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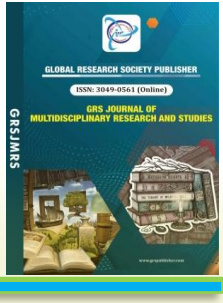

Emerging Contaminants in waste Water: Detection, and Treatment Innovations

Mansir Mahammed Bako[1], Kawaye Tayamika Yankho[2], Adamudu Alexander Ogwuche[3], Iyobosa Eheneden[4]

[1,2,3,4]College of Environmental Science and Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China and UNEP-Tongji Institute of Environment and Sustainable Development, 1239 Siping Road, Shanghai 200092, China.

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Corresponding Author: Mansir Mahammed Bako

Abstract: Emerging contaminants (ECs) have become a growing global concern due to their persistence, bioaccumulation potential, and harmful ecological and health effects. These pollutants ranging from pharmaceuticals, personal care products, endocrine-disrupting compounds, pesticides, surfactants, and microplastics to antibiotic resistance genes are increasingly detected in wastewater and natural water bodies. This review provides a comprehensive analysis of their sources, classifications, and detection methods, emphasizing advanced analytical tools such as LC–MS/MS, GC–MS, HPLC, FT-IR, UV–Vis, Raman, and ICP–MS for accurate identification and quantification at trace levels. It further explores cutting-edge treatment innovations, including advanced oxidation and photocatalytic systems, membrane filtration technologies, adsorptive biochars and nanomaterials, as well as sustainable biological processes like algal–bacterial consortia and enzymatic bioreactors. These technologies demonstrate remarkable efficiency in removing complex contaminants, yet face challenges related to cost, scalability, energy demand, and secondary pollution. The review concludes that solving EC-related challenges requires integrating detection advancements with eco-friendly hybrid treatment systems and supportive regulatory policies. By linking science, technology, and governance, the study highlights a pathway toward sustainable wastewater management and environmental protection in the face of emerging pollutants.

Keywords: *Emerging Contaminants; Wastewater Treatment; Advanced Oxidation Processes; Analytical Detection Techniques; Biochar and Nanomaterials; Algal–Bacterial Consortia.*

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Introduction

Emerging contaminants (ECs) also referred to as contaminants of emerging concern are a broad class of chemical and biological pollutants that have only recently come under scientific and regulatory scrutiny. These include a diverse array of substances such as pharmaceuticals and personal care products (PPCPs), endocrine-disrupting compounds (EDCs like synthetic hormones), per- and polyfluoroalkyl substances (PFAS), micro- and nanoplastics, and even certain microorganisms (Boahen et al., 2025), Many of these compounds are not new; in fact, some (e.g. ingredients in medicines, plastics, or pesticides) have been in use for decades. However, they are considered “emerging” because advances in analytical detection now reveal their presence at trace levels in the environment and because their potential ecological or health effects have only recently been recognized (Boahen et al., 2025). Unlike well-known pollutants such as lead or arsenic, ECs are typically unregulated in water quality standards and not part of routine monitoring programs. This gap means that contaminants ranging from antidepressant metabolites to sunscreen agents have been quietly entering waterways and accumulating in ecosystems. Rapid industrial development and modern lifestyles contribute to the spread of ECs for example, the Chemical Abstracts Service registry surpassed 200 million substances by 2023, adding nearly 15,000 new chemicals each day (F. Wang et al., 2024). Inevitably, some fraction of these myriad chemicals finds its way into wastewater streams and the environment. The growing scientific attention to ECs stems from mounting evidence that even at low concentrations, these contaminants can cause endocrine disruption, antibiotic resistance, developmental or neurologic effects, and other insidious impacts on wildlife and human populations (Roy, 2021; Yu et al., 2024). In short, one major reason ECs demand attention is their widespread occurrence in wastewater and aquatic systems, which highlights the significance of wastewater as both a source and a pathway for these contaminants. Typical municipal wastewater contains residues of countless consumer and industrial chemicals from daily life. For instance, when people use medications and personal care products, unused portions or metabolic byproducts are often excreted or rinsed off into sewage. Conventional wastewater treatment plants (WWTPs), while effective at removing pathogens and nutrients, were never designed to eliminate most of these trace organic chemicals (Owojori et al., 2024; Sangamnere et al., 2023). As a result, many ECs survive treatment processes and are discharged with effluents into rivers, lakes, and coastal waters (Eheneden et al., 2024; Li et al., 2025; Zahmatkesh et al., 2022). Indeed, effluent from WWTPs is now recognized as a primary route by which ECs enter the environment. A recent review noted that even advanced tertiary treatments often fail to completely remove persistent PPCPs and other micro-pollutants, allowing measurable concentrations to appear in downstream surface waters (Boahen et al., 2025). In addition to treated effluent, any untreated or partially treated sewage can greatly amplify EC release. Alarmingly, about 80% of the world’s wastewater is still discharged without adequate treatment (Varatharajan et al., 2025), especially in developing regions, which directly introduces pharmaceuticals, plastic particles, and

industrial chemicals into natural water bodies. Their effects are not just theoretical. For example and researchers warn that antibiotic-laden waters contribute to the global rise of antibiotic-resistant infections (Patra & Dubey, 2025; F. Wang et al., 2024). Secondly, regulatory and scientific knowledge gaps create urgency. Most ECs lack regulatory standards, meaning there are no enforceable limits for their levels in effluent or drinking water (though some regions are beginning to add certain drugs or PFAS to watch-lists). Researchers highlight the urgent need for improved detection tools (e.g. high-resolution mass spectrometry, biosensors) and novel treatment solutions such as advanced oxidation processes, enhanced sorbents, membrane filtration, or bioremediation to target EC removal. In recognition of this, therefore this review responds to that need by examining the state-of-the-art in detecting ECs in wastewater, understanding their health and environmental risks, and exploring emerging treatment innovations to mitigate these contaminants. Through synthesizing recent findings in these areas, we aim to clarify why studying ECs is not only scientifically fascinating but also urgently necessary for safeguarding environmental and public health in the years ahead.

