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Removal of Organic Pollutants from Wastewater Using Adsorbent Synthesis from Bacterial Enzymes

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ABSTRACT

Background: Pharmaceuticals, endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS) and micro plastics, together with personal care items, are increasingly found in the water bodies. These compounds tend to be resistant to the traditional water and wastewater treatment methods since they are persistent, low in concentrations, and possess varying physicochemical characteristics. The fact that they still remain in treated effluent is a great concern to human health and ecological integrity. Objective: The purpose of the review is to critically analyze the existing limitations of EC removal with the available treatment technologies, determine the working of advanced and hybrid systems, and develop a risk-based approach in the integration of the removal efficiency and the protection of the populace and the environment. Methods: The systematic review approach was utilized with the use of Scopus, Web of Science, PubMed, and ScienceDirect literature. Inclusion criteria were peer-reviewed articles that discussed EC occurrence, treatment performance and risk assessment. The analysis was an integration of comparative analysis of removal efficiencies with toxicological indices, including bioaccumulation, pathways of exposure, and persistence. Results: The traditional treatment systems had low EC removal (under 40 percent), especially with persistent and hydrophilic compounds. The removal rates of advanced oxidation processes (AOPs), membrane filtration and adsorption were 60-99 % depending on EC class. The hybrid systems were also superior to single technologies, but they experienced issues concerning the cost, integration, and scalability. Another common gap that was found in the review was the lack of correlation between the effectiveness of the treatment and reduction of health risks. Implications: Results highlight the importance of multi-barrier treatment approaches that are integrated and combine the objectives of technical performance with the objectives of risk mitigation. The paper offers advice to engineers, regulators and policymakers to promote the practices and regulatory standards of water treatment in response to the emergent chemical threats.

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1. Statement of Original Contribution

The review offers an innovative interdisciplinary synthesis in uniting the technical performance of the water treatment technologies with their efficacy in reducing the risks linked to new contaminants. This study fills the gap between the two realms, unlike the case with previous reviews that usually evaluate engineering efficiency or toxicological risk separately. The major innovation is the system comparison of traditional, advanced, and hybrid technologies in different categories of EC, where the efficiency of their removal is not the only criterion; their role in eliminating human and ecological exposure is also taken into account. The review presents the concept of risk-based framework whereby, high-risk contaminants are targeted on the basis of the ability of technologies to remove them according to their toxicity, persistence, and bioaccumulation. This paper outlines the key regulatory and operational weaknesses, such as absence of enforceable standards to a large number of ECs, inadequate monitoring facilities, and lack of connection between the objectives of treatment and the health protection results. This review can be viewed as a decision support tool by both engineers and policymakers by presenting water treatment as a means to protect the health of the population. The synthesis further enhances the state of art by advancing evidence-based and health-oriented solutions to water treatment, and this is applicable to utilities, environmental agencies, as well as international water safety planning.

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2. Introduction

Emerging contaminants (ECs) are a heterogeneous and growing category of synthetic or naturally occurring chemical compounds, which are not fully regulated and are found growingly in water environments throughout the world. These are pharmaceuticals, endocrine-disrupting compounds (EDCs), per- and polyfluoroalkyl compounds (PFAS), microplastics and personal care product constituents (Li et al., 2025). Their worldwide distribution is caused by industrialization, urban wastewater releases, agricultural runoffs, and high consumption of consumer products causing chronic exposure hazards via drinking water, food chains and water bodies.

Traditional water and wastewater treatment technologies, which were traditionally created to eliminate suspended solids, pathogens, and large-scale organics, are not designed to eliminate trace-level ECs (Huang et al., 2022). Most ECs (particularly persistent and hydrophobic chemicals such as PFAS or microplastics) commonly exhibit low removal efficiencies of less than 40 % cent using processes like coagulation-flocculation, activated sludge, and sand filtration. The fact that ECs are chemically diverse compounds worsens this deficiency (Marcu et al., 2023).

