MANTECH Publications

Journal of Water Resource Engineering and Pollution Studies
Volume 11, Issue 1, January-April 2026
ISSN: 3107-8419 (Online)

# *Removal and Treatment of Emerging Contaminants (PFAS & Micropollutants)*

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***Email ID:*** *https//doi.org/10.5281/zenodo.19217322*

## *ABSTRACT*

*Emerging contaminants such as* ***Per- and Polyfluoroalkyl Substances (PFAS)*** *and various* ***micropollutants*** *represent a rapidly growing concern for environmental and human health. These pollutants are widely detected in wastewater, surface waters, and drinking water sources, often at trace levels but with significant ecological and toxicological effects. Traditional water and wastewater treatment technologies usually fail to remove these contaminants efficiently due to their complex chemical properties, persistence, and resistance to degradation. This review paper provides a detailed examination of the sources, characteristics, occurrence, and adverse effects of PFAS and micropollutants, followed by a comprehensive review of their removal and treatment methods. Special focus has been given to recent advancements in physical, chemical, and biological treatment technologies including adsorption, advanced oxidation processes, membrane technologies, and biodegradation. The paper discusses advantages, limitations, and future research needs for effective management of emerging contaminants. Tables and figures are used to explain treatment efficiencies and operational parameters. The challenges and prospects for integrated treatment strategies are outlined. This paper aims to provide guiding frameworks for researchers, regulators, and practitioners working in water treatment disciplines.*

***KEYWORDS:*** *Emerging contaminants; PFAS; micropollutants; water*


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*treatment; adsorption; advanced oxidation; biodegradation; membrane filtration.*

## INTRODUCTION

Water contamination by emerging pollutants is recognized as a global environmental issue in the 21st century. Over the past decades, scientists and regulators have identified **PFAS** (Per- and Polyfluoroalkyl Substances) and **micropollutants** as some of the most persistent and challenging contaminants in water systems. PFAS are a group of highly stable synthetic compounds that have been widely used in industrial and consumer products such as firefighting foams, coatings, and non-stick materials since the 1950s (Kjeldsen & Jensen, 2020).

Micropollutants include pharmaceuticals, personal care products, hormones, pesticides, and endocrine-disrupting chemicals that exist at very low concentrations (<1 µg/L) but may produce chronic effects on ecosystems and human health (Santos et al., 2021). The rapid rise in industrialization, population growth, and the huge reliance on synthetic products have increased emissions of these contaminants into water bodies, posing complex challenges to conventional treatment plants.

In this paper, we review fundamental aspects of PFAS and micropollutants, deras occurrence in various water matrices, toxicity concerns, and most importantly, treatment technologies developed to remove these contaminants efficiently. This review also compares removal efficiencies, technology readiness, economic factors, and limitations of each method.

## PFAS AND MICROPOLLUTANTS: CHARACTERISTICS AND SOURCES

Emerging contaminants, particularly **PFAS (Per- and Polyfluoroalkyl Substances)** and **micropollutants**, have increasingly drawn attention due to their persistence in the environment and potential health risks. These contaminants are widely present in water systems and are challenging to remove through conventional treatment methods. Understanding their chemical characteristics and sources is crucial for developing effective removal strategies.

### PFAS Overview

PFAS are a diverse group of **synthetic fluorinated organic chemicals**, consisting of thousands of compounds that share the common feature of **carbon-fluorine (C–F) bonds**, one of the


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strongest chemical bonds in organic chemistry. This bond confers exceptional chemical and thermal stability, making PFAS highly resistant to degradation in natural and engineered environments.

The **most extensively studied PFAS compounds** include:

- **Perfluorooctanoic acid (PFOA):** Used in non-stick cookware coatings, textiles, and paper packaging.
- **Perfluorooctane sulfonate (PFOS):** Previously used in firefighting foams, stain-resistant fabrics, and certain industrial processes.

Due to their **hydrophobic and lipophobic nature**, PFAS tend to accumulate at interfaces, such as water–air or water–soil surfaces, which contributes to their mobility and persistence. PFAS are highly resistant to microbial degradation, photolysis, and hydrolysis, which is why they are sometimes called "forever chemicals."

