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Chapter 13: Meta-Analysis of Global Water Contaminants and Chemical Treatment Techniques

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Abstract: Ensuring global access to safe water remains a critical challenge due to the persistent occurrence of organic, inorganic, biological, and emerging contaminants. This meta-analysis systematically reviews major classes of pollutants—including pesticides, pharmaceuticals, heavy metals, pathogens, and microplastics—while evaluating the effectiveness of chemical treatment techniques designed for their removal. Treatment by conventional processes, including coagulation–flocculation, oxidation, adsorption, ion exchange, is described in function to operation principle, efficiency, and limitation. By comparison, considering the complementary advantages of different water treatment methods on dealing with different types of contaminants at different basic strengths, it also highlighted the major limitations of the water treatment including generation of byproducts, regeneration of the adsorbents, and energy and/or operational costs. Special attention is given to emerging compounds that, in many cases, escape from elimination in conventional systems—emphasizing the relevance of AOPs, engineered adsorbents, and electrochemical methods. New trends and developments, including solar-driven AOPs, biochar/bio-based AOPs and novel electrode materials, have made impressive progress in addressing emerging contaminants and trace pollutants. In the future, these new strategies will be combined with state-of-the-art chemical methodologies and the development of environmentally benign, and user-friendly, modular systems. Addressing these challenges requires intensive interdisciplinary work between scientists, engineers, and policy makers to develop environmentally and economically sustainable water treatment technologies that can adapt to evolving contamination challenges.

Keywords: Water Treatment, Chemical Processes, Emerging Contaminants, Coagulation–Flocculation, Advanced Oxidation Processes (AOPs), Adsorption, Ion Exchange, Electrochemical Methods, Water Quality Management.

1 Introduction

Safeguarding global water sources is a continued challenge due to high levels of contamination. Chemical treatments are required to remove the pollutants, and to provide safe water. Here we provide a critical overview of the most common pollutants, existing chemical treatment techniques and discuss their advantages and drawbacks. The aim is to present an integrated overview of fundamental chemistry to support development of new water treatment technologies.

Overview of Global Water Contaminants

All over the globe, water is threatened by an ever expanding number of pollutants, categorized as organic, inorganic, biological and emerging pollutants. Obiguous organic pollutants, including pesticides, pharmaceuticals, and chemicals, remained in water and exerted potential disruption on the ecosystem (Richardson & Kimura, 2019). Inorganic pollutants such as lead, arsenic and mercury, found naturally as well as through human activity, are also a threat to the health of humans as well as wildlife. Outbreaks of infectious diseases such as waterborne diseases are caused by biological pathogens bacteria, viruses, protozoa and algae in the water body. The meanwhile newly identified chemicals of emerging concern (e.g., EDCs and microplastics) impede advances and further complicate water treatment, regulation and long-term management (Wang et al., 2024).

The congestion of industrial waste, garbage and agrowaste adds to the pollution. Moreover, an inlet of heavy metals and persistent organic are also a major source into the water bodies from industries. Fertilizers, pesticides and other with an increasing concern, toxic agents e.g., animal waste or, what is becoming more and more worrisome, pollutants like antibiotic residues and drug-resistant microorganisms (Grobelak & Kowalska, 2022) in the case of agriculturally derived ones. In urban areas, the release of pharmaceuticals, biocides, and microplastics from not only inadequate sewage treatment but also stormwater overflows adds to the challenge of managing water quality. These multiple sources of contamination emphasize the need for integrated surveillance and focused chemical treatment for global water safety (Radwan et al., 2023).

The wide spread of these pollutants becomes a growing issue for human health and risk of environment in many areas. Some of such organics and heavy metals for example, act over time in an organism that they accumulate in humans, and with time, cause neurological damages, cancer, hormone disruption (Wang, 2024). The effect on ecosystems is also substantial: not only do pollutants interfere with food webs, but also a loss of biodiversity and disturbances of dominant ecological processes occur. In addition, the occurrence of emerging contaminants (e.g. pharmaceuticals, microplastics) generates a higher degree of concern due to their recalcitrance, thereby potential bioaccumulation and unknown impacts resulting from their combined pressure with other pollutants. All these challenges highlight the pressing need for advanced water treatment technologies for addressing the present and emerging risks associated with public health and environmental sustainability (Chaplin,2019).