As a reaction to this, there is a tendency to move toward a risk-based water treatment. This method focuses not only on the physical elimination of contaminants, but also on their minimization with respect to toxicological relevance, bioavailability and exposure routes. It matches the engineering performance to the mitigation of risks to aid the protection of the health of the people and the sustainability of the ecosystem.

This review presents a critical assessment of the issues of EC elimination in existing water treatment systems, the efficiency of advanced and hybrid technologies, and the ways of enhancing the treatment performance in accordance with health-based risk models (Sangamnere et al., 2023). The article will be informative in designing treatment, regulatory decision-making, and policymaking through a systematic review of the latest literature (2018-2025). The framework consists of literature review, risk-consolidated approach, comparative evaluation, and practical recommendations to the future innovation in water treatment.

3. Literature Review

3.1 Classification and Sources of Emerging Contaminants

Emerging contaminants (ECs) refer to a homogenous group of chemicals of growing concern to waterways due to the development of analytical techniques (Richardson & Ternes, 2021). The most notable ones are pharmaceuticals (e.g., antibiotics, analgesics), endocrine-disrupting chemicals (e.g., bisphenol A, hormones), PFAS, personal care product ingredients (e.g., triclosan, parabens), industrial chemicals, nanomaterials, and microplastics. Their main contributors include municipal wastewater discharges, hospital discharges, agricultural runoff, landfill discharges and urban stormwater (Tran et al., 2019). These pollutants find their way to surface water, ground water and even treated drinking water where they are frequently found in the range of ng/L -µg/L, which is chronic and toxic.

3.2 Physicochemical Properties Influencing Persistence and Treatment Resistance

Physicochemical properties such as molecular weight, polarity, hydrophobicity (log Kow), volatility (Henrys Law constant), and biodegradability, are the most important determinants of the environmental persistence and treatability of ECs (Habimana & Sauvé, 2025). Examples include PFAS that have strong carbon-fluorine bond, which give it thermal and chemical stability, and hydrophilic pharmacokinetics being unable to be eliminated through traditional sorptive methods. Microplastics are biodegradation resistant and act as reservoirs to other pollutants. The structural differences between ECs require specific or hybridized treatment strategies to make use of standard operations in water treatment units complicated (Wang et al., 2024).

3.3 Global Trends in Detection and Regulatory Concern

In the last ten years, the world surveillance has reported rising incidences of ECs in water bodies, usually beyond the precaution health limits (Feng et al., 2023). Directives by European Union (e.g., Watch Lists under the Water Framework Directive), the US EPA Contaminant Candidate List (CCL), and other national regulations have started giving priority to select ECs, in particular, PFAS, antibiotics, and EDCs, in the future (Papagiannaki, 2021). The vast majority of jurisdictions, standards applicable and without exception inspected by a regular program are absent.

3.4 Gaps in Prior Reviews

A variety of reviews have also assessed individual treatment technologies to remove EC, as membrane filtration, ozonation, or

adsorption, and a key focus has been to determine engineering metrics of the technology (e.g., removal efficiency, energy demand). Risk assessment studies have been conducted separately on EC toxicity, persistence and pathways of exposure (Song et al., 2018). Such inability to synthesize continues to create disconnect between the technological optimization and the actual health outcomes of the populations and restricts actionable understanding by the decision-makers.

3.5 Necessity of the Present Study

Considering the growing prevalence of ECs, the insufficiency of old infrastructure and regulatory paralysis (Rani et al., 2024), there is an urgent need to reconsider the concept of there being a direct relationship between treatment efficacy and risk-based outcomes. This paper is the first attempt to combine EC typologies, treatment responses and toxicological endpoints to a unified system, which fills the gap between water engineering and environmental health science. By doing this, it helps in the evidence-based treatment design and policy development to defend the ecosystems and the human population.