Classification and Sources of Emerging Contaminants

Sources of Emerging Contaminants

Emerging contaminants (ECs) are synthetic or naturally occurring chemicals that are not commonly monitored in the environment but have the potential to enter water bodies and cause known or suspected adverse ecological and human health effects (Talreja et al., 2025). As anthropogenic activities intensify, the diversity and load of ECs released into aquatic environments are expanding. These contaminants primarily originate from domestic households, hospitals, agricultural activities, and pharmaceutical industries, as illustrated in Figure 1. Each of these sectors introduces a unique chemical footprint into the hydrosphere, posing a multifaceted challenge to water quality management.

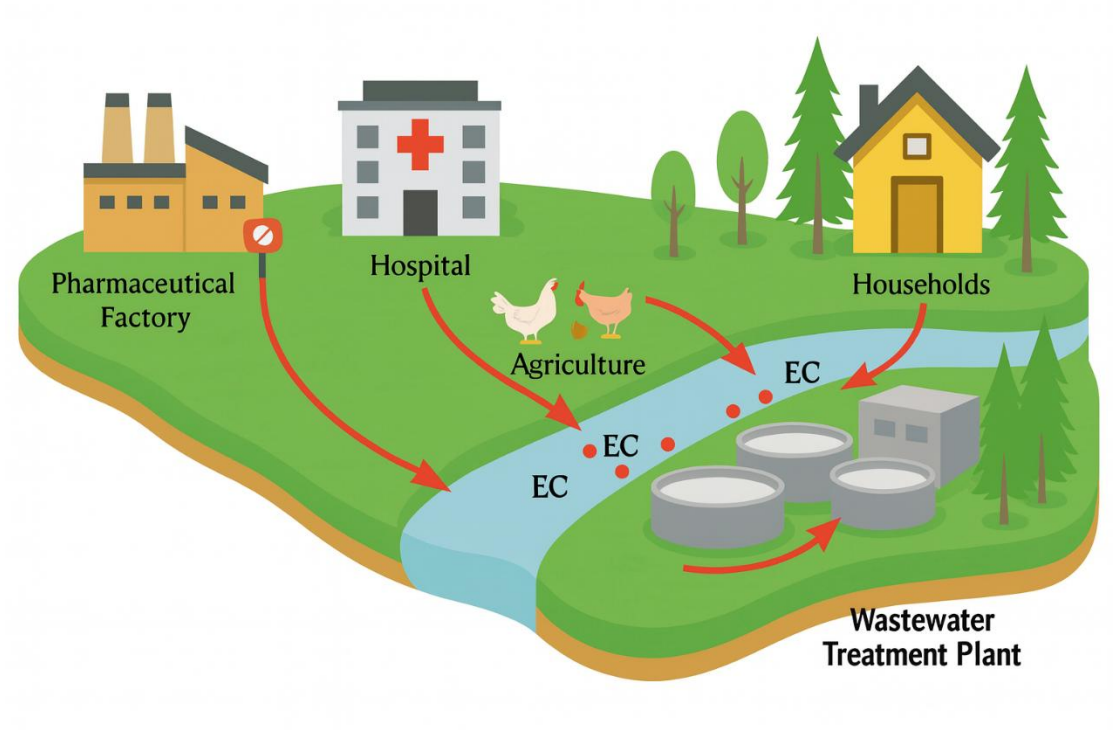

Figure 1: Sources of Emerging Contaminants in the water body

Households are one of the major contributors of ECs, especially via the use and disposal of personal care products, detergents, and medications. These chemicals often bypass conventional wastewater treatment due to their low concentrations and persistent nature (Golovko et al., 2021). Pharmaceuticals such as analgesics, antibiotics, and hormones enter sewage systems through human excretion or improper disposal, making residential discharges a significant point source (Willis Gwenzi, 2023). Hospitals, meanwhile, amplify pharmaceutical loads with high concentrations of radiocontrast agents, antineoplastic drugs, and disinfectants, many of which resist biodegradation and exhibit ecotoxicological effects (Zare et al., 2022). The presence of ECs is now documented on a global scale: for example, a 2022 survey of 258 rivers worldwide detected pharmaceuticals (from analgesics to antibiotics) in over a quarter of the sites at concentrations exceeding safe limits for aquatic life (Wilkinson et al., 2022). Key contributors to pharmaceuticals EC contamination in wastewater include household sewage, hospital and pharmaceutical industry effluents, agricultural runoff, and improper waste disposal (Kotwani et al., 2021; Samal et al., 2022). For instance, hospital wastewater is rich in antibiotic residues and disinfectants, which can select for drug-resistant microbes (a critical One Health concern), and agricultural lands receiving manure or biosolids can leach hormones and veterinary drugs into water (Eheneden et al., 2023; Ren et al., 2025). Even the common practice of land-applying treated sewage sludge (biosolids) as fertilizer can introduce residual PPCPs and persistent compounds into soils,

which then wash into waterways during storms (Boahen et al., 2025).

