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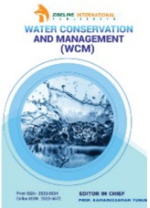

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REVIEW ARTICLE

INSIGHT INTO TECHNOLOGIES FOR REMOVING CONTAMINANTS OF EMERGING CONCERNS FROM WASTEWATER

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ABSTRACT

Various anthropogenic activities result in a continuous discharge of contaminants of emerging concern (CEC) into the natural environment. The remediation of these substances is an emerging concern to safeguard life on Earth. CECs and their removal have become a growing concern, which is being investigated in different wastewater treatment processes. Therefore, a comprehensive study is required to find appropriate low-cost, eco-friendly, and efficient technology to remediate different kinds of CECs from wastewater. The partial removal of CECs, such as endocrine-disrupting compounds, pharmaceuticals, personal care products, and heavy metals have been discussed in this review. The results of the review show that the majority of the research in recent years has focused on using phase-changing processes, including adsorption in different solid matrices and membrane processes, followed by biological treatment and advanced oxidation processes. This paper focuses on the type of CEC being removed, the conditions of the process, and the outcomes achieved. The main trends in the field are also highlighted along with perceptive comments and recommendations for further developments, as well as the identification of the current knowledge gaps and future research directions related to the application of these technologies for water treatment and restoration.

KEYWORDS

Contaminants of emerging concerns; Wastewater; Removal efficiency; Emerging technologies; Risk management

1. INTRODUCTION

Water is essential for supporting life and is crucial for the well-being of both humans and animals. Despite about 75% of the Earth's surface being inundated with water, a small fraction (< 1%) is available as freshwater for human consumption (Archer et al., 2017). The vast pollution of freshwater and seawater sources by chemicals, oils, and other contaminants markedly reduces their availability and quality, presenting substantial threats to both human and animal health (Huynh et al., 2022; Hoang et al., 2021). The rampant application of agricultural chemicals and medications raises significant concerns, as certain toxic components within these substances permeate the environment. These contaminants are deemed hazardous and potentially carcinogenic, even in minimal concentrations. Notwithstanding their hazards, they remain predominantly unregulated and are collectively referred to as emerging contaminants (ECs) or contaminants of emerging concern (CECs) (Gani et al., 2021; Israel Dikobe, 2024). Recently, these contaminants have been identified in water sources, threatening human and aquatic life, as well as the whole ecosystem. Contaminants of growing concern are compounds that have long been present in the environment, although their importance and prevalence are just now being fully acknowledged (Gumbi et al., 2017). ECs and CECs manifest in diverse ways, such as pesticides, endocrine-disrupting substances, medicines, industrial solvents, personal care items, microplastics, hormones, and flame retardants. These ECs and CECs predominantly stem from hospital effluents, industrial discharges, wastewater treatment plant effluents, and runoff from urban and agricultural regions (Bagnis et al., 2020). Fig. 1 depicts the routes and origins of various ECs and CECs in the environment, in which ECs and CECs are routinely introduced into ecosystems, remaining in wastewater and other environments, as traditional treatment systems were not engineered to remove them properly (Shehu et al., 2022).

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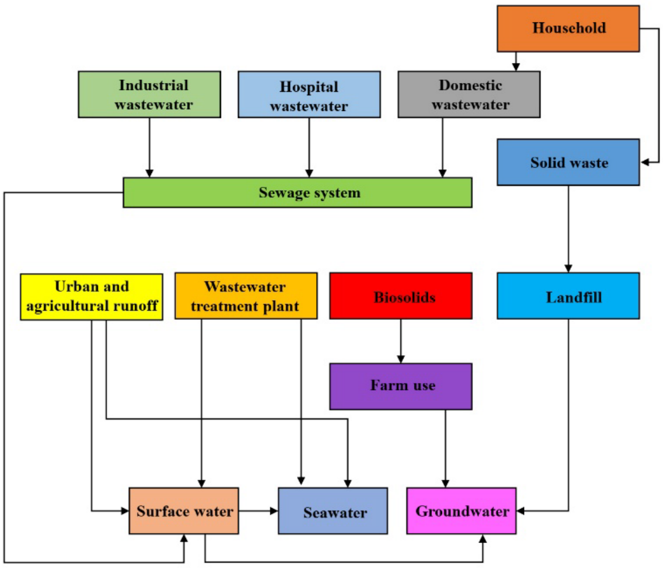

Figure 1: Schematic representation of sources and pathways of CECs in the environment (Shehu et al., 2022).