4. Methodology

A semi-systematic approach was adopted in this review in which the study was designed under the PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) guidelines (Islam et al., 2025). Although it is not a complete meta-analysis, this will provide a structured, transparent, and replicable synthesis of inter-disciplinary research. The reason why the method was chosen is due to the multitude and changing nature of emerging contaminants (ECs), which differ considerably by source, chemical structures, as well as treatment responses.

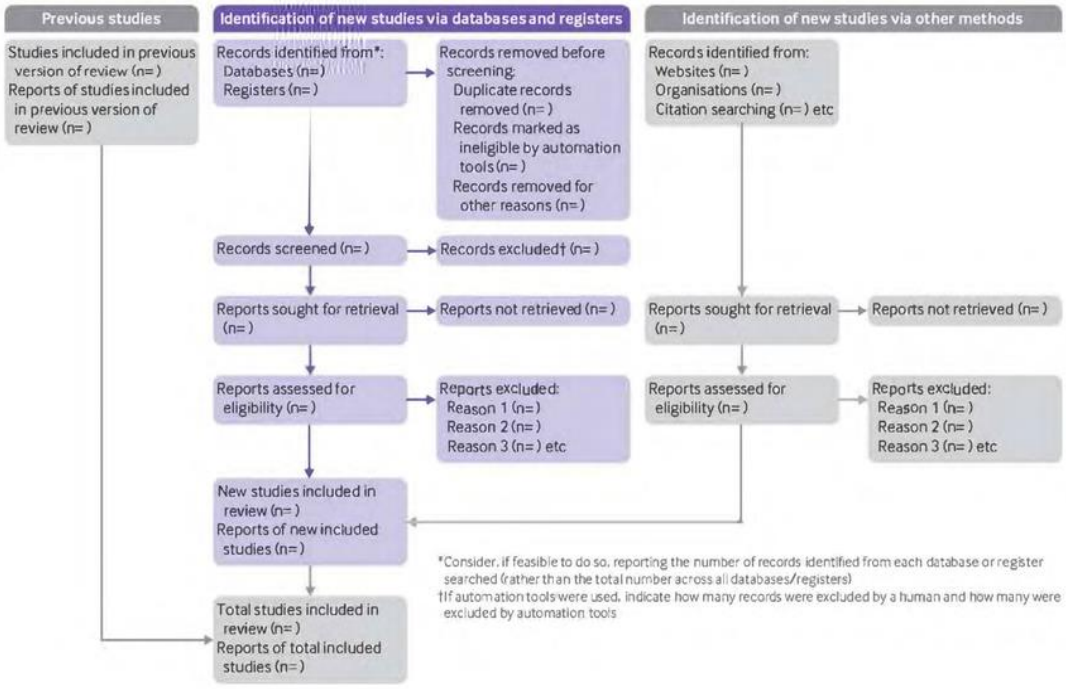


Figure 1: Flow Diagram Suggested in PRISMA Methodology

4.1 Literature Search Strategy

To integrate the fields of the environment, engineering, and environmental chemistry, as well as, the field of environmental engineering, engineering, and environmental chemistry, a literature search was done using four large academic databases, including Scopus, Web of Science, PubMed, and ScienceDirect. Peer-reviewed articles published between 2018 and 2025 were also considered in the search, which is a time related to increased interest and concern about global research and regulation.

The Boolean operators and key terms, including: were used jointly in the search strings.

((emerging contaminants) OR (micropollutants) OR (ECs)) and (water treatment) OR (wastewater) OR (removal technologies) and (advanced oxidation) OR (adsorption) OR (membrane filtration) and (risk assessment) OR (toxicity) OR (exposure reduction).

Additional studies were also determined through reference lists of the relevant review articles.

4.2 Inclusion and Exclusion Criteria

4.2.1 Inclusion Criteria

- Peer-reviewed articles focusing on EC occurrence, treatment technologies, or risk assessment.
- Studies providing quantitative or comparative data on removal efficiency, operational conditions, and/or health or ecological risk indicators.
- Articles addressing one or more EC classes (e.g., PFAS, pharmaceuticals, microplastics, endocrine disruptors).
- English-language publications.