Agriculture introduces ECs predominantly through veterinary pharmaceuticals, pesticides, and hormones used in livestock production (Marcu et al., 2023). Runoff from farms containing antibiotics and growth promoters has been identified as a critical driver of antimicrobial resistance in aquatic ecosystems (Fonseca et al., 2020). As shown in the diagram, pig and poultry farming adjacent to watercourses directly contributes to contaminant loading. Additionally, untreated or poorly treated manure used as fertilizer can leach pharmaceuticals into groundwater and surface water systems (Bijay-Singh & Craswell, 2021).

Pharmaceutical industries, often situated near water bodies for operational efficiency, discharge high concentrations of active pharmaceutical ingredients (APIs) during manufacturing. Despite regulatory improvements, process wastewater from these facilities remains one of the most concentrated point sources of ECs globally. In many cases, these effluents contain compound mixtures with unknown synergistic effects, complicating risk assessments.

Altogether, these diverse sources collectively load aquatic environments with a cocktail of emerging contaminants that evade traditional treatment systems. There is a growing consensus that addressing EC pollution requires source-specific interventions and advanced monitoring tools to safeguard ecosystem and public health.

Table 1. Categories, Sources, and Environmental Implications of Emerging Contaminants (ECs) in Wastewater and Aquatic Environments

Category / Type	**Representative Compounds**	**Common Sources**	**Environmental / Health Concerns**	**References**
Pharmaceuticals and Personal Care Products (PPCPs)	Antibiotics (e.g., Sulfamethoxazole, Ciprofloxacin), Analgesics (Ibuprofen, Diclofenac), Hormones (17α-ethinylestradiol), Sunscreen agents	Hospitals, households, pharmaceutical industries	Development of antibiotic resistance; endocrine disruption in aquatic life; bioaccumulation	(aus der Beek et al., 2016)
Industrial Chemicals	Bisphenol A (BPA), Nonylphenol, Phthalates	Plastics, detergents, textile industries	Endocrine disruption; reproductive toxicity; bioaccumulation	(Salazar-Remigio et al., 2025; Staples et al., 2018)
Pesticides and Herbicides	Atrazine, Glyphosate, Carbamazepine	Agricultural runoff, pest control	Toxicity to non-target organisms; groundwater contamination	(Resende et al., 2025)
Per- and Polyfluoroalkyl Substances (PFASs)	PFOS, PFOA, PFHxS	Firefighting foams, textiles, food packaging	Persistent organic pollutants (POPs); carcinogenicity; bioaccumulation	(Wee & Aris, 2023)
Surfactants and Detergents	Linear alkylbenzene sulfonates (LAS), Sodium lauryl sulfate	Laundry detergents, household cleaning products	Toxicity to aquatic organisms; foaming in waterways	(Freeling et al., 2019)
Microplastics and Nanoplastics	Polyethylene, Polypropylene, Polystyrene particles	Cosmetics, textiles, packaging, wastewater	Ingestion by aquatic life; physical blockages; chemical adsorption	(Lian et al., 2024)
Illicit Drugs and Metabolites	Cocaine, Amphetamines, Methadone	Human excretion, wastewater effluent	Ecotoxicological effects; behavioral alteration in aquatic species	(Zuccato et al., 2008)
Disinfection By-products (DBPs)	Trihalomethanes (THMs), Haloacetic acids	Chlorination of water, swimming pools	Carcinogenic and mutagenic potential	(Sinha et al., 2021)
Flame Retardants	Polybrominated diphenyl ethers (PBDEs), Organophosphate esters (OPEs)	Electronics, furniture, building materials	Bioaccumulation, neurotoxicity, endocrine disruption	(J. Wang et al., 2024)
Heavy Metals (Emerging Focus)	Cadmium, Lead, Mercury, Arsenic	Industrial effluents, batteries, e-waste	Neurotoxicity, carcinogenicity, persistent contamination	(Mitra et al., 2022)

Category / Type	Representative Compounds	Common Sources	Environmental / Health Concerns	References
Artificial Sweeteners	Sucralose, Acesulfame-K	Food industry, household wastewater	Persistence in water; potential ecological impacts	(Mawhinney et al., 2011)
Microbial and Antibiotic Resistance Genes (ARGs)	*blaTEM*, *sul1*, *tetA*, *ermB*	Hospitals, livestock farms, wastewater	Horizontal gene transfer; antibiotic resistance spread	(Berendonk et al., 2015)

Analytical Methods for Detection and Quantification of Emerging Contaminants

Emerging contaminants (ECs) encompass a broad range of chemicals (pharmaceuticals, personal care products, PFAS, endocrine disruptors, etc.) that are not routinely monitored but pose potential risks at trace concentrations (Shyamalagowri et al., 2023). Detecting and quantifying these pollutants in water and other environmental samples require highly sensitive and selective analytical methods. Traditional laboratory techniques (such as chromatography coupled with mass spectrometry) have been the gold standard for EC analysis, while newer sensor-based and biosensing techniques are being developed for faster in situ monitoring. Below, we discuss advanced analytical tools for EC detection: liquid and gas chromatography–mass spectrometry (LC–MS/MS and GC–MS), various sensor and spectroscopic techniques, and biosensing methods.