Chemical Treatment Techniques

Growing concern for pollutant loads has brought chemical treatment processes to centre stage in the protection of water quality for human and ecological health. This is by virtue of the addition of chemical reagents or processes that transform toxic pollutants into nontoxic ones, or in turn remove toxic substances from water matrices (Crini & Lichtfouse, 2019). Conventional methods are coagulation, oxidation, adsorption and ion exchange, application of which depend on the type of contaminant and are based on different chemical principles. These systems are of interest due to the fact that they have shown to work effectively in cleaning up complex contaminated sites that are otherwise hard to remediate using a physical and biological processes (Sheng et al., 2023). Consequently, chemicals can supplement other techniques in an integrated approach to water quality control and are even indispensable to treat traditional and new/worse quality problems.

Coagulation and Flocculation

Coagulation-coagulation-industrie The clarification of surface water and wastewater by coagulation and flocculation is one of the oldest natural technological processes, used accordingly for several thousand years and involving many types of inorganic and organic reagents. This treatment is in fact a coagulation process, whereby coagulants, e.g., aluminum based, and polyhydroxy aluminum chloride are added to destabilize colloidal particles to form large flocs (Sheng et al. Render 2023). Flocculants (for example, polyacrylamide derivatives) will also be required subsequently to promote the formation of higher and more extensive agglomerates of the particles (Mustereț et al., 2021). The two-staged approach achieves effective turbidity and natural organic matter (NOM, as well as other contaminants) removal, and declines of dissolved organic carbon (DOC) and chemical oxygen demand (COD) were observed in experiments in various operational conditions. To obtain optimum performance, it is necessary to control the amount of coagulant used as well as the mixing conditions in order that water treated is subjected to an optimal degree of treatment to result in substantially total removal of residual impurities in product water.

The effectiveness of the coagulation-flocculation was also proven to be ability to remove almost completely the turbidity as well as the reduction in DOC and COD concentration at several process conditions. Another advantage is that it can be incorporated for application across a range of climates, and successful applications of it have been located in the literature for both cold and warm water systems (Fuck et al., 2021). But the method has its disadvantages as well. These involve insufficient removal of dissolved organic carbon (DOC), increased high molecular mass organic fractions, as indicated by absorbance ratio shifts, and possibly with the remaining coagulant reagents up to the plant. Therefore, though essential for initial water clarifications, coagulation and flocculation efficiency is strongly dependent on carefully controlled process conditions and subsequent treatment combination.

Oxidation Processes

Oxidation is an important chemical process in water treatment, and a lot of oxidation technologies such as chlorination, ozonation and advanced oxidation processes (AOPs) have been developed. These processes generate strong oxidant species which can be used for the degradation of organic pollutants, conversion of toxic compounds into less toxic products or the total mineralization of pollutants. Different emerging photocatalytic AOPs like Fenton-like, ozonation and sulfate radical based systems allow higher removal efficiency of contaminants as they allow faster reaction rates and thus reduce the costs. These advances are mainly due to the fabrication of dedicated photocatalytic materials and enhanced activation method(Edit: Liu et al., 2020). Of the multiple new processes trialled, the UV/chlorine process is one in which chlorine species and hydroxyl radicals are used to promote selective degradation, with good performance observed in low dissolved organic matter and ammonia bearing waters (Guo et al., 2022). These developments illustrate the on-going requirement for the optimisation of oxidation processes for either maximising the relative efficient removal of pollutants and the minimisation of disinfection by-product formation and demonstrates the evolving role and requirement for application of these oxidation processes within the context of modern water treatment.