4.2.2 Exclusion Criteria

- Studies without empirical data (e.g., commentaries, editorials).
- Detection-focused studies with no treatment or risk component.
- Grey literature, non-peer-reviewed sources, or those lacking methodological clarity.

4.3 Analytical Framework

The extracted data were organized using a two-tiered analytical framework:

1. Technology Comparison of Performance: The methods of treatment were classified (e.g. conventional, AOPs, membrane systems, adsorption, hybrid systems) and evaluated according to the reported removal efficiencies, by-product generation, scalability and feasibility (Asheghmoalla & Mehrvar, 2024).
2. Risk-Based Evaluation: The removal performance data were overlaid on established risk factors such as toxicity thresholds, the potential of bioaccumulation, the endocrine disruption activity, and environmental persistence. This enabled the analysis to go beyond the percentages of the removal and look at the contribution of the technologies to the actual reduction of the risk of human and ecological receptors (Ma et al., 2018).

Qualitative evaluations of technology trades were made to life-cycle and sustainability where appropriate.

4.4 Methodological Justification

This is because ECs are complex and the literature on the subject is not consolidated in a single field, so a semi-systematic review can provide structure and flexibility. The PRISMA elements enhance reproducibility and the dual analysis framework is a bridge between engineering performance data and the public health/environmental risk outcomes, which is one of the objectives of this research (Properzi et al., 2025). The methodology facilitates high impact and policy relevant conclusions in a fast-changing discipline.

5. Data Extraction and Analytical Framework

This section is the data extraction process and the analysis plans to be employed to synthesize and interpret the findings of the chosen literature. Review is based on a multi-criteria framework of both performance in the treatment and mitigation of risks that incorporates the evaluation of environmental engineering, toxicology, and sustainability.

5.1 Data Extraction Parameters

Data were systematically collected out of all eligible studies and then grouped into thematic categories according to the core parameters as follows:

5.1.1 Type and Concentration of the Contaminant

The classification of the studies was done according to the targeted emerging contaminants (ECs), such as pharmaceuticals (e.g., diclofenac, carbamazepine), endocrine-disrupting compounds (e.g., bisphenol A, estradiol), PFAS, microplastics, personal care products (e.g., triclosan), and illicit drugs (García-Fernández et al., 2021). The influent concentrations were reported to be nanograms to micrograms per liter, which is typical of both municipal and industrial wastewater sources and drinking water sources.

5.1.2 Treatment Technologies

The methods of treatment were divided into five major categories (1) conventional (e.g., activated sludge), (2) advanced oxidation

processes (AOPs), (3) membrane filtration (e.g., nanofiltration, reverse osmosis), (4) adsorption (e.g., activated carbon, biochar, MOFs), and (5) hybrid/ multi-barrier systems. Dependent variables of operation like hydraulic retention time (HRT), pH, oxidant dosage, membrane flux and the type of adsorbent were noted to place performance results in perspective.

5.1.3 Removal Efficiencies and Formation of By-Products

EC removal rates were isolated and, mostly, comparative values across technologies were of interest (Islam, 2019). Along with primary removal data, the generation of transformation products and secondary pollutants (e.g., bromate, ozone-generated aldehydes; breaking microplastic into fragments) was observed particularly when the toxicity was higher than the toxicity of parent compounds.

5.1.4 Risk Indicators

Toxicological endpoint data, bioaccumulation potential data, and data on exposure pathways (e.g. drinking water, fish consumption) in the environment were surveyed where available. The removal performance, associated with risk reductions, through the use of tools, including the Risk Quotient (RQ), Predicted No Effect Concentration (PNEC), or toxic equivalency factors, was a priority (Savoca & Pace, 2021).