**Sources of PFAS contamination** include:

- **Industrial discharge:** Manufacturing facilities that produce or use PFAS-containing products.
- **Firefighting sites:** Military bases, airports, and training sites where aqueous film-forming foams (AFFFs) were used.
- **Landfills and sludge:** PFAS can leach from disposed consumer products and biosolids applied to land.
- **Wastewater effluents:** Treated water may still contain residual PFAS due to their chemical stability.

**Health and environmental concerns:** PFAS bioaccumulate in humans and wildlife, leading to long-term exposure even at low concentrations. Studies have linked PFAS to **liver toxicity, thyroid disruption, developmental toxicity in infants, immune system suppression, and possibly cancer** (Liu et al., 2020). Their persistence in ecosystems means they can travel long distances, contaminate groundwater, and enter the food chain.

**Micropollutants**

Micropollutants are a heterogeneous group of chemicals present at **trace concentrations**, usually in the **nanogram to microgram per liter range** that can have significant biological


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and ecological effects. Unlike PFAS, many micropollutants are **partially biodegradable**, but their continuous introduction into water systems makes them persistent environmental concerns.

Key categories of micropollutants include:

- **Pharmaceuticals:** Antibiotics, painkillers, antidepressants. For example, diclofenac and ibuprofen are commonly detected in surface waters.
- **Hormones and endocrine-disrupting compounds (EDCs):** Estradiol, estrone, testosterone, which can alter reproductive cycles and development in aquatic organisms.
- **Personal care products:** Triclosan, parabens, and synthetic fragrances, often released through domestic wastewater.
- **Pesticides and herbicides:** Atrazine, glyphosate, and chlorpyrifos, which enter water bodies via agricultural runoff.
- **Industrial chemicals:** Bisphenol A (BPA), phthalates, and surfactants from plastics, paints, and coatings.

**Sources of micropollutants** include:

- **Municipal wastewater:** Pharmaceuticals and personal care products are often excreted unmetabolized.
- **Agricultural runoff:** Fertilizers, pesticides, and veterinary medicines leach into rivers and lakes.
- **Improper disposal:** Household chemicals, industrial effluents, and untreated sludge contribute to contamination.

Even at trace levels, micropollutants can **disrupt endocrine systems, impair reproductive health, and cause bioaccumulation in aquatic organisms**. Their continuous input into water systems and partial resistance to conventional wastewater treatment increases their environmental risk.

**Occurrence in Water Systems**

Emerging contaminants are **widely detected in global water bodies**, including surface water, groundwater, drinking water, and treated wastewater. Concentrations vary depending on the **proximity to sources**, seasonal changes, and hydrological conditions.


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**PFAS occurrence:**

- Typically range from **ng/L to µg/L** in surface water, groundwater, and drinking water.
- Higher concentrations are observed near industrial sites, landfills, and firefighting training areas.
- PFAS are mobile in water and resist conventional treatment, leading to their accumulation in sediments and aquatic life.

**Micropollutant Occurrence:**

- Pharmaceuticals, personal care products, and pesticides are frequently detected in **treated wastewater effluents**, often because conventional treatment plants are not designed to remove them completely.
- Concentrations in rivers and lakes are typically in the **ng/L range**, but **continuous release** can lead to chronic exposure for aquatic organisms.
- Certain micropollutants, like steroid hormones and antibiotics, can persist even after biological treatment due to their chemical stability and low biodegradability.

In summary, both PFAS and micropollutants are **ubiquitous in water systems** and pose challenges for treatment due to their chemical properties, persistence, and widespread use. Understanding their sources, chemical behavior, and occurrence patterns is essential for designing effective removal strategies.

## IMPACTS ON ENVIRONMENT AND HEALTH

Emerging contaminants such as **PFAS** and **micropollutants** have far-reaching consequences for both natural ecosystems and human health. Their persistence, bioaccumulative nature, and biological activity make them particularly concerning, even at trace concentrations. Understanding these impacts is critical for prioritizing treatment strategies and regulatory policies.

### Environmental Impacts

**PFAS and micropollutants pose significant threats to aquatic ecosystems.** Their effects can be both direct, by causing toxicity in organisms, and indirect, by altering ecological balance and food webs.


