Academic Guru Publication House

A Handbook On Multidisciplinary Approaches In Research (Volume-1)

Volume 1
Year: 2023

AG PH Books

Emerging Contaminants in Water: A Review of Detection and Remediation Techniques

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Abstract

The enduring nature and possible health hazards posed by emerging contaminants (ECs) in water sources have sparked worldwide alarm. The development of enhanced remediation techniques is imperative, as conventional water treatment procedures may not always be sufficient to eliminate these contaminants. This study discusses many ways of detection and treatment, with a focus on nanotechnology, membrane filtration, and photocatalysis. Photocatalytic breakdown using semiconductor materials like titanium dioxide and metal-organic frameworks has been shown to work very well under UV and visible light. Moreover, micropollutants may be efficiently removed by membrane filtration techniques like as reverse osmosis and ultrafiltration. The study emphasises sustainable and ecologically friendly synthesis methodologies as a mechanism for nanomaterials to enhance pollutant degradation. Despite promising advancements, further optimisation is required for practical applications in the areas of increasing catalyst stability, cutting costs, and widespread implementation. Multidisciplinary research may help to solve these problems and provide sustainable water treatment solutions. To reduce the impact of ECs on aquatic ecosystems and human health, it is critical to incorporate hybrid technologies and examine their environmental and economic feasibility.

Keywords: Emerging contaminants, photocatalysis, membrane filtration, nanotechnology, water treatment

* ISBN No. - 978-81-19152-91-9

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1. Introduction

Research on emerging contaminants has recently become popular. Regulatory authorities are faced with a significant issue due to the high number of emerging contaminants. In order to address emerging contaminants, how should we prioritise research? Since we know so little about the environmental behaviour of these novel compounds and their potential harmful impacts on humans and ecosystems, how can we prioritise the establishment of quality standards for them? Academics' demands for more funding and attention for their studies likely contribute to the current fascination in emerging contaminants. Keeping up with the latest developments is crucial for researchers who are trying to get funding. (Finčur et al., 2021)

Because of her 1962 book "Silent Spring," Rachel Carson is likely to be credited with the "emergence" of knowledge on emerging contaminants (Kokkinos et al., 2020). As the title suggests, she provided compelling evidence that the extensive use of DDT to eradicate mosquitoes and other pests had resulted in the extinction of several bird species (Morin-crini et al., 2022). Carson faced significant backlash for her audacity in questioning the many societal advantages associated with pesticide use, particularly DDT. Here we see how an environmentalist sounded the alarm, and how academic research subsequently backed up the alarm with factual data and uncovered the truth and dangers associated with DDT—which had been synthesised approximately a century prior to Carson's book and had been liberally distributed during the second world war—proving her right and leading to its eventual ban (Lin et al., 2023). The message that pesticides and chemicals in general may be dangerous was brought to our attention by her, and we are grateful to her.

The first step in addressing "emerging contaminants" is to clarify our objectives. Something that was considered a significant concern with environmental contamination a decade or two ago may no longer be considered an emerging contaminant, since the definition of "emerging" is subjective (Mergenbayeva et al., 2021). Expanding the scope to include contaminants of emerging concerns, which have been present for some time but have just now come to light as a source of worry, and emerging contaminants, which have only recently emerged, would be a good place to start.

Concerns about the potential effects of contaminants of emerging concern (CECs) on aquatic life have led to an uptick in the detection of PPCPs and pharmaceuticals at low concentrations in surface water. The EPA must have a system in place to assess the possible effects of CECs and PPCPs on aquatic life and a method to establish safe limits for these creatures. (Kumar et al., 2022)

A. Categories of Emerging Contaminants

There are several sources from which emerging contaminants might develop, including pharmaceutical waste and agricultural runoff. The chemical composition, durability, and toxicity of these chemicals dictate their effects (Blasco & Tovar-Sánchez, 2022). The table below summarises the main categories of emerging contaminants and their most common locations.