Chromatography and Mass Spectrometry (LC–MS/MS and GC–MS)

Liquid Chromatography–Mass Spectrometry (LC–MS/MS): LC–MS/MS is one of the most powerful and widely used techniques for identifying and quantifying ECs in complex samples. By coupling high-performance liquid chromatography with tandem mass spectrometry, this method can separate and detect polar, non-volatile compounds at extremely low concentrations (down to ng/L levels)(Catarro et al., 2025). For example, pharmaceuticals, hormones, and other polar ECs in water are routinely measured by LC–MS/MS in multi-residue analyses. LC–MS/MS offers remarkable sensitivity and specificity, often allowing detection of ECs and even their transformation byproducts at trace levels (Boahen et al., 2025). High-resolution MS variants (LC-HRMS) further enable the identification of unknown or new contaminants. owever, matrix effects from complex environmental samples (e.g. natural organic matter in wastewater) can suppress or enhance signals and thus intensive sample pretreatment (filtration, solid-phase extraction, etc.) is often required to ensure accuracy.

Gas Chromatography–Mass Spectrometry (GC–MS):

Gas Chromatography–Mass Spectrometry (GC–MS) remains one of the most reliable analytical tools for monitoring emerging contaminants (ECs) in water, soil, and biological samples. Its combination of high-resolution chromatographic separation and mass-spectrometric detection provides exceptional sensitivity and selectivity, allowing trace-level identification (ng L^{-1}) of volatile and semi-volatile organic pollutants. This versatility makes GC–MS particularly effective for detecting compounds such as polycyclic aromatic hydrocarbons (PAHs), plasticizers, and selected pharmaceuticals after derivatization (Catarro et al., 2025). For instance, GC–MS has been widely used to quantify the anticonvulsant carbamazepine in surface waters and wastewater effluents using solid-phase extraction and derivatization techniques (Loos et al., 2010). Similarly, sulfamethoxazole, a sulfonamide antibiotic, and the anti-inflammatory diclofenac have been identified in river water and sediments across Europe using GC–MS/MS (Albero et al., 2020). In addition, GC–MS methods have detected triclosan a common antimicrobial in personal care products in wastewater at concentrations up to several µg L^{-1} (Liang et al., 2022), and phthalate esters such as DEHP and DBP, which act as endocrine disruptors, have been quantified in both water and sludge matrices (Fan et al., 2019). These findings underscore GC–MS's essential role in understanding contaminant distribution and persistence in the environment.

Despite these achievements, GC–MS has inherent limitations. Many ECs are polar, ionic, or thermally unstable for example, per- and polyfluoroalkyl substances (PFAS), certain antibiotics, and pesticide metabolites making them unsuitable for direct GC–MS analysis unless chemically modified. Moreover, complex matrices often introduce co-eluting interferences and ion suppression, reducing precision and reproducibility (Albero et al., 2020). Another gap is the lack of non-target screening capabilities, as GC–MS workflows traditionally focus on known compounds.

From my perspective, future efforts should focus on developing automated on-line preconcentration systems (e.g., thermal desorption, SPME) coupled with GC–MS/MS and combining GC–MS with high-resolution LC–MS for polar ECs. Building shared spectral libraries for derivative ECs and promoting standardized analytical protocols would also improve data comparability and foster global monitoring efforts.

High-Performance Liquid Chromatography (HPLC) for Emerging Contaminants in the Environment

High-Performance Liquid Chromatography (HPLC) has long been a central tool for environmental scientists seeking to detect and quantify emerging contaminants (ECs) in water, soil, and biota. Its ability to separate compounds in liquid phase without the need for volatilization makes it particularly suitable for polar and thermally labile substances, which are difficult to analyze by GC–MS. HPLC has been successfully used to detect a wide range of ECs. For instance, nonylphenol, an endocrine-disrupting alkylphenol, has been quantified in river and wastewater effluents using HPLC coupled with UV detection (de Araujo et al., 2020). Similarly, pharmaceuticals such as ibuprofen and carbamazepine have been monitored in surface waters and hospital effluents, highlighting their persistence even after conventional treatment. Antibiotics like sulfamethoxazole, triclosan from personal care products, and caffeine, a widely consumed stimulant, have also been measured using HPLC-MS/MS, demonstrating the method's versatility for both targeted and multi-class analyses (Paíga et al., 2024; Santos et al., 2025). In addition, emerging pollutants such as UV filters in sunscreens, plasticizers like DEHP, and bisphenol A have been

successfully detected in environmental waters using HPLC with diode array or fluorescence detection.

Despite these strengths, HPLC faces limitations. Its sensitivity for ultra-trace concentrations (ng L^{-1}) may be lower than LC-MS/MS, and complex matrices often introduce co-elution and matrix suppression, reducing accuracy. Many HPLC methods are still optimized for a few compounds rather than comprehensive, multi-class screening. From my perspective, integrating automated on-line sample preparation (e.g., solid-phase extraction) with HPLC-MS/MS, adopting high-resolution mass detectors, and building standardized, shared protocols would greatly improve reliability, reproducibility, and global comparability. Such efforts could help environmental scientists more efficiently track the fate of ECs, anticipate emerging risks, and inform water treatment strategies to protect ecosystems and human health.