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1. **Bioaccumulation and Biomagnification:**

- PFAS are highly persistent and resist natural degradation processes. Once released into water bodies, they can adsorb onto sediments or dissolve in water, entering the food chain. Small aquatic organisms such as plankton absorb PFAS, which then accumulate in fish, amphibians, and birds through **biomagnification**.
- Micropollutants like pharmaceuticals and pesticides can also accumulate in tissues, affecting organism physiology even at low environmental concentrations.

2. **Endocrine Disruption:**

- Many micropollutants mimic natural hormones, leading to **endocrine disruption** in aquatic species. For example:
  - Synthetic estrogens from contraceptives can cause feminization of male fish.
  - Certain pesticides interfere with thyroid and steroid hormone pathways in amphibians, affecting metamorphosis and growth.
- Such disruptions can reduce reproductive success, alter sex ratios, and decrease population viability over time.

3. **Altered Behavior and Physiology:**

- Exposure to PFAS and micropollutants has been observed to affect behavior in aquatic organisms, such as reduced feeding, altered predator avoidance, and impaired locomotion.
- Liver enzyme activity, immune response, and growth patterns can also be disrupted, weakening overall ecosystem resilience.

4. **Reduced Biodiversity:**

- Chronic exposure to these contaminants creates **sub-lethal stress** on sensitive species, potentially leading to local extinctions.
- Changes in microbial communities due to antibiotic micropollutants can reduce natural biodegradation capacity in sediments and soils.

5. **Persistence in Sediments and Soil:**

- PFAS compounds tend to bind to sediments and soils near water bodies, remaining in the environment for decades.


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- Micropollutants like pesticides can similarly persist, leaching slowly into groundwater and affecting terrestrial and aquatic ecosystems.

**Human Health Concerns**

Humans are primarily exposed to PFAS and micropollutants through drinking water, contaminated food, and recreational contact with contaminated water bodies. Chronic exposure, even at low levels, can lead to multiple health risks:

1. **PFAS-Related Health Effects:**

- **Liver damage:** PFAS interfere with liver metabolism, altering lipid and enzyme profiles.
- **Immune dysfunction:** Some PFAS reduce antibody production and impair immune responses, increasing susceptibility to infections.
- **Developmental and reproductive toxicity:** Prenatal exposure may lead to low birth weight, developmental delays, and hormonal imbalances.
- **Carcinogenicity:** Long-term exposure to certain PFAS, including PFOA, has been associated with kidney and testicular cancers.

2. **Micropollutant-Related Health Effects:**

- **Endocrine disruption:** Hormone-mimicking compounds (e.g., synthetic estrogens, bisphenol A) can impair reproductive health, alter puberty onset, and affect fertility in humans.
- **Neurological effects:** Certain pharmaceuticals and industrial chemicals may affect neurological development, particularly in infants and young children.
- **Antimicrobial resistance:** Chronic exposure to antibiotics in water bodies may contribute to the proliferation of resistant bacteria, indirectly affecting human health.

3. **Vulnerable Populations:**

- **Infants and children:** More susceptible due to developing organs and higher water intake relative to body weight.
- **Elderly:** Often have weaker immune systems and reduced detoxification capacity.
- **Immunocompromised individuals:** Exposure may exacerbate existing health issues.


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4. **Long-Term and Combined Exposure Effects:**

- Humans are rarely exposed to a single contaminant. The **cumulative and synergistic effects** of multiple PFAS and micropollutants remain largely unknown, but preliminary studies suggest amplified toxicity when compounds interact.
- Chronic exposure over decades, even at trace levels, poses significant **public health challenges**, making treatment and regulatory control crucial.

## OVERVIEW OF TREATMENT TECHNOLOGIES

Emerging contaminants such as **PFAS and micropollutants** present unique challenges for water and wastewater treatment. Their **persistence, low concentrations (ng/L–µg/L), and diverse chemical structures** make conventional treatment methods partially ineffective. These contaminants often resist biological degradation and conventional chemical treatments, requiring specialized or **advanced treatment technologies**.

Treatment technologies can be broadly categorized into **physical**, **chemical**, and **biological** methods. Each approach has its advantages and limitations depending on contaminant type, water quality, cost, and operational complexity.

### Physical Treatment Methods

Physical methods primarily **remove contaminants without chemically altering them**, often through adsorption, filtration, or separation processes.

