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Review Article

Overview of Treatment Techniques for Parabens and Phenolic Compounds in Water

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ABSTRACT

The frequent occurrence of parabens and phenolic compounds in drinking water sources has become a trending environmental and public health concern due to their complex physical and chemical characteristics, persistent nature, ability to interfere with the normal functioning of vital body hormones, and their tendency to bypass conventional water treatment techniques. Over the last decade, research focus has shifted to the development of efficient and eco-friendly abatement technologies that can address this severe environmental and public health concern. This study provides an overview of the progress made in treating parabens and phenolics in drinking water sources by evaluating physical, chemical, biological, and integrated treatment methods, along with their drawbacks. Adsorption, membrane filtration, and advanced oxidation processes are some of the remediation strategies that have successfully removed these trace and persistent compounds. However, some factors like matrix interferences, stability of the materials, reusability, cost, and energy intensity, as well as the generation of secondary metabolites, continue to frustrate field applications. While nature-based treatment strategies such as biofiltration, bioremediation, and phytoremediation have shown sustainable remediation, their efficiency requires intense optimization to improve kinetics and increase the activities of microorganisms. This review recommends that future studies should be centered on the development of sustainable treatment technologies that will improve the mechanistic understanding of degradation pathways and products. Also, an integrated approach that will support eco-friendly water treatment methods for emerging and endocrine-disrupting compounds should be prioritized.

Keywords: Emerging contaminants; parabens; phenolics; treatment techniques; endocrine-disrupting compounds; drinking water.

1.0 INTRODUCTION

The surge in global population and urbanization has intensified agricultural and industrial activities (Nnamani, Bayode, Otitoju, Alfred, & Omorogie, 2025). This outcome has contributed significantly to chemical pollution in diverse drinking water supplies, including surface and groundwater (Giri, 2021). Wastewater discharge, industrial effluent, leachate, and surface runoff comprise both organic and inorganic complex chemicals that affect the potability of our drinking water sources and lead to worsening water-borne diseases (Archer et al., 2023; Nnamani et al., 2025). Different classes of compounds have been detected in groundwater sources due to leachate infiltration from open dumpsites and improper waste disposal practices (Chidichimo, De Biase, & Straface, 2020). Parabens and phenolics (bisphenol A, hydroquinone, benzoquinone, and resorcinol) are among the frequently

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occurring groups of compounds in drinking water sources like surface or groundwater (Mohanta & Mishra, 2021; Ramutshatsha-Makhwedzha & Munonde, 2024; Santa-Cruz-Mérida et al., 2025).

The United States Environmental Protection Agency (USEPA) has categorized parabens, bisphenol A, and resorcinol as endocrine-disrupting compounds (EDCs), while hydroquinone and benzoquinone have been noted as suspected endocrine disruptors (Azeredo et al., 2023; Johnson et al., 2022; Kawa et al., 2021; Sciarrillo et al., 2024). Generally, EDCs have the tendency to distort the endocrine system and affect vital hormones in both human and aquatic organisms. They are also known to biodegrade slowly, leach into shallow aquifers, and affect the quality of our drinking water supply, such as groundwater, because the primary water treatment strategies cannot completely remove them. It is worth noting that the trace concentration of EDCs and their ability to bioaccumulate in human tissues can trigger health-threatening reproductive and neurological disorders, confirming the need for urgent attention by all relevant stakeholders (Amir et al., 2021; Rispo et al., 2024). Studies in recent times continue to showcase how parabens can lead to genotoxicity, oxidative stress, and immunotoxicity (Isaac et al., 2025). Also, the generation of potentially more toxic daughter compounds exacerbates the eco-human impacts of these compounds. For instance, during water purification involving chlorination, parabens sometimes undergo complex reactions that may lead to the production of paraben-chlorinated derivatives (Lincho, Gomes, & Martins, 2021).