The existence of CECs in drinking water raises significant concern due to the potential for prolonged exposure, which may result in serious and probably carcinogenic health consequences. These pollutants often resist destruction in current wastewater treatment techniques, resulting in their persistent accumulation with an ever-increasing concentration in the surrounding environment. They infiltrate ecosystems via several channels, including agricultural runoff, industrial effluents, and wastewater discharges (Yang et al., 2019). Conventional water purification techniques, such as flocculation and sand filtration, while efficient against pathogens, have demonstrated inefficacy in eliminating CECs (Sörengård et al., 2019). Therefore, a focused study on CEC removal is essential to improve existing therapy methodologies. Although adsorption technologies, such as granular activated carbon (GAC), have demonstrated efficacy in the removal of these contaminants, total eradication continues to pose a difficulty (Tröger et al., 2018). The constrained efficiency results from inadequate adsorption of certain pollutants, diminished removal efficacy over prolonged operational durations, and competitive sorption with dissolved organic matter. Although various CECs have been identified, regulatory measures have been enacted for just a restricted subset. In the last twenty years, the European Union (EU) has intensified its political awareness of water quality management to protect aquatic ecosystems, preserve their health, and reduce negative effects on human populations (Viegas et al., 2021). These initiatives are evident in the regulatory frameworks, as illustrated in Fig. 2.

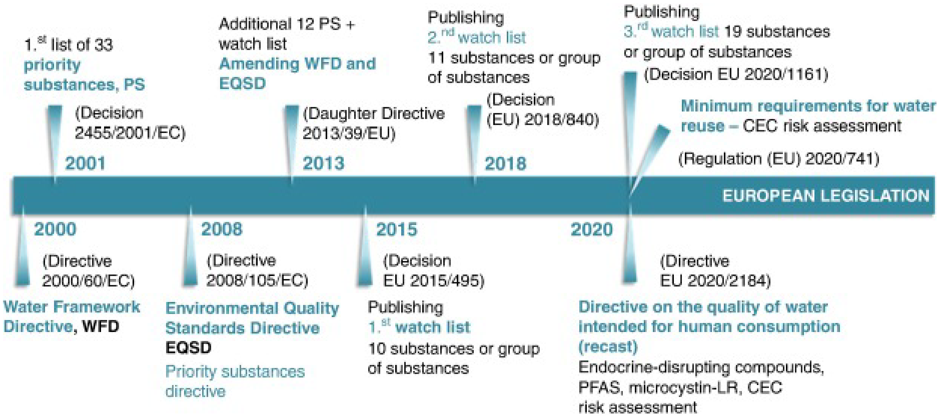

Figure 2: Evolution of water-related European legislation concerning CECs (Viegas et al., 2021).

The principal legislation regulating water resources in the EU is the Water Framework Directive 2000/60/EC. This directive sets concentration limits for 45 priority substances, including herbicides, pesticides, insecticides, industrial solvents, hydrocarbons, polycyclic aromatic hydrocarbons, and heavy metals, which must adhere to the Environmental Quality Standards specified in Directive 2008/105/EC. To enhance monitoring initiatives, the WFD established the Watch List in 2013 (Directive 2013/39/EU), which identifies uncontrolled pollutants necessitating immediate evaluation. First released in 2015, three versions of the Watch List have primarily concentrated on medicinal substances and insecticides. While the EU does not possess explicit wastewater regulations concerning CECs, Regulation EU/2020/741 introduces minimum standards for agricultural water reuse, incorporating supplementary criteria for the evaluation of pesticides, disinfection by-products, pharmaceutical residues, and other ECs predicated on risk assessments.