**1. Adsorption**

Adsorption is widely regarded as a **benchmark technology for PFAS and micropollutants**. It involves transferring contaminants from water to a solid adsorbent material.

**Common Adsorbents:**

- **Granular Activated Carbon (GAC):** Widely used for PFAS removal in drinking water. Effective for long-chain PFAS, but short-chain PFAS may pass through.
- **Powdered Activated Carbon (PAC):** Suitable for micropollutants in wastewater. High surface area allows rapid adsorption.
- **Ion-Exchange Resins:** Specifically designed to capture ionic PFAS like PFOS and PFOA.
- **Biochar:** Low-cost, environmentally friendly adsorbent with variable performance depending on preparation method.


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**Advantages:**

- Simple operation.
- Effective for a wide range of compounds.
- Can be implemented in existing treatment plants.

**Limitations:**

- Adsorbent saturation requires frequent regeneration or disposal.
- Efficiency may decrease in the presence of competing organic matter.

## PHYSICAL TREATMENT APPROACHES

### Adsorption

**Adsorption** is the most widely studied method for PFAS and micropollutant removal. Activated carbon remains the benchmark adsorbent.

***Table 1: Typical Adsorbents and Their Removal Efficiencies***

| Adsorbent | Target Contaminants | Removal Efficiency | Remarks |
|---|---|---|---|
| GAC (Granular Activated Carbon) | PFAS | Up to 90% | Widely used, needs frequent regeneration |
| PAC (Powdered Activated Carbon) | Micropollutants | ~70–95% | Good for trace compounds |
| Ion Exchange Resins | PFAS | ~80–98% | Can be tailored to chain length |
| Biochar | Micropollutants & PFAS | ~30–80% | Low cost, variable results |

**Advantages:** Simple operation, high capacity for a range of pollutants.

**Limitations:** Spent adsorbents require regeneration or safe disposal; performance varies with water quality.


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### Membrane Filtration

Membrane processes such as **nanofiltration (NF)** and **reverse osmosis (RO)** are effective for removing dissolved contaminants.

***Table: 2***

| Membrane Type | Target Pollutants | Removal Efficiency | Challenges |
|---|---|---|---|
| RO | PFAS, micropollutants | >95–99% | High energy, concentrate disposal |
| NF | Micropollutants | ~70–95% | Limited removal of low MW compounds |

**Remarks:** RO is highly effective but energy-intensive; concentrate management is a concern.

## CHEMICAL TREATMENT METHODS

### Advanced Oxidation Processes (AOPs)

AOPs include Fenton, UV/$H_2O_2$, ozonation, and photocatalysis. They generate highly reactive radicals to oxidize contaminants.