Oxidation processes are known for their quick decomposition of contaminants and ability to be applied over a wide range of classes of compounds (Garrido-Cardenas et al., 2020). AOP especially photocatalysis-based AOP, has been reported effective for the removal of recalcitrant industrial effluents, drugs, and biocontaminants. Due to their operational versatility, they can be used in municipal, industrial, and potable water treatment. New catalyst designs, such as defect-engineered materials and heterostructures, are reported that lead to enhanced degradation efficiency and broadening the scope of treatment of refractory compounds in recent publications (Liu et al., 2020). However, limitations remain. The byproducts of oxidation are of unknown toxicity, whereas its efficiency is largely dependent on the composition and presence in the water matrix of natural organic matter and scavengers. Hence, the optimization of parameters and the monitoring for potential secondary pollutants are essential for the safety and sustainability discharge of such treatment in the practice (Garrido-Cardenas et al., 2020).

Adsorption Techniques

Unlike oxidation, adsorption relies on solid phase (media) to selectively remove solute(s) from water by bringing them in contact with its surface. Activated carbon is especially attractive as an adsorbent because of high specific surface area, controllable porous structure, and flexible adsorption mechanisms, thus it is commonly used for municipal and industrial treatment units (Rashid et al., 2021). Both powder and granular activated carbon have shown high removal performance for various pollutants, such as traditional organic matter and trace pharmaceuticals. Removal efficiencies of more than 85% have been reported for compounds like carbamazepine and sildenafil citrate under SWat conditions (Delgado et al., 2019). Recent studies have also highlighted sustainable biomass-based activated carbon, where the controlled fabrication and activation methods are seen to enhance the removal properties for heavy metals with a reduced environmental footprint (Wang et al., 2023).

Adsorption is under wide consideration as a simple and environmentally friendly treatment technique. For the last few years, at active carbon is still a preferred material due to its simplicity, versatile operation, and low-cost (Rashid et al. 2021). The efficiency of adsorption systems is primarily affected by production processes, mainly including a chemical/ physical activation agent, which determines the surface area, pore structure, and regenerability (Heidarinejad et al., 2020). Although the capital costs are much lower than advanced oxidation or ion exchange, operational costs can escalate substantially with the frequent need to regenerate or replace the adsorbents every few years. Furthermore, adsorption efficiency may decrease in water with a high competition of solute and the capacity may be reduced after several cycles of regeneration.

Ion Exchange Processes

Ion exchange is another important purely chemically-based method to remove ionic contaminants, including heavy metal, hardness minerals and inorganic salts. It works via a reversible, positive exchange ion from it and the external liquid phases by ion exchange, if an ion exchange site of the resin material has not reached its exhaustion with ions, a stationary state of the counter agent with Fmediation is achieved (Crini & Lichtfouse, 2019). Synthetic ion-exchange resins are subjected to be able to remove specific live function material contention to a particular pollutant, making this technique extremely useful in a treatment for a contamination that is ineffective for a different technology to bombard, in examples such as low-grade nitrates or toxic metals in municipal and industrial discharge. Accordingly, the flexibility and selectivity of ion exchange makes it a critical part of modern water treatment.

Tunability is likely one of the most attractive characteristics of ion-exchange, as the resins can be designed to remove the undesirable ions from even quite complex water sources. This characteristics to of the method is suitable to the treatment of concentrated or dilute contaminants pollutant is persistent for example heavy metal and nitrate (Crini & Lichtfouse, 2019). However, even the systems using ion exchange have their own difficulties. Competing ions or organic foulants can degrade the performance of the resin, lowering effectiveness. Resin must be regenerated compulsorily for smooth operation, and the resin-regenerated brines are saline brines which should be managed carefully to prevent secondary ecological damage. Hence, economic viability and environmental sustainability are of prime importance for their sustained long-term application. Efficient combination of ion exchange with other treatment scenarios requires this technology to be optimised, and also to be compatible with its disposal in soils and wastewater (Crini & Lichtfouse, 2019).