Switzerland was the inaugural nation to enforce comprehensive regulations on CEC emissions from point sources. Since 2016, the Swiss Water Protection Act requires an 80% reduction in CEC levels at designated wastewater treatment plants, with complete compliance anticipated across all pertinent facilities by 2040 (Mestre et al., 2022). According to this rule, treatment facilities must provide financial contributions until they implement and validate the effectiveness of innovative treatment technologies. In Germany, Federal Centers for Trace Substances (KomS) in regions like Baden-Württemberg, North Rhine-Westphalia, and Berlin actively advocate for the elimination of CECs, thereby expediting the implementation of modern treatment technologies. By late 2019, more than 20 wastewater treatment facilities had been enhanced to attain an 80% reduction in critical indicator pollutants, with an additional 27 facilities in different phases of development (Metzger et al., 2019; Mestre et al., 2022). The situation is most dire in low- and middle-income nations, where swift population expansion, inadequate regulatory frameworks, and deficient wastewater treatment infrastructure intensify pollution issues (Shafi et al., 2023). In some areas, around 80–90% of wastewater is released straight into rivers, lakes, and seas without sufficient treatment (Hsieh et al., 2023). As a result, CEC contamination levels in certain situations may be significant. Notwithstanding these concerning discoveries, extensive documentation of CEC prevalence across various geographical regions is still inadequate. Current study predominantly emphasizes water bodies, while investigations into pollutants in sediments, aquatic creatures, food chains, and human biological samples are few. Due to the significant impact of water quality factors and CEC-specific characteristics on pollutant transport processes, a comprehensive study on membrane-based remediation solutions is required. This paper seeks to synthesize existing knowledge on CEC treatment methodologies in water and wastewater, identify research deficiencies, and suggest future research avenues to enhance effective mitigation measures.

2. TYPES AND HEALTH EFFECTS OF CECS

2.1 Types of CECs

Contaminants of emerging concerns (CEC) encompass a range of pollutants, including pharmaceuticals, personal care products, pesticides, industrial chemicals, flame retardants, surfactants, plasticizers, and nanomaterials (García-Fernández et al., 2021). These CECs stem from multiple anthropogenic sources and are released into different environmental compartments via industrial effluents, domestic wastewater, and agricultural runoff. This paper delineates novel contaminants classified as microplastics, antibiotics, endocrine-disrupting compounds, and persistent organic pollutants, according to global research trends. The widespread use of industrial and agricultural chemicals makes the release of new ECs into the environment inevitable. The enduring characteristics of these pollutants and their extensive distribution underscore the necessity for improved monitoring methods and regulatory structures to alleviate their environmental effects. Notwithstanding the extensively recorded chemical structures of various CECs, a significant knowledge deficit remains about their comprehensive composition and toxicity (Zengel and Michel, 2013).

Comprehending their long-term bioaccumulation potential and interactions with biotic and abiotic variables presents a considerable challenge for environmental scientists. Personal care products constitute a significant category of developing CECs due to their extensive use and persistence in aquatic environments. These compounds serve several functions, including ultraviolet filtration, fragrance enhancement, preservation in cosmetic formulations, antibacterial characteristics in creams, soaps, and toothpaste, and as insect repellents. Owing to their enduring characteristics and prevalent application, they have been identified in wastewater, surface water, and groundwater. This group comprises numerous chemical structures, some of which are not efficiently eliminated by conventional wastewater treatment techniques. Consequently, they can persist in ecosystems and bioaccumulate in organisms, leading to harmful biological effects (Golovko et al., 2021). The bioaccumulation of these compounds can interfere with endocrine functions and reproductive processes in aquatic creatures, resulting in modified population dynamics and environmental imbalances. These contaminants have been detected in wastewater influents and effluents, groundwater, rivers, lakes, marine environments, and sediments worldwide (Petrie et al., 2015). Ongoing improvements in analytical methods have facilitated the identification of these pollutants at ultra-trace concentrations, underscoring their environmental importance.