The wide industrial applications, domestic use, and inappropriate disposal of their products, such as plastic materials and pharmaceuticals, demand the urgency to develop an environmentally-friendly removal approach that can degrade these compounds to beneficial compounds to the ecosystem. As earlier stated, fundamental treatment techniques such as chlorination, filtration and, sedimentation lack the capacity to treat these contaminants (Latosińska & Grdulska, 2025; Mutegoa, 2024). Therefore, recent studies are shifting research focus to the design of modified advanced methods like adsorption, membrane filtration, and advanced oxidation processes like photocatalysis, electrocoagulation, and sono/electro-photocatalysis (Kanakaraju, Glass, & Goh, 2025; Olvera-Vargas et al., 2025; Wenchao, Allan Sriratana, Amarakoon, Kang, & Xia, 2025). In a study by Lee et al., they investigated the reaction kinetics and degradation of chlorinated methylparaben using ozonation and UV/H_2O_2 in drinking water and wastewater effluent. The studies reported that parabens were degraded via ozonolysis, with over 97% removal, and ozone dosage exceeded 0.26 g of ozone applied per gram of dissolved organic carbon (DOC). The study validated the efficiency of the UV/H_2O_2 system to successfully degrade methylparaben and its chlorinated derivatives in both secondary and tertiary water treatment plants (Lee et al., 2022). In another study, hydroquinone was removed successfully in industrial wastewater discharge by electrocoagulation with a flow cell setup (Prabhakaran, Basha, Kannadasan, &

Aravinthan, 2010). The use of chitosan-based hydrogels shows increase adsorption capacity of bisphenol A (BPA), highlighting its strong stability. The study also reported that after five consecutive cycles, the material still maintained approximately 94% of its adsorption–desorption efficiency (Aricov & Leontieș, 2025). The use of electrochemical polymerization loaded on carbon aerogel electrodes have also been deployed in the treatment of BPA. This is because of the increased active sites that enhance adsorption capacity (Aricov & Leontieș, 2025; Hou, Huang, Chou, & Den, 2015).

Although the molecular structures and application of these targeted endocrine-disrupting emerging contaminants may be different, they relatively have similar environmental characteristics and fate. Therefore, it is important to direct research focus into the development of efficient treatment technologies that can remediate these contaminants in complex matrices. This review study aims to give an exposition of the recent trends in the treatment of parabens and phenolic compounds in drinking water sources. This is achieved by identifying recent advances in sustainable and emerging remediation methods, as well as their limitations and research gaps. This will help develop methodologies toward eco-friendly removal of these contaminants from our drinking water supplies, especially in the sub-Saharan region, where approximately 65% of her population depends on groundwater as their predominant drinking water source (Ibrahim et al., 2024).

2.0 Treatment Techniques for Parabens and Phenolics

Despite the progress made in developing treatment technologies for parabens and phenolic contaminants in drinking water sources, several challenges, such as the degree of selectivity, matrix interference, formation of secondary harmful byproducts, material engineering, energy, and cost intensity, have significantly affected their use in real water systems. Therefore, it is imperative to appraise the successes recorded in recent times to form the basis for designing more effective remediation techniques. The following sections discuss selected treatment approaches as applicable to parabens and phenolic compounds.