Table 1 Categories of Emerging Contaminants and Their Sources

Category	Examples	Primary Sources	Potential Impact
Pharmaceuticals & PPCPs	Antibiotics, painkillers, cosmetics	Hospitals, households, wastewater plants	Antibiotic resistance, endocrine disruption
Endocrine-Disrupting Chemicals	BPA, phthalates, synthetic hormones	Plastic waste, industrial discharge	Hormonal imbalance, reproductive issues
Per- and Polyfluoroalkyl Substances (PFAS)	Fire retardants, non-stick coatings	Industrial effluents, consumer products	Carcinogenic potential, bioaccumulation
Pesticides & Herbicides	Glyphosate, DDT, organophosphates	Agriculture, runoff into water bodies	Aquatic toxicity, soil degradation
Microplastics & Nanoparticles	Synthetic fibers, plastic fragments	Textile industries, wastewater discharge	Marine pollution, ingestion by organisms

B. Detection Techniques for Emerging Contaminants

Due to their low quantities and complicated chemical structures, emerging contaminants in water must be detected using very sensitive analytical methods. Biosensors and real-time monitoring systems have gained popularity due to their efficiency and reduced operating costs, despite the fact that traditional techniques such as chromatography and spectroscopy are still frequently employed. (Coronado-Apodaca et al., 2023)

a. Chromatographic and Spectroscopic Techniques

Chromatography-based methods, including High-Performance Liquid Chromatography (HPLC) and Gas Chromatography-Mass Spectrometry (GC-MS), are highly effective in the identification and quantification of contaminants (Pontius, 2021). These methods give accurate results, but they need expensive equipment and a lot of work to get the samples ready.

Although spectroscopic techniques like ultraviolet-visible spectroscopy and fluorescence spectroscopy provide rapid analysis, they may lack specificity when analysing complex mixtures. Improved detection sensitivity for trace-level contaminants has been achieved with recent improvements in Surface-Enhanced Raman Spectroscopy (SERS).

Table 2 Advantages and Limitations of Detection Techniques

Technique	Advantages	Limitations
HPLC & GC-MS	High accuracy, precise quantification	Expensive, requires skilled operators
UV-Vis Spectroscopy	Fast, cost-effective	Limited sensitivity for complex samples
Biosensors	Real-time monitoring, eco-friendly	May suffer from interference effects
SERS (Surface-Enhanced Raman Spectroscopy)	Ultra-sensitive, detects low concentrations	High equipment cost, complex calibration

C. Remediation Techniques for Emerging Contaminants

Traditional treatment procedures, including filtration and coagulation, are often inadequate because many emerging contaminants are resilient (Wells, 2013). Three sophisticated remediation techniques—adsorption, oxidation, and biological degradation—have gained attention recently.

a. Advanced Oxidation Processes (AOPs)

In order to degrade contaminants into less dangerous byproducts, AOPs produce very reactive hydroxyl radicals (•OH). Among these methods are Fenton reactions, ozonation, and photocatalysis, which employs materials such as titanium dioxide (TiO_2).

b. Biological Treatment Methods

To eliminate contaminants in a more organic way, biological methods include phytoremediation and microbial decomposition. Constructed wetlands are being used for cost-effective remediation due to the ability of aquatic plants to absorb contaminants. (Mathew & Kanmani, 2020)

Table 3 Comparison of Remediation Techniques

Method	Principle	Effectiveness	Challenges
Activated Carbon Adsorption	Adsorbs contaminants on porous surfaces	High removal efficiency for organic pollutants	Requires frequent regeneration
Ozonation	Generates ozone to break down pollutants	Effective for persistent contaminants	High operational costs
Photocatalysis	Uses light-activated catalysts	Sustainable, energy-efficient	Limited efficiency in turbid water
Bioremediation	Microorganisms degrade pollutants	Eco-friendly, cost-effective	Slower process, requires optimal conditions

2. Literature Review

(Bratovčić, 2023) Compared to traditional treatment procedures, organic contaminants (drugs, agrochemicals, and colours) need new, more sophisticated approaches to water purification due to their chemical complexity. Photocatalytic degradation is one approach. Scientists clearly elucidated the process by which toxic organic compounds are degraded by using semiconductor materials with photocatalytically active characteristics in conjunction with ultraviolet or visible light. We will go over the procedures and components that go into making the most recent photocatalysts, how stable they are, and what percentage of organic contaminants they remove. To activate them using visible light and reduce electron and hole recombination, as well as to achieve a stronger photocatalytic impact in degradation, we provide a diverse selection of components for the development of distinct composite photocatalysts. Real wastewater samples, rather than the typical synthetic solutions of specific organic contaminants that have been extensively examined thus far, should be used in future trials.