Table 2. Summary of HPLC-Based Analytical Methods for Detection and Quantification of Emerging Contaminants (ECs) in Environmental Matrices

Emerging Contaminant (EC)	**Matrix**	**HPLC method (example)**	**Typical reported LOD / LOQ**	**reference**
Carbamazepine	Wastewater, surface water	SPE + LC-ESI-MS/MS (UHPLC family)	0.01–0.05 µg L^{-1} (10–50 ng L^{-1})	(Miao & Metcalfe, 2003)
Ibuprofen	Surface water, hospital effluent	SPE + UHPLC-MS/MS	1–10 ng L^{-1}	
Sulfamethoxazole (SMX)	Treated wastewater, soil	SPE/on-line SPE + UHPLC-MS/MS	1–10 ng L^{-1}	(Stando et al., 2023)
Triclosan	Wastewater, sediments, urine	RP-HPLC with FLD or UV (or UHPLC-MS for traces)	0.02–0.5 µg L^{-1}	(Karikari et al., 2023)
Caffeine	Surface water, wastewater	On-line SPE + LC (HPLC-UV or UHPLC-MS)	0.02–0.2 µg L^{-1}	(Burkhardt et al., 1999)
Bisphenol A (BPA)	Bottled water, effluent	HPLC on-column trace enrichment + FLD	ng L^{-1} (sub-µg L^{-1})	(Honeychurch, 2024)
DEHP (phthalate)	Water, sludge, beverages	HPLC-UV / HPLC-DAD after SPE or LLE	0.05–1 µg L^{-1}	(Gemenetzis & Alygizakis, 2023)
4-Nonylphenol (4-NP)	River water, sediments	LLE/SPE + HPLC-FLD	0.01–0.1 µg L^{-1}	(Cruceru et al., 2012)
Diclofenac	Wastewater, surface water	SPE + UHPLC-MS/MS	1–50 ng L^{-1}	(Paíga et al., 2015)
Naproxen	Wastewater, river water	SPE + UHPLC-MS/MS	1–20 ng L^{-1}	(Paíga et al., 2015)
Phthalate mixture (DEHP, DBP, DnBP)	Water, sludge, food	HPLC-UV / GC after derivatisation (some HPLC methods exist)	0.05–1 µg L^{-1}	(Gemenetzis & Alygizakis, 2023)
Octocrylene (UV filter)	Recreational waters, sand	SPE + HPLC-DAD / UHPLC-MS	0.02–0.1 µg L^{-1}	(Sakaguchi et al., 2023)
Parabens (methyl-, propyl-paraben)	Wastewater, surface water	SPE + HPLC-DAD/FLD or UHPLC-MS	0.01–0.1 µg L^{-1}	(Santos et al., 2025)
Bisphenol S (BPS)	Surface water, food contact	SPE + HPLC-FLD / UHPLC-MS	ng–sub-µg L^{-1}	(Gbylik-Sikorska et al., 2023)
Antibiotics (e.g., ciprofloxacin, enrofloxacin)	Wastewater, soil, sediments	SPE + UHPLC-MS/MS (fluoroquinolones)	1–10 ng L^{-1}	(Kokoszka et al., 2021)
Steroid hormones (estrone, 17β-estradiol)	Surface water, sludge	SPE + HPLC-MS/MS or HPLC-FLD after derivatisation	0.1–10 ng L^{-1}	(Loos et al., 2017)
Phenolic UV-filters (oxybenzone)	Seawater, estuarine waters	SPE + HPLC-DAD/FLD or UHPLC-MS	0.02–0.1 µg L^{-1}	(Sakaguchi et al., 2023)

Emerging Contaminant (EC)	Matrix	HPLC method (example)	Typical reported LOD / LOQ	reference
Antimicrobials (e.g., triclocarban, chloroxylenol)	Wastewater, sludge	HPLC-UV/FLD or UHPLC-MS	0.05–1 µg L^{-1}	(Alshishani et al., 2019)

Spectroscopic and Spectrometric Techniques

Spectroscopic and spectrometric techniques play an increasingly vital role in the detection, characterization, and quantification of emerging contaminants (ECs) in environmental matrices. These methods such as Fourier Transform Infrared Spectroscopy (FT-IR), Ultraviolet–Visible Spectrophotometry (UV–Vis), Fluorescence Spectroscopy, Raman Spectroscopy, and Inductively Coupled Plasma Mass Spectrometry (ICP–MS) offer versatile, often non-destructive approaches for chemical identification and structural elucidation.

Among these, FT-IR spectroscopy has become indispensable for identifying microplastics and polymeric contaminants through vibrational fingerprints of functional groups like C–H, C=O, and O–H bonds. For instance, Nava et al, successfully applied FT-IR and Raman spectroscopy to characterize polyethylene and polypropylene microplastics in river sediments, achieving detection down to the micrometer scale (Nava et al., 2021). Similarly, UV–Vis spectrophotometry has been employed for the quantification of pharmaceuticals such as diclofenac, acetaminophen, and naproxen in wastewater effluents due to their distinct absorbance in the 200–400 nm range (Queral-Beltran et al., 2023).

Fluorescence spectroscopy has shown promise for tracing aromatic and conjugated ECs such as polycyclic aromatic hydrocarbons (PAHs) and fluorescent dyes. A researcher applied excitation-emission matrix (EEM) fluorescence combined with parallel factor analysis (PARAFAC) to detect trace levels of PAHs and humic-like fluorophores in urban stormwater (X. Wang et al., 2022). Likewise, Raman spectroscopy, including surface-enhanced Raman spectroscopy (SERS), has been increasingly used to detect antibiotics such as sulfamethoxazole and tetracycline, even at sub-µg/L concentrations, after adsorption onto metallic nanostructures (X. Wang et al., 2022).