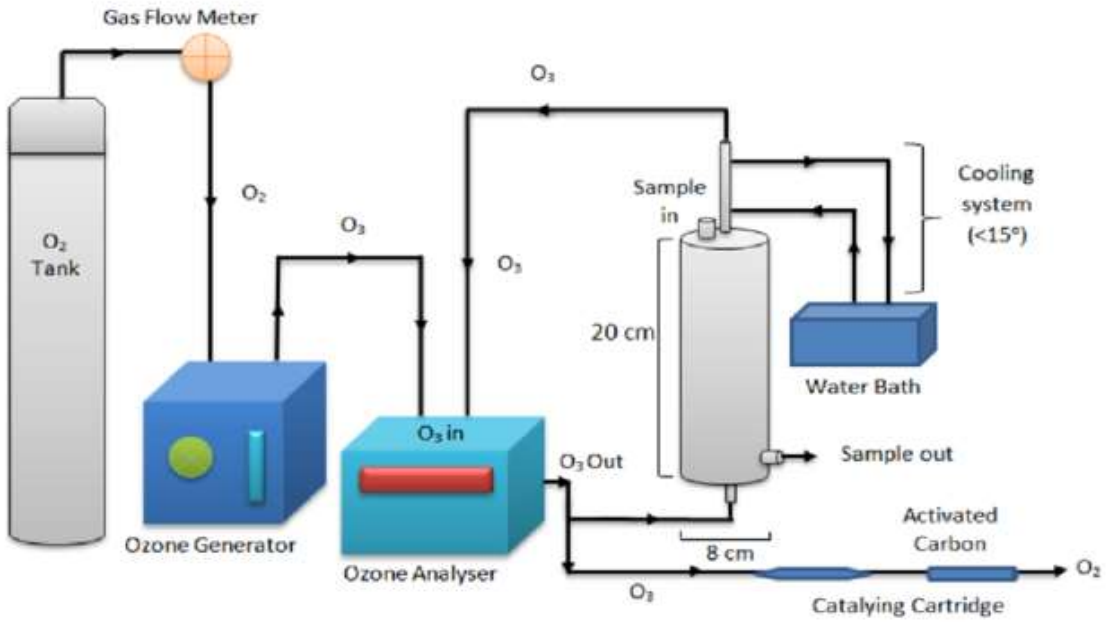



***Figure 1: Schematic of AOP for Water Treatment***


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**Strengths:** AOPs can degrade micropollutants that are resistant to conventional treatment.

**Weaknesses:** Costly, requires chemical dosing, may form by-products.

**Chlorination and Ozonation**

Ozonation can partially remove micropollutants and break PFAS chains under high dosages.

**Issue:** Formation of disinfection by-products (DBPs) that may be toxic.

## BIOLOGICAL TREATMENT METHODS

a) **Conventional Activated Sludge**

   Effective for biodegradable micropollutants, but limited for PFAS due to their stability and non-biodegradable nature.

b) **Specialized Bioaugmentation**

   Introduction of specific microbial strains that can degrade certain micropollutants has shown promise. However, effective PFAS-degrading microorganisms are still under research.

c) **Constructed Wetlands**

   Wetlands enhance natural biodegradation and adsorption processes. They are cost-effective for low-strength wastewater but slow and space-demanding.

## COMBINED TREATMENT STRATEGIES

Emerging contaminants often require **hybrid treatment trains** that combine physical, chemical, and biological methods.

**Example Treatment Train:**

Pre-ozonation → Activated Carbon → Membrane Filtration → AOP polishing

This multi-barrier approach enhances removal efficiency and mitigates limitations of individual technologies.

## CASE STUDIES AND PRACTICAL APPLICATIONS

**Case Study 1: PFAS Removal Using Ion Exchange in a Small Town**

A small water plant used ion exchange resins to reduce PFAS from 500 ng/L to <70 ng/L, demonstrating practical feasibility in rural settings.


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**Case Study 2: Constructed Wetlands for Micropollutant Reduction**

A constructed wetland system reduced pharmaceutical concentrations by ~60% over 12 months, indicating ecological treatment potential.

## CHALLENGES AND LIMITATIONS

Despite advancements, several challenges remain:

1. **Detection limits:** Measuring contaminants at ng/L levels requires sophisticated instrumentation.
2. **Treatment costs:** High costs for AOP and membrane systems limit wide adoption.
3. **By-products:** Some oxidation processes generate transformation products with unknown toxicity.
4. **Concentrate disposal:** Membrane processes generate brines that require safe disposal.

## FUTURE RESEARCH DIRECTIONS

Research priorities include:

- Development of **low-cost adsorbents** with high selectivity.
- Identification of **microbial consortia** capable of PFAS degradation.
- Integrated **sensing technologies** for real-time monitoring.
- Life cycle assessment (LCA) of treatment processes.

## CONCLUSION

Emerging contaminants such as PFAS and micropollutants present significant challenges for water treatment due to their persistence, diversity, and low concentration. Traditional treatment technologies are often insufficient to achieve complete removal. Advanced technologies including adsorption, membrane filtration, advanced oxidation, and hybrid treatment trains offer promising solutions, but each has limitations related to cost, complexity, by-products, or waste disposal. Future work should focus on optimizing integrated systems that balance efficiency, sustainability, and affordability. Collaboration between researchers, industry, and policymakers will be essential to safeguard water quality in the face of these emerging threats.

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**Cite as:**

Abhay Pathak, Subhendu Chandra. (2026). Removal and Treatment of Emerging Contaminants (PFAS & Micropollutants). Journal of Water Resource Engineering and Pollution Studies, 11(1), 72-84.

https//doi.org/10.5281/zenodo.19217322


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