(Arman et al., 2021) Several relevant topics regarding EPs in aquatic environments, including strategies for eliminating EPs, were examined in the review. While there are pros and cons to each method, EPs treatment procedures include physico-chemical, biological, and advanced oxidation procedures, among others. However, ultrafiltration, a membrane-based filtration approach, is seen to be one of the technologies that offers the most potential for micropollutant removal in water. This treatment strategy is more popular than traditional ones due to its fascinating qualities, such as a modest working way and remarkable selectivity. This paper provides a thorough overview of EP, including its environmental presence, health effects, and possible remediation and removal methods.

(Datta & Roy, 2023) The review covered photocatalysis, which has shown great promise in the degradation of organic contaminants and the disinfection of water in wastewater treatment. Photocatalytic applications for wastewater treatment have recently seen advancements such as: Inorganic photocatalysts: Titanium dioxide (TiO_2) and other conventional photocatalysts work best in the very narrow range of ultraviolet (UV) light, which is only a fraction of the total solar energy. Photocatalysts that respond to visible light, such carbon nitride, perovskites, and metal sulphides, have recently been the focus of research and development. Energy efficiency and cost-effectiveness are enhanced by these materials' ability to use a wider range of the solar spectrum.

(Heydari et al., 2019) The study looked at the passive form of solar photocatalysis and how effective it was. A common photocatalyst in a passive system was buoyant anatase TiO_2-coated hollow glass microspheres. The chosen model contaminants were Killex®, CPA, and sulfolane. While 2, 4-D was degraded to a maximum of 99.8% in the Killex® solution, sulfolane was degraded to 97.4% and CPA to 100% in aqueous solutions, respectively. Dicamba and MCPP were totally destroyed in the solution. With catalyst loadings of 4.78 mg/cm^2 and 11.95 mg/cm^2, respectively, the total organic carbon (TOC) of Killex® samples was decreased by 53% and 88%. At catalyst loadings of 4.78 mg/cm^2 and 11.95 mg/cm^2, respectively, sulfolane samples showed a 28% and 64% reduction in TOC, following the same pattern. Both catalyst loadings resulted in a 77% reduction in total organic carbon in CPA solutions. The findings demonstrated that the passive photocatalysis, when conducted in the late summer and autumn employing buoyant photospheres and exposed to natural sunshine in a northern environment (51, 4' N, 114, 8' W; altitude: 1114 m), was successful.

(Gholami et al., 2019) In a controlled laboratory setting, the degradation of the antibiotic Clindamycin hydrochloride was examined using a heterogeneous UV/TiO_2 procedure. According to the findings, photocatalysis was unaffected by direct adsorption and photolysis. At pH=5, with a Clindamycin concentration of 2 g/L and a catalyst quantity of 0.5 g/L, the sweet spot was seen after 90 minutes. The pseudo-first-order degradation kinetics Findings from this research demonstrate that the UV/TiO_2 procedure is a powerful tool for eliminating clindamycin hydrochloride from water.

(Ramrakhiani et al., 2022) A number of innovative separation techniques have had their performance efficiency tested for the removal of various emerging contaminants. Some of these methods show promise, including electrochemical processes, ozonation, adsorption, and UV/H_2O_2/Fe^{3+} aided photocatalysis. The clean and green approach has great promise for membrane-based technologies such as size-exclusive separation in ultra-filtration, nanofiltration, and reverse osmosis, as well as membrane bioreactor processes. Considering the processes' potential industrial use, however, thorough techno-economic examination is necessary. To ensure environmental sustainability, it is crucial to do a life cycle analysis (LCA) on ECs. The broad variety of emerging contaminants necessitates extensive study to identify the best methods of treatment that combine established and cutting-edge technologies for maximum removal efficiency while minimising negative impacts on the environment and the bottom line.