In the realm of elemental pollutants, ICP–MS remains one of the most powerful tools for the quantification and speciation of trace metals and metalloids (e.g., arsenic, cadmium, lead) in water, soil, and sediments. It can achieve detection limits below 1 ng/L (Guo et al., 2024; Jakkielska et al., 2024). When coupled with chromatography (LC–ICP–MS), it can even distinguish between inorganic and organometallic species, providing insight into toxicity and bioavailability (Guo et al., 2024). Despite these successes, significant limitations persist. Spectroscopic techniques such as UV–Vis and FT-IR often lack sufficient selectivity and sensitivity for trace EC detection in complex matrices. Overlapping spectra, interference from natural organic matter, and high detection limits (often µg/L) hinder accurate quantification. Additionally, while ICP–MS is highly sensitive, it cannot directly characterize organic contaminants unless coupled with separation techniques. FT-IR and Raman analyses also face challenges in aqueous samples due to strong water absorption bands and fluorescence interference, respectively.

From my perspective, addressing these gaps requires hybrid and integrative approaches. Coupling chromatographic separations (HPLC, GC) with high-resolution mass spectrometry (HRMS, TOF–MS, Orbitrap) can enable both targeted and non-target screening of ECs, including transformation products. Moreover, machine learning-assisted spectral interpretation can enhance discrimination between overlapping signals in spectroscopic data. The development of portable, in-situ spectrometric sensors for instance, miniaturized Raman and IR systems could revolutionize environmental monitoring by providing rapid, real-time analysis directly in the field. Future studies should also prioritize creating standardized spectral libraries for ECs to improve inter-laboratory reproducibility and data sharing.

In essence, spectroscopic and spectrometric techniques provide powerful foundations for environmental monitoring. However, their full potential will only be realized through innovation in coupling strategies, automation, and data analytics to meet the growing challenge of emerging contaminants in complex ecosystems.

Innovative Treatment Technologies and Hybrid Systems for Emerging Contaminants

Emerging contaminants (ECs) such as pharmaceuticals, endocrine-disrupting chemicals (EDCs), microplastics, and per- and polyfluoroalkyl substances (PFAS) represent a significant challenge in environmental pollution control due to their persistence, bioaccumulation, and low biodegradability. Conventional wastewater treatment processes are insufficient for their complete removal, leading to the increasing exploration of innovative and hybrid technologies that combine biological, physicochemical, and electrochemical mechanisms for enhanced degradation and mineralization.

Membrane-Based and Electrochemical Hybrid Technologies

Membrane-based hybrid systems have emerged as a key innovation for the removal of emerging contaminants (ECs), combining physical separation, electrochemical oxidation, and biological degradation. Reactive electrochemical membranes (REMs) and electrochemical membrane bioreactors (EMBRs) integrate filtration with in situ oxidation, enabling both pollutant degradation and electron transfer. EMBRs have achieved over 90% removal of antibiotics, hormones, and phenolic compounds, while generating bioelectricity (Xue et al., 2025). Similarly, carbon-based REMs achieved 94% removal of sulfamethoxazole and 90% of diclofenac, demonstrating the efficiency of electroactive surfaces for antibiotic degradation (Soares et al., 2022). Comparative

studies show that membrane PAC–MBR hybrids outperform conventional MBRs by coupling adsorption and oxidation, reaching up to 95% removal of carbamazepine and triclosan (Asheghmoalla & Mehrvar, 2024). Recent improvements include the integration of conductive nanomaterials such as TiO_2, graphene oxide, and carbon nanotubes to enhance electron transfer and catalytic efficiency (Huang et al., 2018). For instance, TiO_2-coated CNT membranes improved fluoroquinolone degradation by 37% compared to unmodified systems (Peterson et al., 2015). Despite progress, challenges remain regarding energy consumption, membrane fouling, and concentrate management. Current efforts focus on developing low-energy, self-regenerating electrochemical membranes with adaptive bio electrochemical functions for sustainable, modular wastewater treatment.

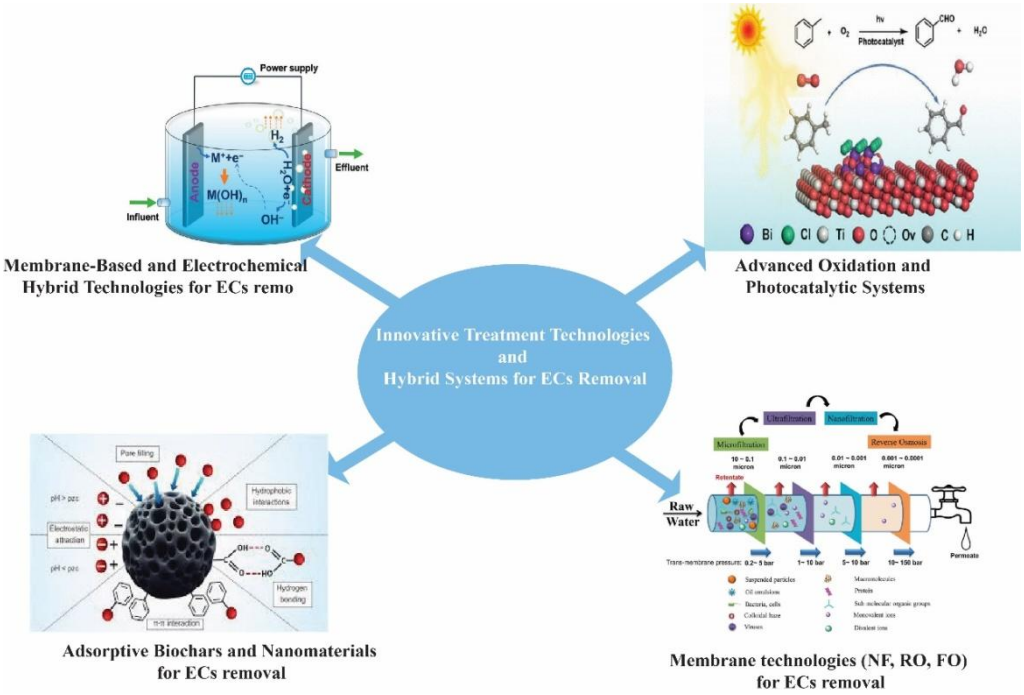

Figure 2: Innovative Treatment Technologies and Hybrid Systems for Emerging Contaminants treatment