2.1 Physical Methods: Adsorption and membrane techniques are examples of physical treatment strategies that have been used rigorously in the treatment of parabens and phenolic compounds in drinking water supplies. Adsorption makes use of activated carbon (AC) from agricultural waste such as rice husk, plantain peel, pawpaw seed, and tea bags. This technique is widely used because of the sorbent's high affinity for hydrophobic and aromatic pollutants due to the π–π interactions and van der Waals forces that exist between the aromatic rings of adsorbates and active carbon surfaces (Akhtar, Ali, & Zaman, 2024). Research findings reveal that both powdered and granular AC achieve about 65-99% removal of BPA, hydroquinone, and parabens under controlled parameters such as optimized pH and contact time (Ahmadi, Azhdarpoor, & Hoseini, 2025; Liao, Sun, & Gao, 2008; Miguel et al., 2020; Nicomel, Li, Mohamed, & Ramim, 2022; Ruqin et al., 2023; Wei et al., 2022). Besides the use of agricultural waste materials as sorbents, there has been a significant shift toward the use of biochar and magnetic nanocomposites (Akhtar et al., 2024; Eniola, Sizirici, Fseha, Shaheen, & Aboulella, 2023). According to recent studies, doped modified biochars with metal oxides or functional groups have shown significant adsorption capacities of about 150 mg/g for BPA and parabens at a very rapid rate over repeated cycles (Feng, Zhai, & Sun, 2022; Gonzalez-Hernandez et al., 2021). The adsorption mechanism is driven by the interaction between the adsorbent and the contaminant, which can occur either through physisorption or chemisorption (Agboola & Benson, 2021). Physisorption is controlled by weak van der Waals forces that make it reversible and most appropriate for materials like AC, nanocellulose, and selected biochars (Verma et al., 2023). This mechanism makes it very easy for regeneration, but may lead to a low degree of selectivity. Chemisorption, on the other hand, involves covalent or ionic bonding, which provides a very high specificity, and in most cases, they are irreversibly bound to the sorbent materials. Metal-organic frameworks (MOFs), zeolites, and modified clays typically operate principally through a chemisorption mechanism because of their ability to form stable complexes with the contaminants. This technique is very suitable because of the high degree of selectivity for complex phenolics. A significant drawback of this technique is matrix interference of ions and natural organic matter (NOM), especially in complex water systems. This affect the efficiency of adsorbents, affecting material stability, and may degenerate to toxic secondary by-products, distorting the environmental sustainability of this technique (Satyam & Patra, 2024).

Membrane-based technologies like nanofiltration (NF) and reverse osmosis (RO) have been used in the removal of trace organic pollutants, achieving 90-95%, predominantly through molecular size and charge-exclusion pathways (Obotey Ezugbe & Rathilal, 2020; Ramutshatsha-Makhwedzha & Munonde, 2024). Typically, membranes are categorized into two groups based on their structure, namely: isotropic or anisotropic. Isotropic membranes have uniform physical structure across their setup (Obotey Ezugbe & Rathilal, 2020). They are microporous with relatively high permeation and are commonly used in microfiltration or ultrafiltration. This membrane setup allows the passage of tiny molecules that may constitute these emerging contaminants; this factor limits their application in complex water treatment. Conversely, anisotropic membranes are non-uniform with unique multiple-layered compositions, which feature a thin selective surface layer supported by a denser permeable substrate. The anisotropic membranes are commonly applied in a pressure-controlled system like RO. Despite the progress made with this technique for emerging contaminant removal, RO systems are faced with challenges, including high cost of energy, membrane odour, and high load of brine concentrate (Alshami, Taylor, Ismail, Buelke, & Schultz, 2021). To overcome some of these challenges, researchers are focusing on integrating membrane treatment with other advanced techniques. For instance, antifouling surface coatings have been designed alongside photocatalytic mechanisms to successfully remove these trace and recalcitrant contaminants as well as reduce odouring to the barest minimum. Notably, the combination of magnetic ion exchange (MIEX) pre-treatment with nanofiltration (NF) also showed improved removal efficiency for parabens. The combined usage of MIEX Dissolved Organic Carbon (DOC) and NF-90 or DESAL-HL recorded over 90% removal of propylparaben and butylparaben, 91% for methylparaben, and 97% for ethylparaben, with very minimal matrix interference. Unfortunately, the use of MIEX GOLD heightened membrane smell, accenting the need for careful choice of resin in hybrid membrane processes (Carmen, Irene, Pedro, Salvador, & Daniel, 2018).

2.2 Chemical Methods: Chemical treatment processes, particularly Advanced Oxidation Processes (AOPs), have been extensively studied for the degradation of parabens and phenolic compounds (Alshami et al., 2021; Vellingiri, Choudhary, Boukhvalov, & Philip, 2022). AOPs' mechanism depends on the production of highly reactive radicals, such as •OH and SO^{4-}, that can oxidize complex organics into simpler, less harmful compounds or complete mineralization of the contaminants to products such as carbon dioxide, methanol, and water. Frequently studied chemical methods are discussed below.