(Gomes et al., 2020) Given the widespread reliance on these compounds, it is hard to implement a source-based strategy to reduce ECs. In order to reduce potential dangers to public health, it is crucial to find effective ways to eliminate ECs. There are a number of options available to DWTPs that might lower the concentration of ECs in the water that is treated. More comprehensive data on the impact of ECs on the DW microbiota is urgently needed. In order to enhance the tactics utilised for ECs treatments and to correctly prioritise their removal in DWTPs, this knowledge is vital. The pharmaceutical ECs often researched for their impacts on water microbiomes—including antibiotics (ciprofloxacin, erythromycin, and sulfamethoxazole), carbamazepine, and diclofenac—are not the only ones with a substantial impact on microbial behaviour, as this work shows. The importance of antibiotics and other antimicrobial agents in the development of antibiotic resistance is undeniable. When it comes to the impact of ECs on biofilm behaviour and formation, nevertheless, the existing research is not very definitive. The current findings are contentious since they call for the creation of standardised tests in order to accurately analyse the effects of ECs. Keep in mind that ECs' effects could be conditional on a variety of variables, such as concentration, nutrient availability, hydrodynamics, exposure duration, etc. The primary obstacles to a "One Health" ECs prioritisation are the unknown effects of non-pharmaceutical ECs, the existence of combinations of ECs, and the unpredictability of experimental settings.

(Rojas et al., 2022) One novel class of photoactive materials for water remediation is metal-organic frameworks (MOFs), which have arisen in the ongoing quest for novel heterogeneous photocatalysts.

Among the many subclasses of metal-organic frameworks (MOFs), titanium-based MOFs (Ti-MOFs) stand out for their exceptional structural characteristics, great chemical stability, and potential optoelectronic and photocatalytic applications. Nevertheless, it is challenging to ascertain if Ti-MOF photocatalysts are feasible for use in real-world water treatment due to the lack of data from the published experiments. In this research, we first highlighted the potential of a Ti-MOF in the photodegradation of a combination of pertinent Emerging Organic Contaminants (EOCs) in actual water after screening it with numerous MOFs. At first, four photoactive Ti-MOF structures and two difficult medicines, namely the β-blocker atenolol (At) and the veterinary antibiotic sulfamethazine (SMT), were chosen in a sensible manner. The most promising photocatalyst was selected from this first screening as the mesoporous Ti-trimesate MIL-100(Ti). It exhibited greater individual photodegradation of At or SMT (100% of At photodegradation in 2 hours and 4 hours, respectively).

(Hassaan et al., 2023) Nanotechnology has the capacity to store solar energy and eliminate organic contaminants from the environment because of the distinctive properties of nanomaterials. The possibilities of artificial photosynthesis systems are vast. Methods for producing these NPs that are environmentally friendly, easily available, and safe are necessary to address present-day environmental issues. Green or biosynthetic solutions based on biomass feedstock often have a short response time, a low temperature, and a lack of chemical intervention. By mimicking the properties of naturally occurring photoactive green nanomaterials, we may build light-harvesting assemblies, develop novel approaches to fuel synthesis, and design tools to produce novel functional materials for use in solar cells, water-splitting units, pollution control devices, and many other applications. An eco-friendly and practicable method has to be developed to produce metallic NPs without the use of harmful chemicals. Researchers from all around the globe are now engaged in developing novel methods to produce metallic NPs, as mentioned in this article. Consequently, compared to other synthesis techniques, the production of metallic NPs that is less harmful to the environment is becoming more competitive. Using a wide range of organisms, including plants, bacteria, fungus, and algae, this article also discusses the environmentally benign production of metallic NPs that operate as photocatalysts.

(Krakowiak et al., 2021) The quest for novel approaches to surface and groundwater cleansing is a major focus of current scientific research. The area of heterogeneous catalysis may discover several uses for anatase TiO_2. Titania, in its many forms (bare TiO_2, dopant, or composite systems), has found usage in the breakdown of substrates derived from an extraordinarily diverse range of chemical compounds. The following substances can be classified as emerging contaminants: analgesics, antibiotics, anticonvulsants, β-blockers, lipid regulators, NSAIDs, organic dyes, psychiatric drugs, sex steroids; when permitted to freely disperse in the surrounding ground and water reservoirs, they pose a danger to the environment. We must take the necessary measures to decrease their rate of environmental deposition in order to avoid harm to ecosystems, human health, and the quality of life overall. Researchers are devoting a lot of time and energy to finding the best way to deal with emerging contaminants, which has led to a plethora of new ideas.