Pharmaceuticals, derived from natural and synthetic origins, are widely utilized in human and veterinary care. These chemicals infiltrate aquatic habitats chiefly through urine and the incorrect disposal of surplus drugs. Pharmaceuticals rank among the most commonly detected CECs in environmental matrices, with an estimated yearly per capita consumption in rich countries ranging from 50 to 150 grams (Zhang et al., 2008). Over 600 active pharmaceutical ingredients have been identified in sewage effluents and surface water, with their presence extending to groundwater and soil environments (Kar et al., 2018). The existence of these CECs in the environment raises concerns about antimicrobial resistance and the disturbance of microbial populations. Pharmaceuticals and personal care products are the most frequently recognized CECs in surface and groundwater systems. Water samples often contain chemicals like atenolol, sulfamethoxazole, meprobamate, carbamazepine, gemfibrozil, phenytoin, ibuprofen, naproxen, estrone, and trimethoprim (Kleywegt et al., 2011).

The principal sources of developing contaminants are industrial and agricultural operations, municipal waste, hospital and laboratory effluents, and improper disposal of hazardous materials. These pollutants infiltrate the ecosystem by direct discharges, air deposition, rainwater runoff, or unforeseen contamination incidents. As emerging toxins change, aggregate, and degrade in environmental media, their chemical behavior influences their persistence and impact. For instance, hydroxyl radicals in the atmosphere impede the degradation of organophosphorus flame retardants, whereas perfluorooctanesulfonamides convert into perfluorooctane sulfonate in earthworms, and perfluorohexane sulfonic acid and perfluorobutanesulfonate transform plants like wheat (Chen et al., 2015). These pollutants can accumulate via food chains, resulting in biomagnification in apex predators. Microplastic particles of diverse sizes demonstrate differing toxicity levels; smaller microplastics (500 nm) intensify the detrimental effects of persistent organic pollutants, while larger microplastics (30 μm) seem to provide reduced dangers (Tang et al., 2020). Investigations into the synergistic impacts of CECs remain nascent, and existing risk evaluations predominantly depend on concentration-based models, potentially resulting in erroneous projections. The prolonged buildup of these CECs in sediments leads to their bioaccumulation in benthic species, which are then ingested by fish, resulting in elevated CEC concentrations in apex predators. Compounds that are very hydrophobic or possess positive charges typically demonstrate significant adsorption properties, hence diminishing their likelihood of biodegradation, long-distance transport, or absorption by plants (Borgert et al., 2004). Bisphenol A exhibits negligible degradation in anaerobic or hypoxic circumstances, while it has an estimated half-life of 3–37 days in aerobic soil and sediment environments (Chang et al., 2014). Advanced probabilistic risk assessment methodologies have discovered around 50 pharmaceutical and personal care chemicals that exert considerable ecological effects on aquatic organisms (Liu, et al., 2020).

2.2 Environment and health effects of CECs

Both naturally occurring and manmade emerging contaminants (ECs) are linked to potential or verified adverse impacts on human health and ecosystems. Nevertheless, the assessment and categorization of the environmental and health concerns associated with these hazardous substances remain hard due to insufficient evidence on their impacts. Assessing the ecotoxicological impacts of ECs requires a precise metric to measure their toxicity levels in aquatic and air ecosystems. In this bioassay, ECs with concentrations ranging from 10 to 100 mg/L are designated as hazardous, those within the 1–10 mg/L range as toxic, and those below 1 mg/L as highly toxic to aquatic ecosystems (Cleuvers, 2003). The presence of antibiotic residues in water strongly impacts the effectiveness of wastewater treatment operations and the functionality of microbial communities. Increased levels of these chemicals can foster the emergence of antibiotic-resistant bacteria and resistance genes in host organisms. Moreover, endocrine-disrupting chemicals can obstruct hormonal pathways, resulting in disturbances within the endocrine system. Through agricultural irrigation employing wastewater, ECs can easily infiltrate food systems, impacting both humans and animals directly. Despite existing in comparatively low concentrations, from nanograms per liter (ng/L) to micrograms per liter (μg/L), persistent exposure may lead to significant health issues over time. Numerous ECs and their derivatives endure in the ecosystem due to insufficient degradation, resulting in adverse effects on biodiversity (Bilal et al., 2019). Due to their elevated quantities, diversity, and potential for environmental pollution, ECs have predominantly been examined in surface water systems. Significant environmental issues related to ECs encompass their toxicity to bacteria, earthworms, crops, wildlife, invertebrates, amphibians, and fish, along with their influence on the management of algal, bacterial, and fungal populations (Maurer-Jones et al., 2013).