2.2.1 Ozonolysis: Ozone, as a strong oxidizing agent can break down complex and recalcitrant compounds within a short period. Ozone decomposes quickly, may not require harmful post-treatments, and is most appropriate for in situ treatment (Witt, Todd, Oladele, & Guzman, 2025). Studies conducted between 2015 and 2022 showed the efficacy of this method, as removal efficiency of 60-100 % of parabens and BPA was achieved. Parameters such as ozone concentration, acidity, alkalinity, and water system are crucial to the degradation efficiency of the system (Ahmadi et al., 2025; Han et al., 2022; Penrose & Cobb, 2022; Umar, Roddick, Fan, & Aziz, 2013). One of the drawbacks of this method is the formation of low-molecular-weight intermediates such as benzoquinone, resorcinol, and carboxylic acid. Consequently, a need for sequential biological treatment to ensure further breakdown into simpler and harmless compounds.

2.2.2 Photocatalysis: This technique is gaining substantial attention due to its capacity to degrade a wide range of organic micropollutants into less harmful or fully mineralized products through light-driven catalytic reactions (Karina, Karla, Juan, Felipe de, & José, 2025; Paiu, Lutic, Favier, & Gavrilescu, 2025; Rahman, Shaheen, & Ahmad, 2025). Unlike conventional oxidative treatments, photocatalysis offers the advantage of using light energy, like visible and ultraviolet (UV) light sources, to generate highly reactive species in situ without the need for excessive chemicals or the production of secondary waste in most cases (Eman et al., 2024). This makes it particularly promising for environmentally benign treatment of recalcitrant contaminants such as bisphenol A, hydroquinone, and parabens. UV irradiation has long been applied in drinking water treatment, with UV-B (280-315 nm) and UV-C (200-280 nm) demonstrating the highest germicidal and oxidative abilities. Unlike chemical disinfectants, UV, through the photocatalytic oxidation mechanism, is suitable for the treatment of EDCs in drinking water because of its inability to generate harmful disinfection by-products (DBPs). UV-based AOPs, including UV/H_2O_2, UV/persulfate, and UV/chlorine, have shown high efficiency for degrading parabens and phenolic compounds (Sun et al., 2023). In most cases, these systems typically achieve more than 90% degradation within minutes under controlled laboratory conditions (Koliai, Djaballah, Derbal, & Kabouche, 2024). In UV/H_2O_2 systems, photolysis of H_2O_2 generates ·OH, which rapidly attacks aromatic rings and enhances mineralization. However, energy demand and scavengers can suppress oxidation efficiency (BŁędzka, Gryglik, Olak, Gębicki, & Miller, 2010). To combat these deficiencies, semiconductor-based photocatalysis has gained considerable prominence. Semiconductor materials generate electron–hole pairs upon exposure to visible or ultraviolet light sources, leading to the production of reactive oxygen species (ROS) that are capable of oxidizing EDCs. Recent studies are centered on modifying these catalysts to improve natural solar light irradiation, charge recombination, and quantum efficiency. More so, metals like iron, silver, copper, and non-metals such as nitrogen and phosphorus doped photocatalytic materials have shown improved photocatalytic activity. Studies have also reported removal efficiency up to 95% for bisphenol A, hydroquinone, and butylparaben at pH 6-8 with irradiation times of about 60-120 min (BŁędzka, Gryglik, Olak, Gębicki, & Miller, 2010; Guin, Bhardwaj, & Varshney, 2017). Despite these significant advancements, some limitations, including catalyst recovery, leaching, and performance stability in continuous flow systems, impede scalability. Therefore, it is imperative to develop immobilized photocatalysts, magnetic composite catalysts, and integrated photocatalytic systems that will support scalability.