Comparative Analysis of Treatment Techniques

Evaluation of Chemical Water Treatment Techniques

They are widely applied in primary water clarification and show high efficiency when optimized for dosage and mixing parameters. However, they often fail to achieve complete elimination of dissolved organic matter, and residual coagulants can present downstream challenges (Crini & Lichtfouse, 2019).

Oxidation processes, including advanced oxidation techniques, are highly versatile due to their capacity to degrade a broad spectrum of organic pollutants, including refractory compounds. Their utility in removing pharmaceuticals and endocrine-disrupting chemicals, often overlooked by conventional treatment plants, is particularly significant (Morin-Crini et al., 2022). Still, the risk of toxic byproduct formation and the energy intensity of some advanced systems highlight the need for careful optimization and monitoring. Adsorption, particularly using activated carbon, offers simplicity, adaptability, and strong performance for trace organic removal and emerging contaminants. It is cost-effective at installation and can be scaled across municipal and industrial contexts. Yet, performance is hampered by adsorbent exhaustion, competition among solutes, and regeneration requirements, which can elevate operational costs (Anfar et al., 2019).

Ion exchange provides precision by selectively targeting ionic contaminants such as heavy metals, nitrates, and hardness ions. The engineered selectivity of resins makes the method especially suitable for challenging cases with low contaminant concentrations. However, frequent regeneration cycles and the disposal of brine remain persistent obstacles to sustainability and cost-effectiveness (Crini & Lichtfouse, 2019). In practical applications, especially in municipal wastewater treatment plants, the integration of advanced oxidation with complementary processes such as adsorption has yielded superior outcomes. Studies consistently report enhanced degradation of complex organic pollutants and reductions in residual loads when hybrid strategies are employed (Morin-Crini et al., 2022). These findings emphasize the importance of combined and context-specific treatment trains, rather than reliance on any single chemical method. Overall, while chemical treatment strategies have advanced considerably, their continued refinement will depend on adapting to the chemical diversity of emerging contaminants, balancing operational costs, and minimizing unintended environmental impacts. The most effective future frameworks will likely involve integrated, multi-process solutions tailored to site-specific water quality challenges.

Emerging Contaminants and Treatment Challenges

At the same time, the rise of emerging contaminants—such as pharmaceuticals, personal care products, and microplastics—has introduced significant new challenges for global water treatment systems. These pollutants often enter aquatic environments due to incomplete removal in traditional wastewater treatments, improper waste disposal, or diffuse runoff from agriculture and urban settings, leading to their persistent presence even at trace levels (Morin-Crini et al., 2022).

Simultaneously, various types of novel adsorbents and photocatalysts have been pursued to be economically and practically attractive to large-scale application. Furthermore, the scientific and regulatory response to emerging pollutants such as antibiotic residues, biocides, and resistant microorganisms has been growing due to the escalating risks arising from their discharge into the environment from TWW or for agricultural purposes

(Grobelak & Kowalska, 2022). Such changes highlight the pressing need for continued research, monitoring, and policy innovation to successfully address this changing face of water pollution.

Conclusion

the impact of chemical treatments The outcome of this meta-analysis also reflects the significant role of chemical treatment processes in protecting water quality against the variety of pollutants including organic, inorganic, biological, and emerging substances. It features comparative analyses of the most relevant treatment processes, such as coagulation-flocculation, oxidation processes, adsorption, and ion exchange regarding performance, cost, space, and energy requirement, and presents studies and recommendations for those processes, considering the constraints on their use throughout the world. As traditional processes are put to the test by new, persistent (and trace) pollutants, the realization of chemical treatment processes - and those that will be capable of integrating new materials, intelligent process operation, and multifunctional treatment process - is essential in any new water treatment technology that may emerge. But the true successes will be defined not only by scientific and technical innovation but by the spirit of coöperation that must endure among researchers, engineers, managers and industry players alike. Ultimately, further and sustained interdisciplinary effort is required to translate new technologies into practical, cost-effective and deployable means of water treatment. These are vital steps on the path to the provision of fair, safe and sustainable access to water in the context of mounting environmental and public health pressures.

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