Advanced Oxidation and Photocatalytic Systems

Advanced oxidation processes (AOPs) have become fundamental in degrading persistent emerging contaminants (ECs) by generating highly reactive oxygen species (ROS) such as hydroxyl (•OH) and superoxide ($O_2^{\bullet-}$) radicals. Techniques including ozonation, UV/H_2O_2, and Fenton-based oxidation have demonstrated outstanding performance in removing pharmaceuticals and personal care products from wastewater. For instance, ozonation coupled with biological activated carbon (BAC) achieved over 90% removal of carbamazepine, diclofenac, and sulfamethoxazole in pilot-scale treatment (Asheghmoalla & Mehrvar, 2024). Similarly, UV/H_2O_2 systems achieved up to 95% degradation of ibuprofen and naproxen under optimized conditions (da Luz et al., 2022).

Photocatalytic systems, particularly TiO_2-based catalysts, are equally effective. Kalantarian et al. (2024) reported that TiO_2–ZnO composites degraded sulfonamides and fluoroquinolones within 30 minutes, with near-complete detoxification of treated effluents (Kalantarian & Sheibani, 2024). Other catalysts, such as graphitic carbon nitride (g-C_3N_4) and Fe_2O_3-doped TiO_2, have shown enhanced visible-light activation and reduced electron-hole recombination, further improving degradation kinetics (Zhang et al., 2023). Although high efficiencies are frequently reported, the performance of AOPs is influenced by operational parameters such as pH, oxidant dosage, catalyst reuse, and matrix composition. Integration of AOPs as pretreatment steps before biological processes has shown synergistic effects, increasing effluent biodegradability and enhancing microbial stability downstream (xiangyu et al., 2025). These findings reinforce a growing consensus that process sequencing and optimization are essential to maximize radical utilization while minimizing by-product formation and energy consumption.

Membrane technologies (NF, RO, FO)

Membrane technologies including Nano filtration (NF), reverse osmosis (RO), and forward osmosis (FO) have emerged as crucial tools for removing emerging contaminants (ECs) such as pharmaceuticals, endocrine-disrupting compounds and personal-care products from water and wastewater streams. A recent systematic review found that both NF and RO frequently achieve removal efficiencies exceeding 90% for a wide range of ECs under optimal conditions; RO performs particularly well for small molecular compounds, while NF shows strong results for intermediate-sized contaminants (García-Ávila et al., 2025a). The scalability of membrane technologies is considerable modular NF/RO units are commercially available yet critical challenges remain, including membrane fouling, concentrate (retentate) management, high operational pressures (especially for RO) and energy consumption typically in the range of 1–8 kWh/m³ (García-Ávila et al., 2025b). Additionally, newer research is expanding the role of FO and hybrid membrane systems (membrane + AOP or

adsorption) to improve sustainability and reduce energy demands (Kim et al., 2025). In general, while NF/RO/FO technologies offer very high removal efficacy for ECs and are increasingly scalable, their practical deployment must pay careful attention to energy use, fouling mitigation, and management of the concentrated waste streams to ensure truly sustainable operation.

Adsorptive Biochars and Nanomaterials

Adsorptive biochars and nanomaterials are complementary technologies that together create powerful, flexible tools for pollutant removal in water and soil. Biochar a porous, carbon-rich product of biomass pyrolysis provides high surface area, abundant pore networks, and oxygen-containing functional groups that bind cationic metals, organics, and nutrients through a mix of electrostatic attraction, complexation, and pore-filling mechanisms (Y. Wang et al., 2024). However, pristine biochar can be limited by its native surface chemistry, pH sensitivity, and lower reactivity toward some contaminants; these limitations are routinely overcome by nano-scale modifications. By decorating biochar surfaces with nanoscale oxides, layered double hydroxides, metal nanoparticles, or graphene like sheets, researchers increase active surface sites, catalytic activity, and electron-transfer capacity which raises adsorption capacity, broadens the range of target contaminants, and enables in-situ degradation as well as sequestration (Arabzadeh Nosratabad et al., 2024). Practically, nanomaterial-modified biochars are produced by impregnation, in-situ growth, hydrothermal anchoring, or co-pyrolysis with metal precursors; these routes create stable bio-nanocomposites in which nanoparticles are immobilized on the carbon matrix to reduce particle agglomeration and leaching while preserving high reactivity (Arabzadeh Nosratabad et al., 2024). Mechanistically, pollutant removal combines classic adsorption (ion exchange, surface complexation, hydrophobic partitioning) with nanoscale-enabled processes such as Fenton-like catalysis, photocatalysis, and redox transformations (e.g., Cr(VI) → Cr(III) reduction) (Chaubey et al., 2023). The hybrid approach delivers several practical advantages: higher removal efficiencies at lower dosages, potential for regeneration and reuse, and the ability to target mixed contaminant streams (heavy metals + organics). At the same time, lifecycle and ecotoxicity considerations are important immobilizing reactive nanoparticles on biochar lowers the risk of nanoparticle release, but thorough leaching, aging, and risk-assessment studies are still required before widescale field deployment (Chaubey et al., 2023).