2.2.3 Fenton and Photo-Fenton Reactions: Photo-Fenton is more effective than the Fenton reaction because of the light irradiation from the UV source that speeds up the regeneration of iron catalysts and compresses reaction time (Carlos Dante, Dawany, Géssica Oliveira Santiago, Marcos, & Artur, 2022). Generally, the process involves the catalytic decomposition of H_2O_2 by Fe^{2+} ions, generating •OH. Approximately 70-98% degradation of BPA, methylparaben, and BPA at acidic conditions has been reported (Lucas & Peres, 2015; Martins et al., 2016). In addition, photo-fenton and heterogeneous fenton processes using immobilized iron oxides have improved treatment efficiency while reducing sludge generation (Deb, Rumky, & Sillanpää, 2023; Nath, Biswas, & Pal, 2022). Notwithstanding this progress, the effect of pH and iron sludge generation reduces the potential for largescale application in drinking water systems (Ziembowicz & Kida, 2022).

2.2.4 Sulfate-based oxidation: The use of persulfate (PS) or peroxymonosulfate (PMS) activation has recently emerged as an alternative AOP. This technique is gradually becoming an alternative to hydroxyl radicals because of its high oxidation potential and its ability to work over a wide pH range (Hassani, Scaria, Ghanbari, & Nidheesh, 2023). Different activation methods are used to activate this technique (heat, UV, transition metals, or carbon materials) to generate SO4- radicals with longer lifetimes and a greater degree of selectivity than hydroxyl radicals. It is worth noting that this method has shown efficient degradation of BPA and parabens even in slightly alkaline conditions (Chen, Maqbool, Hou, Fu, & Zhang, 2022; Metheniti et al., 2018).

2.3 Biological Methods: This approach relies on microbial or enzymatic breakdown of pollutants into less harmful compounds (Bose & Shreenidhi, 2022). Activated sludge and bio-filtration are some of the commonly used biological methods for the treatment of parabens and phenolics. These techniques have shown partial breakdown of paraben within 50-90% and 40-85% for phenolics, based on the operating media and the activities of the microorganism (Francisca, Cátia, Henrique, Lúcia, & Manuel, 2022). However, emerging contaminants such as BPA and benzoquinone have resisted these conventional methods, underscoring the need for robust biodegradation designs. Laccase and peroxidase enzymes from fungi and bacteria are some of the cultured organisms that support the bioremediation of emerging contaminants in water matrices. In a very recent study, laccase-based systems successfully removed approximately 90% of phenolic compounds through oxidative polymerization (Anil Kumar et al., 2025). It was also observed in another study that immobilized enzymes on polymer or silica surfaces improved stability and were used over several cycles with very minimal loss in activity of the microorganism (Yaashikaa, Devi, & Kumar, 2022). Fungal strains such as Trametes versicolor and Phanerochaete chrysosporium showed enhanced performance in the degradation of BPA, triclosan, and hydroquinone using their extracellular oxidative enzymes (Singh, Kumar, Saharan, & Kapoor, 2019; Suzuki, Mori, Kato, & Shimizu, 2023). Irrespective of the successes of this remediation approach, the high cost of the enzymes, culturing of microorganisms, and technical expertise are some of the challenges posed by this technique. It is worth noting that microalgae-based systems have also gained attention as eco-friendly and energy-efficient alternatives. They have simultaneously removed nutrients and phenolic contaminants and can be integrated into hybrid systems for tertiary treatment.

2.4 Integrated Method: Integrated treatment techniques have become a major focus in recent times due to their enhanced synergistic removal efficiency (Kumar & Singh, 2025). Commonly explored integrations include adsorption/AOP, membrane/photocatalysis, and biological/AOP sequences (Arya, Thapliyal, & Sen, 2025; Lata Deso et al., 2025;

Nidheesh, Couras, Karim, & Nadais, 2022). For photocatalysis (AC/TiO_2 composites) enhances the adsorption of pollutants on the active sites, leading to quick degradation of the contaminants (Yue et al., 2024). The combination of UV/H_2O_2 system with biological treatment removes residual intermediates and minimizes the generation of toxic byproducts (Bar-Niv et al., 2022). Also, the synergistic effect of UV/H_2O_2 and photo-Fenton processes removed about 90% of butylparaben (Lucas & Peres, 2015). Algal-bacterial systems also showed improved degradation rates through adsorption and biotransformation mechanisms (Trivedi & Chhaya, 2021). It is imperative to note that studies have demonstrated significant example, the synergy between adsorption and progress in hybrid treatment due to its capacity to remove a wide range of organic recalcitrant pollutants, including parabens and phenolics (Ramutshatsha-Makhwedzha & Munonde, 2024; Vieira, de Farias, Spaolonzi, da Silva, & Vieira, 2020). Unfortunately, cost-intensity, maintenance, scalability, and sustainability under different water quality parameters remain significant research gaps that need to be addressed (Asheghmoalla & Mehrvar, 2024). Table 1 shows a review of the major treatment techniques, including their mechanisms, removal capacities, advantages, and limitations, while Figure 1 illustrates the degradation mechanism of methylparaben.