5.2 Synthesis and Analytical Strategy

The method of comparative synthesis was applied to compare the removal efficiencies between treatment technologies and classes of contaminants. In the cases when direct comparisons could not be made because of different experimental designs, qualitative synthesis was used to describe patterns in the performance, point out major trade-offs, and technological constraints.

5.3 Integration with Risk-Based Frameworks

The analytical model finally compares the treatment information with the results of risk mitigation, allowing the recognition of the technologies that not only result in a high removal but also the exposure to priority contaminants in lie- and health-relevant manner (Alizadeh Tataki Afshar et al., 2025). This helps to shift to evidence-based water treatment approaches that are risk-based.

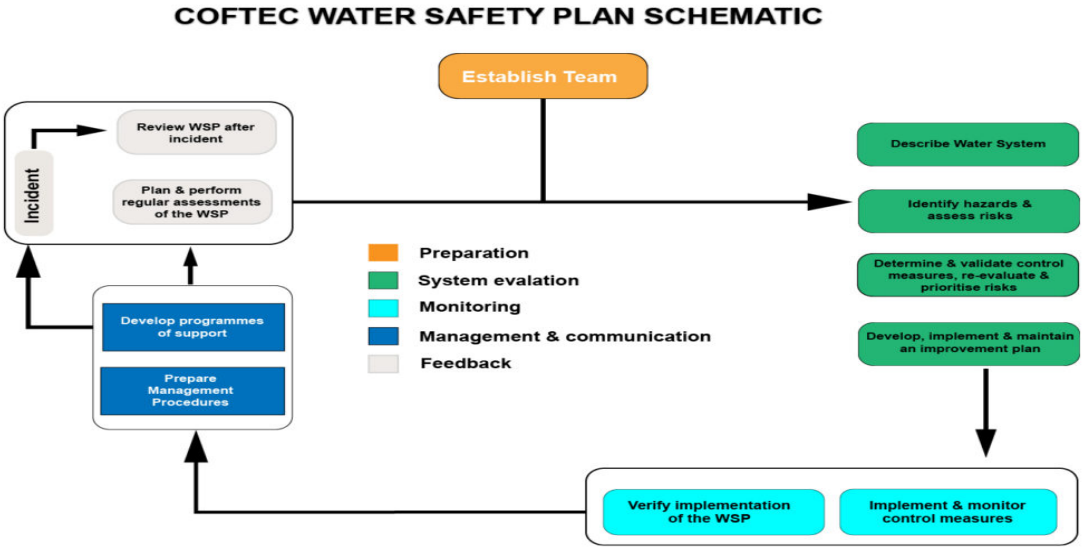


Figure 2: Conceptual Risk-Based Framework Integrating Emerging Contaminant Characteristics, Treatment Technology Performance, and Human and Ecological Risk Mitigation Outcomes

6. Results

6.1 Overview of Technology Performance

The effectiveness of the water and wastewater treatment technologies in eliminating emerging contaminants (ECs) is closely dependent on the nature of the contaminants (e.g., polarity, molecular weight, and persistence), the structure and optimization of the treatment systems, and the magnitude of the systems that are implemented (Mahmood et al., 2022). Table 1 gives a comparative overview of five large classes of treatment technologies in terms of removal efficiency and specificity to contaminant.

Traditional treatment systems such as the activated sludge, coagulation-flocculation and sand filtration systems have limited EC

removal capacities. These methods have a low effectiveness in treating recalcitrant and hydrophilic contaminants like scale of Pfas, pharmaceuticals, and residues of personal care product, despite a common removal efficiency of 10-40 %. Adapted Oxidation Processes (AOPs) such as ozonation, UV/H 2 O 2 and Fenton-based systems exhibit much better performance especially on ECs that are prone to oxidative degradation (Roslan et al., 2024). Efficiencies of removal are usually between 60 and 95 per cent and are increased with post-treatments that are catalytic or biological.