Algal–bacterial consortia and enzymatic bioreactors

Algal–bacterial consortia and enzymatic bioreactors represent promising biologically-driven technologies for treating emerging contaminants (ECs) with lower energy demands compared with high-intensity physico-chemical methods. In such systems, microalgae and heterotrophic bacteria work synergistically the algae generate oxygen via photosynthesis, supporting bacterial degradation of organic pollutants, while bacteria supply CO_2 and nutrients back to the algae (Abate et al., 2024). Recent research (2024–2025) demonstrates that these consortia can achieve removal efficiencies of 60-80% (sometimes higher) for pharmaceuticals, endocrine disruptors and industrial micro-pollutants when operated in well-controlled photobioreactors or integrated pond-reactor systems. For example, a recent study found that a tubular photobioreactor inoculated with *Chlorella vulgaris* and a mixed bacterial culture removed 75% of a pharmaceutical mixture after 7 days at 25 °C, with negligible external aeration apart from sunlight (Flores, 2023)(Palikrousis et al., 2025). Concurrently, enzymatic bioreactors using immobilised enzymes such as laccase, peroxidase or hydrolase are gaining traction for catalysing transformation of specific ECs (e.g., synthetic dyes, persistent phenolics, micropollutants) at mild conditions. A 2025 review on enzymatic bioreactors reports that by coupling enzyme-immobilisation on carriers and magnetic separation, removal efficiencies of 85–90% for target ECs are achievable, and the setup enables low-energy operation with potential reuse of enzymes across multiple cycles. Nonetheless, scalability challenges remain: large reactor volumes, light-dependence (for algae), seasonal variability, enzyme stability/renewal costs and the need for post-treatment polishing for residual ECs. **Figure 3**. This highlights that while both systems show high removal potential, algal bacterial consortia emphasize sustainability and nutrient recycling, whereas enzymatic bioreactors provide higher specificity and faster kinetics. Despite these challenges, algal bacterial and enzymatic systems offer a sustainable, lower carbon footprint alternative for EC management especially in decentralized or resource-limited settings (Chen et al., 2025).

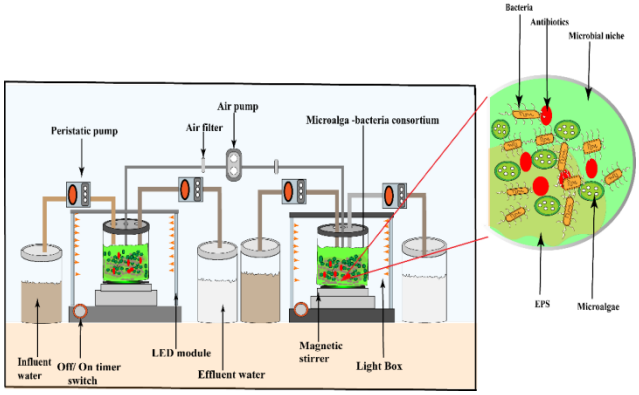

Figure 3. Algal-bacteria consortia and Enzymatic bioreactor for emerging contaminants (ECs) treatment.

Conclusion

The widespread occurrence of emerging contaminants (ECs) in wastewater underscores a pressing global challenge for water quality management. Conventional treatment processes originally intended to remove nutrients and pathogens are inadequate for eliminating trace-level pharmaceuticals, personal care products, PFAS, and other persistent compounds. As a result, these pollutants continue to enter aquatic ecosystems, where they contribute to endocrine disruption, antibiotic resistance, and ecological toxicity.

Advancements in analytical techniques, particularly high-resolution mass spectrometry and chromatographic-spectroscopic integrations, have enabled the detection of ECs at nano- to microgram concentrations. These technologies not only enhance understanding of EC fate and transport but also support early warning systems and regulatory compliance. On the treatment front, hybrid technologies such as electrochemical membrane bioreactors, advanced oxidation systems, and biochar–nanomaterial composites demonstrate removal efficiencies exceeding 90% for various ECs. Similarly, algal–bacterial consortia and enzymatic bioreactors offer eco-friendly and low-energy alternatives that align with the principles of circular bioeconomy and resource recovery.

Despite these promising advances, scalability, operational stability, and cost-effectiveness remain key barriers. Moreover, incomplete degradation can lead to transformation products with unknown toxicities. Therefore, the future of EC management lies in combining innovative technologies with systems thinking linking molecular-scale understanding to process optimization, ecological safety, and global policy implementation.

Recommendations

1. Integrated Monitoring Framework: Develop standardized global protocols that combine chemical and biological monitoring tools to identify ECs and their metabolites in wastewater and surface waters.

2. Hybrid and Modular Treatment Design: Promote hybrid systems that merge biological, physicochemical, and electrochemical processes such as AOP–biofilm or algal–bacterial–membrane reactors to enhance efficiency and minimize energy consumption.

3. Green and Circular Approaches: Encourage the adoption of biochar-based adsorbents, nanocomposites, and enzyme-assisted systems derived from renewable materials to advance sustainable remediation.

4. Risk Assessment and Regulation: Establish data-driven guidelines and enforceable discharge limits for high-risk ECs such as antibiotics, hormones, and PFAS, integrating One Health perspectives to prevent antimicrobial resistance.

5. Collaborative Research and Policy Support: Strengthen partnerships between academia, industry, and governments to fund large-scale pilots, life-cycle analyses, and socio-economic assessments that guide technology adoption and environmental policy reforms.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, manuscript).

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