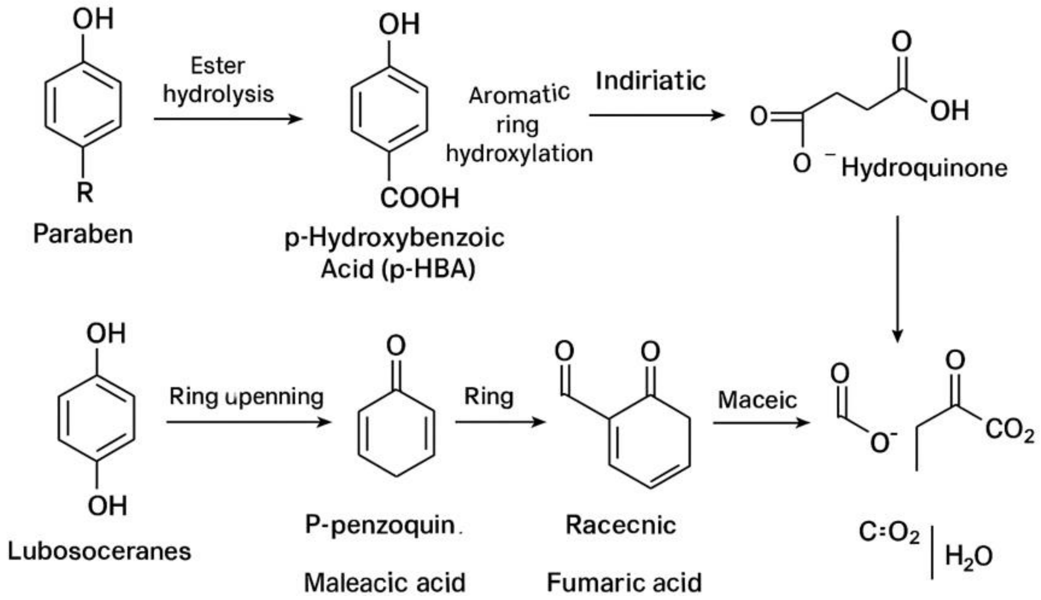

Figure 1: Degradation Pathway for the degradation of a representative paraben (methyl) compound

Table 1: Overview of the Treatment Technique of Parabens and Phenolic Compounds

Method	**Treatment technique**	**Mechanism**	**Removal efficiency**	**Key operating conditions**	**Advantages**	**Limitations/Challenges**
Physical	Adsorption (activated carbon, biochar, MOF, zeolites, magnetic nanocomposites)	Physisorption (π–π interactions and van der Waals forces); Chemisorption (covalent/ionic bonding)	65-99%	Optimized pH, contact time, adsorbent dose, and functionalization	High affinity for aromatic compounds	Interference of ions and natural organic matter, especially in complex water matrices, low degree of selectivity.
	Membrane Filtration (NF, RO)	Size-exclusion and charge-exclusion	90-95%	Pressure-driven, membrane-type (isotropic vs anisotropic), water matrix	High selectivity, effective for trace pollutants	High energy cost, brine concentrate, membrane fouling, and odour formation.
	Hybrid membrane system (MIREX plus NF/RO)	Pre-treatment DOC removal with catalytic degradation	>90% for methyl-, ethyl-, propyl-, butylparaben	Resin selection, the nature of the membrane material, and	High removal efficiency	Improper resin can cause odoring, cost intensive.
Chemical	Ozonolysis	Driven by ozone dosage	60-100% for BPA, HQ, and parabens	Ozone dose, pH, water matrix	Rapid reaction, reduced persistent residues	Formation of secondary intermediates requires secondary treatment.
	Photocatalysis	ROS generation through electron-hole pairs	90-95 % for BPA, HQ, parabens	UV/Visible light source, catalyst dosage, effect of contact time, oxidant, pH, and contaminant dosage	Eco-friendly, minimal generation of byproducts, and effective mineralization to beneficial compounds	Catalyst recovery, leaching, high energy demand, scavenger interference
	Fenton/Photo-Fenton	$Fe^{2+} + H_2O_2 \rightarrow {}^{\bullet}OH$, enhanced by UV	70-98% for BPA, methylparaben	Acidic pH, the intensity of the UV source, and Fe dosage	Fast degradation, slow generation of sludge with a heterogeneous catalyst	Sludge generation, pH limitation, and minimal efficiency in complex matrices