Activated carbon, biochar, or new materials such as MOFs (metal-organic frameworks) are used in adsorption technologies, and remove 50-90% of moderately hydrophobic and aromatic ECs. They are relatively simple and relatively inexpensive to use and remove capacity is related to affinity between the sorbent and contaminant and during saturation, regeneration or replacement is required.

Hybrid systems that consist of AOPs, membranes, or adsorption units are the most efficient. These systems are able to cater to a large number of EC classes at the same time and be redundant to increase operational resilience. The need sophisticated design and monitoring systems and their complexity can be a hindrance to scalability and affordability (Ejraei et al., 2019).

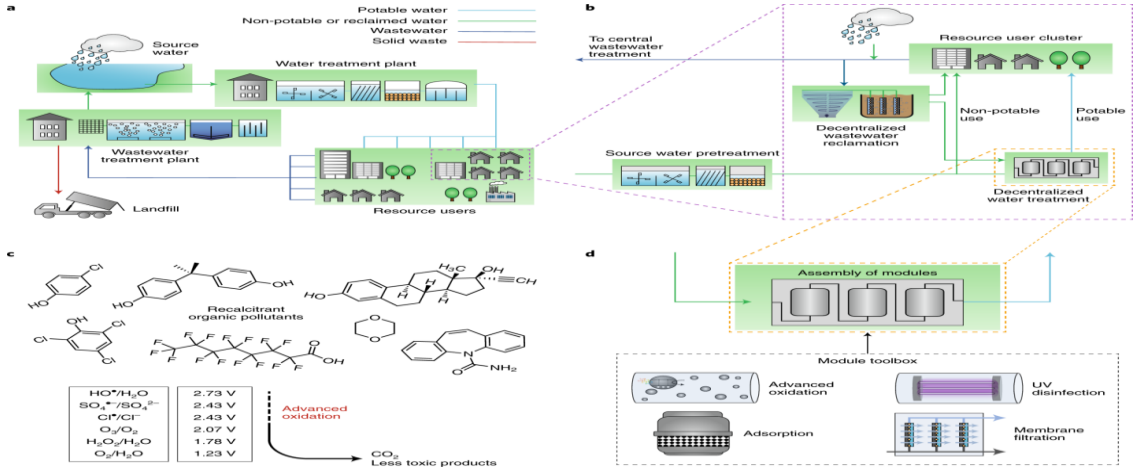


Figure 3: Advanced Oxidation in Decentralized Water Treatment (Hodges et al., 2018)

Table 1: Treatment Efficiency by Technology

Technology Type	Typical Removal Efficiency (%)	Primary ECs Removed
Conventional (e.g., Activated Sludge, Sand Filtration)	10–40	Low removal for most ECs; ineffective for PFAS, MPs
Advanced Oxidation Processes (AOPs)	60–95	Pharmaceuticals, EDCs, some pesticides
Membrane Filtration (NF/RO)	70–99	PFAS, microplastics, wide EC spectrum
Adsorption (AC, Biochar, MOFs)	50–90	EDCs, pharmaceuticals, hydrophobic compounds
Hybrid Systems (AOP + Membrane, etc.)	80–99	All major EC classes depending on configuration

6.2 Operational Considerations and Scalability

The viability of a treatment technology implementation is determined by the complexity of operation, infrastructure requirements, and economic feasibility. Table 2 is an outline of these factors.

In spite of the fact that conventional systems do not suit ECs because of their inefficiency, they are still popular since they are not expensive and are available in the infrastructure. The generate large amounts of sludge and are not highly selective to remove ECs making them ineffective when it comes to removing trace pollutants without further polishing process.

Though effective, AOPs demand strict control of variables of dosage of oxidant, contact time, and pH (Parsa et al., 2024). They may be power-consuming and they produce harmful by-products in the case they are not handled appropriately. In this way, they would be better adapted as third-line interventions in well-equipped facilities.

