosser and A. Grobelak, Assessment of the Effectiveness of Atmospheric Plasma on the Removal of Selected Pharmaceuticals from Water, *Desalin. Water Treat.*, 2024, **320**, 100600, DOI: 10.1016/J.DWT.2024.100600.

78 M. Zupanc, G. Primc, M. Dular, M. Petkovšek, R. Roškar, R. Zaplotnik and J. Trontelj, Proof-of-Concept for Removing Micropollutants through a Combination of Sub-Atmospheric-Pressure Non-Thermal Plasma and Hydrodynamic (Super)Cavitation, *Ultrason. Sonochem.*, 2024, **111**, 107110, DOI: 10.1016/J.ULTSONCH.2024.107110.

79 R. Klymenko, E. de Kroon, L. L. F. Agostinho, E. C. Fuchs, J. Woisetschläger and W. F. L. M. Hoeben, Characterization of a Hyperbolic Vortex Plasma Reactor for the Removal of Aqueous Phase Micropollutants, *J. Phys. D: Appl. Phys.*, 2024, **57**(21), 215204, DOI: 10.1088/1361-6463/AD2B22.

80 D. Joshi, G. V. Prakash, S. Z. Ahammad, S. Kar and T. R. Sreekrishnan, Development of Low Power Non-Thermal Plasma Jet and Optimization of Operational Parameters for Treating Dyes and Emerging Contaminants, *Plasma Sci. Technol.*, 2022, **24**(10), 105501, DOI: 10.1088/2058-6272/AC6E34.

81 D. Gerrity, B. D. Stanford, R. A. Trenholm and S. A. Snyder, An Evaluation of a Pilot-Scale Nonthermal Plasma Advanced Oxidation Process for Trace Organic Compound Degradation, *Water Res.*, 2010, **44**(2), 493–504, DOI: 10.1016/J.WATRES.2009.09.029.

82 G. Iervolino, V. Vaiano and V. Palma, Enhanced Removal of Water Pollutants by Dielectric Barrier Discharge Non-Thermal Plasma Reactor, *Sep. Purif. Technol.*, 2019, **215**, 155–162, DOI: 10.1016/J.SEPPUR.2019.01.007.

83 J. O. Back, T. Obholzer, K. Winkler, S. Jabornig and M. Rupprich, Combining Ultrafiltration and Non-Thermal Plasma for Low Energy Degradation of Pharmaceuticals from Conventionally Treated Wastewater, *J. Environ. Chem. Eng.*, 2018, **6**(6), 7377–7385, DOI: 10.1016/J.JECE.2018.07.047.

84 K. H. Hama Aziz, H. Miessner, S. Mueller, D. Kalass, D. Moeller, I. Khorshid and M. A. M. Rashid, Degradation of Pharmaceutical Diclofenac and Ibuprofen in Aqueous Solution, a Direct Comparison of Ozonation, Photocatalysis, and Non-Thermal Plasma, *Chem. Eng. J.*, 2017, **313**, 1033–1041, DOI: 10.1016/J.CEJ.2016.10.137.