Numerous ECs have been recognized as detrimental due to their adverse effects on ecosystems and human health. Research has demonstrated that drugs like propranolol and fluoxetine display significant toxicity to aquatic species, including benthic invertebrates and zooplankton (Jacob et al., 2016). While prolonged exposure to pharmaceutical pollutants may result in enduring detrimental effects on humans and animals, their existence in minimal concentrations does not inherently pose immediate health risks. The recent surge of antibiotic-resistant bacteria in animals has been associated with the overuse of antibiotics. Perfluorinated compounds have been linked to detrimental health effects, such as thyroid dysfunction, decreased sperm count, and infertility. Furthermore, pharmaceuticals and personal care products have been associated with developmental anomalies, endocrine system malfunction, and reproductive diseases in humans and animals alike (Corsini et al., 2014).Furthermore, certain nanomaterial-based electrochemical cells have been recognized as carcinogenic, presenting significant reproductive hazards. Emerging nanoparticle contaminants are significantly associated with heightened occurrences of lung cancer and reproductive problems (Enyoh et al., 2020).

3. ADSORPTION TECHNOLOGY FOR CEC TREATMENT

Adsorption is a process in which molecules from a gas or liquid phase attach to the surface of a solid material referred to as an adsorbent. This method is extensively utilized in industrial water treatment, especially for pollution removal. For large-scale use, adsorbents must exhibit high porosity and surface area, as well as facile regeneration for economic viability. Various environmental conditions, such as pH, temperature, pressure, and the presence of competing molecules, might affect an adsorbent's ability to collect pollutants. The adsorption efficiency is contingent upon the initial concentrations of the adsorbate, the properties of the adsorbent, and the duration of contact between the two phases (de Andrade et al., 2018). In industrial environments, adsorption is generally performed in continuous-flow devices, such as fixed-bed columns, owing to their superior processing efficiency. In contrast, batch adsorption is frequently employed in laboratory research to assess adsorption capacity and processes (Antunes et al., 2021).

Activated carbon (AC) has substantial porosity and an extensive surface area, making it highly effective in removing diverse contaminants (Sotelo et al., 2012). The extensive network of pores in AC enhances its remarkable capacity to absorb pollutants efficiently (Hoang et al., 2022). Its adsorption efficiency has been demonstrated in the elimination of several pollutants, attaining rates exceeding 90% in numerous tests and under different environmental conditionsm (AL-Othman et al., 2012; Rodríguez-Narváez et al., 2017). AC exhibits selective adsorption characteristics, evidenced by its effectiveness in eliminating ciprofloxacin, attaining pollutant concentrations beneath detection limits even at modest dosages (AL-Othman, 2012). Prolonged exposure to AC is effective in reducing pollutant concentrations by around 90% thereby dramatically lowering even persistent pollutants over time. **Table 2** presents an overview of specific studies concerning the removal of developing contaminants by activated carbon (Bernal-Romero del Hombre Bueno et al., 2019).

Table 2: Removal efficiency of ECs with activated carbon

AC Source	EC	Removal efficiency, %	Notes	Reference
LS by wet oxidation (LSN)	Ibuprofen	60	pH = 4; 10 mg AC, 0.5 h Ultra-pure water	(Ruiz, et al., 2010)
Chemical activation of cork (CAC)		70		
Cork powder waste (CPAC)		62		
Physical activation of coal (Q)		85		
Physical activation of wood (LS)		95		
Physical activation of PET (P)		70		
Sugar beet pulp	Tetracycline	>90	Batch, 250 h	(Torres-Pérez, et al., 2012).
Peanut hulls		>90		
Coconut shell		30		
H_3PO_4-activated wood		75		
Olive-waste cake	Ibuprofen	70	T = 25°C, pH = 4.12	(Baccar et al., 2012)
	Ketoprofen	88		
	Naproxen	90		
	Diclofenac	91		
Coal	Paracetamol	74	T = 30 °C	(Cabrita et al., 2010)
Wood		97		
Plastic waste		60		
Powder waste		87		
Peach stones		82		
Norit® Rox 0.8 from Sigma	Ciprofloxacin	>99	T = 25 °C, pH = 5	(Carabineiro et al., 2011)
Albizia lebbeck seeds pods	Cephalexin	57	Activated with KOH	(Ahmed and Theydan, 2012)
		52.5	Activated with K_2CO_3	
Calgon Filtrasorb 400	Diclofenac	5	T = 25 °C	(Sotelo et al., 2012)
	Caffeine	98		
	Norfloxacin	100		