The membranes systems offer high levels of contaminant rejection, but are constrained by membrane contamination, high-pressure systems, and generation of concentrated brine which has secondary disposal issues. They are mainly used in high income settings or in special purposes, such as potable reuse.

The adsorption technologies can be scaled and varied in the environments, especially as the use of low-cost, bio-based adsorbents such as biochar grows in popularity (Al-Gethami et al., 2024). But their effectiveness is short-lived and within a frequent regeneration or replacement will affect the long-term sustainability of operation.

Hybrid systems are the most promising in their performance, but have the highest barriers concerning their expenses (capital investment), operation and maintenance (O&M) difficulties, and compatibility with already available infrastructure. They have continued to be used at pilot or demonstration levels.

Table 2: Operational Constraints and Scalability

Technology	Key Limitations	Scalability
Conventional Treatment	High sludge yield, low EC removal	High (already widespread)
AOPs	High energy use, toxic by-products, chemical dosing	Moderate (used as tertiary)
Membrane Filtration	Fouling, high cost, brine disposal	Moderate (in high-income settings)
Adsorption	Saturation, regeneration or replacement needed	High (low-cost options available)
Hybrid Systems	Complex integration, high capital and O&M cost	Low to moderate (pilot/demo stage)

6.3 Risk Mitigation and Toxicological Relevance

The main goal of the EC removal, with respect to public health and the environment, is to decrease the exposure to toxic, bioaccumulative, and persistent contaminants (Werkneh et al., 2022). As such, one cannot only measure the effectiveness of treatment by its removal. Table 3 provides a relative evaluation of the technologies in terms of their ability to reduce risks and the probability of the formation of harmful by-products.

Hybrid systems and membrane filtration show the greatest risk mitigation, because they are capable of eliminating contaminants with low-risk acceptable daily intake levels, e.g. hormones, PFAS and some antibiotics. These systems are considered as efficient physical or combined chemical-physical blockade against bioactive contaminants.

AOPs, especially optimized and preceded by polishing processes can reduce toxicity in a major way by degrading parent compounds. But when mismanaged, they can have transformation by-products that are worse than the contaminants themselves.

Traditional systems have a disadvantageous kind of toxicological view where many ECs found in the effluent streams have minimal effects on human or ecological exposure mitigation (Singh et al., 2024).

Table 3: Risk Mitigation and Toxicological Relevance

Technology	Risk Reduction (Human & Ecological)	Concerns on By-products
Conventional Treatment	Low: Limited EC removal and exposure reduction	Minimal (but ineffective primary removal)
AOPs	Moderate–High: Effective for toxic pharmaceuticals & EDCs	Moderate–High (e.g., aldehydes, bromate)
Membrane Filtration	High: Effective barrier to bioaccumulative ECs	Low (concentrate/brine must be managed)
Adsorption	Moderate: Depends on media and compound affinity	Low (media disposal or regeneration needed)
Hybrid Systems	High: Multi-pathway removal improves overall protection	Variable (depends on component integration)

6.4 Patterns and Critical Shortcomings

These were several recurring patterns and constraints:

- The traditional treatments do not have the ability to deal with contemporary chemical pollution.
- The high potential of AOPs and membranes needs to be improved in relation to real-time monitoring and by-product control.
- Financially and technically, hybrid technologies are not available to many utilities: they provide the most comprehensive elimination.
- Formation of by-products is one of the issues that is not well considered in research and practice, especially in AOP-based systems.
- The performance metric of treatment has a significant misalignment with the risk threshold based on health or ecosystem.
- Other sustainability indicators, including: life-cycle energy consumption, greenhouse gases and costs benefits, have not been adequately reported in most studies.

These lessons indicate that a shift away on single technology-based appraisals to integrated and risk-based approaches to treatment that are both backed by regulatory innovation and cross-sector investment is needed.