	Sulfate radical oxidation	$SO_4^{\bullet-}$ radicals generated through heat, UV, or metal activation	High degradation efficiency for BPA and parabens	Transition metals, effect of temperature and pH	Broad pH range, selective oxidation, longer radical shelf life.	Metal leaching, residual oxidants, and the high cost of activators.
Biological	Activated Sludge/Biofiltration	Microbial metabolism	50-90% for parabens; 40-85% for phenolics	Nature of the microorganisms, retention type, media type	Low cost of setup, widely adopted	Ineffective for BPA and BQ, slow kinetics, microbial inhibition.
	Enzymatic Biodegradation (Laccase peroxide)	Enzymatic oxidation and polymerization	90% for phenolic compounds	Enzyme immobilization, effect of pH and temperature	High degree of selectivity, reusable if immobilized	High cost of enzymes, stability, and high cost of technical know-how
	Fungal Biodegradation	Extracellular oxidative enzymes	High degradation efficiency for BPA, triclosan, and hydroquinone	Aeration, nutrient supply	Suitable for recalcitrant EDCs	Organism culturing challenges, longer treatment time.
	Microalgae-based system	Biosorption and biodegradation	Moderate to high degradation efficiency	Light intensity, nutrient levels	Eco-friendly	Slow growth, high degree of selectivity for toxins
Integrated System	Combined processes such as Adsorption-Oxidation/Membrane–Advanced Oxidation processes and Biological Hybrids	Sequential or synergistic removal via adsorption, ROS oxidation ($^{\bullet}OH$, $SO_4^{\bullet-}$), membrane separation, and biodegradation of intermediates	Broad-spectrum and rapid removal; typically, >90% for parabens/phenolics; high mineralization and reduced toxicity	Catalyst loading, irradiation/UV dose, oxidant concentration (H_2O_2, PMS/PS), pH control, membrane type, mixed cultures	Strong synergistic effects, reduced toxic intermediates, improved biodegradability, high water quality, energy-efficient, nutrient cycling	Higher cost, catalyst/membrane separation, iron sludge membrane fouling, pH limitations, radical scavenger interference, slow biological kinetics, culture maintenance.

3.0 Key Challenges in Removing Parabens and Phenolics from Water Systems

The treatment of parabens and phenolic compounds from drinking water supplies remains challenging, largely due to their physicochemical characteristics, environmental persistence, and potential production of toxic byproducts during treatment that may pose serious health issues to both human and aquatic organisms. It is important to thoroughly understand these limitations as they are pivotal to the development of eco-friendly and effective removal techniques of parabens and phenols in drinking water sources. Notable challenges that may be encountered while developing any of the remediation techniques are discussed below.

3.1 Physicochemical Parameters: The structural characterization, functional groups, and hydrophobicity level of the targeted compounds are pivotal to how they interrelate with the mode of treatment and varying oxidizing agents. Low molecular weight parabens like methyl and ethyl parabens, as well as simple phenolics such as hydroquinone and resorcinol, are more water-soluble and less hydrophobic, so they sorb weakly to the surface of the adsorbent. Unlike long-chain parabens and more aromatic phenolics, which tend to have a stronger adsorption capacity. Although in some cases, they may resist biodegradation due to steric hindrance and an electron-withdrawing group (Ramutshatsha-Makhwedzha & Munonde, 2024).