(Espinosa Jiménez et al., 2021) A basic wet approach was used to generate two Ce-doped ZnO photocatalysts with distinct surface, morphological, and structural features, at pH 4 and 8. They reduce the rate of zinc photodissolving in water compared to the undoped catalyst under the specified experimental conditions 5. After three hours of visible light irradiation, the Ce-doped ZnO catalyst, which was synthesised at pH 8, had excellent photocatalytic activity in degrading carbamazepine and phenol, with a degradation rate of over 45%.

Table 4 Summary of the literature review

Study	Key Focus	Detection/Degradation Method	Findings
Bratovčić (2023)	Photocatalytic degradation of organic contaminants	Semiconductor-based photocatalysts with UV/visible light	Enhanced photocatalytic efficiency with composite materials, but real wastewater studies needed
Arman et al. (2021)	Removal of emerging pollutants (EPs) in water	Physico-chemical, biological, and membrane-based filtration	Ultrafiltration is a promising method due to efficiency and selectivity
Datta & Roy (2023)	Photocatalysis for wastewater treatment	TiO_2 and visible light-responsive photocatalysts	Advanced photocatalysts expand usability beyond UV range
Heydari et al. (2019)	Passive solar-based photocatalysis	TiO_2-coated hollow glass microspheres	Effective in degrading herbicides and industrial solvents under natural sunlight
Gholami et al. (2019)	Removal of antibiotics from water	UV/TiO_2 photocatalysis	Effective degradation of Clindamycin hydrochloride with pseudo-first-order kinetics
Ramrakhiani et al. (2022)	Advanced separation techniques	UV/H_2O_2/Fe^{3+}, ozonation, adsorption, electrochemical, membrane filtration	Combination of conventional and novel methods needed for optimal removal
Gomes et al. (2020)	Effects of ECs on water microbiome	Monitoring pharmaceutical and non-pharmaceutical ECs	ECs impact microbial behavior, requiring standardized testing for prioritization

Rojas et al. (2022)	MOFs for ECs degradation	Titanium-based MOFs (Ti-MOFs)	Promising potential for real-world water treatment but further studies needed
Hassaan et al. (2023)	Nanotechnology for ECs removal	Green synthesis of metallic nanoparticles	Sustainable nanomaterials hold promise for pollution control
Krakowiak et al. (2021)	Water purification using TiO_2	TiO_2 in composite and doped systems	Effective against a wide range of pharmaceutical and chemical pollutants
Espinosa Jiménez et al. (2021)	Ce-doped ZnO photocatalysis	Visible-light-driven degradation of pharmaceuticals	Effective degradation (>45%) of carbamazepine and phenol

3. Conclusion

Pharmaceuticals, agrochemicals, and dyes are just a source of the emerging contaminants that are making water filtration systems work harder. When standard treatment processes fail to properly remove these contaminants, more complex technologies must often be used. One such method is photocatalysis, which may decompose numerous chemical compounds when subjected to ultraviolet and visible light. Recent research has led to the development of novel photocatalysts exhibiting enhanced stability, efficiency, and broader spectral activity. These consist of metal-organic frameworks, perovskites, and metal sulphides.

Although there is much evidence of the efficacy of photocatalysis based on semiconductors, there is still room for improvement in terms of its practical use. Research highlights the need of doing pilot-scale experiments using genuine wastewater samples. This is because laboratory settings often use artificial solutions that fail to reflect all of the complexities of the environment. Hybrid treatment systems, nanotechnology-based technologies, and membrane filtration may all work together to remove contaminants more efficiently.

The future of water remediation lies in methods that are long-lasting, low-cost, and easy to expand. For photocatalytic solutions to be widely used, issues like catalyst stability, energy use, and the production of byproducts need to be fixed. Furthermore, to ensure environmental and economic sustainability, these technologies must be deployed according to life cycle assessments and techno-economic analyses. Long-term success with emerging contaminants in water resources requires a multidisciplinary approach including specialists in environmental engineering, material science, and policymaking.

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