7. Discussion

7.1 Engineering Limitations and Technological Feasibility

The findings demonstrate that there are huge discrepancies between the existing water treatment capacities and the emerging contaminants (ECs) requirements. Activated sludge systems and sand filtration systems traditionally used to treat water were not developed to manage pollutants at trace levels, at the persistent stage, and at such a chemically varied level as PFAS, endocrine-disrupting chemicals (EDCs), and pharmaceuticals. The very low removal efficiency of 40 or less that they have highlights their incompetence to handle the current water safety issues. State-of-the-art technologies are advanced oxidation processes (AOPs), membrane filtration and adsorption systems, which are shown to be better but are limited by the barrier to operation and cost.

7.2 Health and Ecological Risk Mitigation

The actual efficacy of any given treatment technology should not be measured on the basis of efficacy in contaminant removal alone but rather on measures of reducing the exposure to high-risk ECs. Membrane systems and hybrid treatments offer very high degrees of risk reduction particularly that of persistent, bioaccumulative, and toxic substances. AOPs are also able to break toxic pollutants down, however their transformation products can be a new danger unless monitored.

7.3 Regulatory Alignment and Practical Barriers

Regulatory activity on ECs is still uneven across the world. Most ECs do not have enforceable standards even though in some countries watchlists or advisory thresholds have been adopted. This discourages the utilities to invest in high-tech treatment methods. In addition, the performance of treatment is not often related to any toxicological or exposure outcome in the current regulations. Technical complexity, inadequate funding as well as operational expertise of most water utilities are additional factors that hinder implementation.

7.4 Toward Integrated and Sustainable Solutions

It is important to transition to multi-barrier risk-aligned and cost-effective treatment strategies. Integrated systems a combination of AOPs, membranes, and adsorption are the way to go, especially when local needs are taken into consideration and lifecycle and sustainability assessments provided. To ensure global health and water security, future endeavors should be based on a congruence of engineering performance to the protection of public health, the sustainability of the environment as well as regulatory innovation.

8. Conclusion and Recommendations

Treatment of water faces an expanding challenge due to the growing number of emerging contaminants (ECs) such as pharmaceuticals, endocrine-disrupting chemicals (EDCs), PFAS, microplastics, and personal care products, in water treatment systems all over the world. This review illustrates that traditional treatment technologies that are being used are not effective in the treatment of the persistence, toxicity, and complex behavior of ECs in water bodies. When chosen and optimized properly, membrane filtration, advanced oxidation processes (AOPs), and adsorption methods can eliminate a large variety of ECs. Hybrid systems that combine different processes provide the most resilient performance though these include planning, investment, and operational capacity.

The evidence supports the fact that there is a strong urgency to align the choice of the treatment with the risk-based selection criteria not only based on the percentage of removal but also on the routes of the exposure, bioactivity of the contaminants and the vulnerability of the ecosystem. In a bid to align the existing practice with the emerging threats, it is recommended that the following are adopted:

1. Implement Multi-Barrier Strategies: Integrate complementary technologies (e.g. AOP + membrane + adsorption) to local EC profiles and reuse targets (Yu et al., 2018).
2. Introduce Risk Assessment in Design: Ranking of the treatment solutions should be based on health benchmarks, toxicity levels, and length of stay in the environment (Olker et al., 2022).
3. Enforce Monitoring and Control: Intensify the monitoring programs on EC nationally and put in place the enforceable targets of removal based on science-based risk indicators (Bruinen de Bruin et al., 2022).

4. Advance Research and Life-Cycle Assessments: Support Studies assess sustainability, energy consumption as well as long-term performance of treatment systems (Gangwar et al., 2025).

5. Further Capacity Building and Technology Transfer: Provide the knowledge and the tools to enable the water utilities to establish and operate the advanced EC treatment systems (Alaerts & Kaspersma, 2022).

The water sector can drive towards a more health protective and resilient future by instilling the aspect of risk-awareness and sustainability into the treatment planning.

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