3.2 Formation of Toxic Intermediates: Chemical treatment methods such as ultraviolet/hydrogen peroxide, ozonation, and photocatalysis can lead to incomplete breakdown of parabens and phenolics, thereby generating intermediate products that may be more toxic, persistent, or estrogenic than their parent compounds. Typically, it has been observed that the treatment of parabens led to the formation of p-hydroxybenzoic acid, while phenolic degradation generated quinones and other aromatic intermediates that were found to be more dangerous to the overall well-being of the ecosystem (Alvarez et al., 2020). The need for complete oxidation of these persistent compounds and the prevention of hazardous by-products remains an unaddressed concern.

3.3 Matrix Interference: Matrix interferences, including natural organic matter (NOM), suspended solids, inorganic ions, and co-existing trace pollutants present in drinking water sources, sometimes adversely affect the overall performance of the deployed treatment technology. In most cases, NOM competes with the available adsorption sites and scavenges ROS, reducing the efficiency of the AOP. Additionally, the ionic strength may distort membrane permeability and cause odouring or competitive exclusion. These limiting factors lead to the inability to upscale successfully simulated studies (Yang et al., 2022).

3.4 Reduced Biodegradability and Microbial Inhibition: Low biodegradability and microbial activities are some of the challenges faced by the conventional biological treatment. Activated sludge and biofiltration have shown poor biodegradability of many parabens and phenolic compounds. This is because of parabens' antimicrobial properties that can slow down the activities of the microorganism. For phenolics, electron-withdrawing functional groups may affect the activities of the organism and lead to incomplete removal of the compounds. The use of immobilized bioreactors is promising but can be capital-intensive and requires optimization for scale-up, stability, and sustainability (Lu, Li, Tu, & Yang, 2018).

3.5 Scalability, Cost, and Sustainability Constraints: The high cost of setup, energy demands, transformation intermediates, stability, and reusability of the synthesized materials have significantly challenged the deployment of successfully simulated laboratory studies into field operations. Also, some of the techniques, like adsorbents, may generate concentrated waste streams that require further treatment. Photocatalysis and membrane remediation approaches sometimes face challenges, including catalyst recovery and membrane odouring in some cases. These factors remain a significant research concern necessitating the need for sustainable, low-carbon, and circular treatment of parabens and phenolics in drinking water sources (Ababay Ketema et al., 2025).

4.0 Perspectives

It is integral to understand the profile of intermediates generated during the degradation mechanism through the use of advanced analytical tools such as liquid chromatography-mass spectrometry (LC-MS/MS). It is imperative to design technologies that can improve stability, reusability, and fouling resistance of these materials for optimal field applications. It is also important to thoroughly examine the eco-friendliness of the different treatment technologies. Therefore, there is a need to assess their life-cycle assessments and techno-economic analyses that will guide the appropriate choice of treatment technique and help in the development and formulation of policies. More studies should focus on the development of integrated approaches that can treat mixtures of emerging and endocrine-disrupting compounds like parabens and phenolics. Additionally, it is important to comprehensively understand the eco-toxicological profile of intermediates, necessitating the need to characterize the risks associated with these intermediates alongside their removal efficiency. While laboratory studies have shown promising removal efficiencies, full-scale applications remain inadequate. To address this challenge, it is important to collaborate with relevant stakeholders and safeguard our drinking water sources.

5.0 Conclusion

This study reviewed recent treatment techniques deployed in the treatment of parabens and phenolic compounds in drinking water sources. Despite the considerable progress made, many challenges and research gaps have been identified in this study. Researchers can focus on developing integrated sustainable treatment methodologies driven by data from environmental assessment. It is also important to address these challenges, especially with green techniques that can reduce the generation of toxic daughter compounds. More so, full-scale field applications should be prioritized to bridge the gap between simulated studies and field applications. This strategy will contribute to the achievement of the United Nations Sustainable Goal 6, hinged on clean water and sanitation.

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