The selective adsorption capacity of activated carbon is illustrated by its effectiveness in removing ciprofloxacin, reducing it to undetectable levels practically immediately, thereby showcasing its quick adsorption ability (Carabineiro et al., 2011). In contrast, the removal of several other pollutants requires extended treatment durations, despite documented efficiencies exceeding 90% in numerous instances. A case study of a granular AC-based advanced wastewater treatment facility demonstrated substantial removal efficiencies for various ECs, including lincomycin, levofloxacin, diclofenac, ibuprofen, trimethoprim, ciprofloxacin, erythromycin, carbamazepine, caffeine, primidone, and N, N-diethyl-m-toluamide, underscoring its extensive applicability, as shown in **Fig. 3** (Torres-Pérez et al., 2012; Yang, et al., 2011).

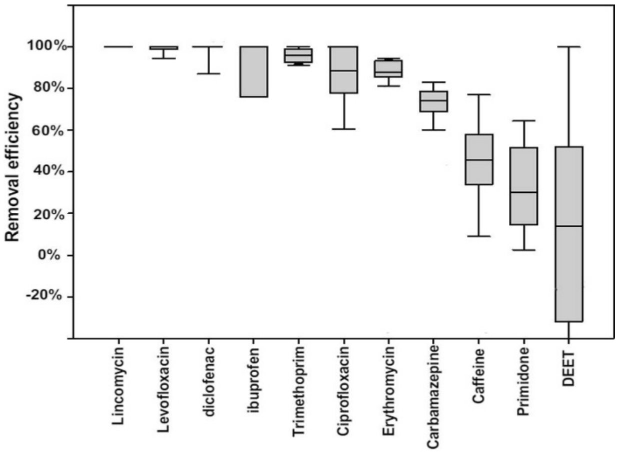

Figure 3: Removal efficiency of different ECs by AC (Rodríguez-Narváez et al., 2017; Yang et al., 2011)

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The source of AC significantly influences its adsorption efficacy, as various raw materials yield different removal efficiencies. The characteristics and content of the precursor material are essential in determining its adsorption capacity. For example, acetaminophen adsorption rates from non-wood sources range from 60% to 87%, but wood-based AC achieves removal rates of 90%, demonstrating greater efficacy when sourced from wood materials (Cabrita et al., 2010). The removal efficacy of diclofenac exceeds 90% when employing olive waste cake and granular AC, but Filtrasorb 400 produces somewhat lower removal rates, illustrating the variability of adsorption based on the nature of AC (Baccar et al., 2012). Studies indicate that AC sourced from various biomass materials, including beet pulp, peanut hulls, coconut shell, and phosphoric acid-treated wood, can effectively adsorb tetracycline from wastewater. Wood-based AC achieves removal efficacy above 75%, whereas coconut shell AC exceeds 30% (Torres-Pérez et al., 2012). In contrast, AC derived from beet pulp and peanut shells exhibits removal rates surpassing 90%, suggesting that particular biomass sources can improve adsorption efficiency. The reduced effectiveness of coconut shell AC results from its thick fibrous structure, which causes smaller pore diameters, and the absence of further activation methods that could enhance porosity, rendering it less efficient than other biomass-derived AC (AL-Othman et al., 2012). AC adsorption has proven highly effective in eliminating pollutants of increasing concern from water sources, hence underscoring its significance in water treatment applications (Khan et al., 2022).

Lignocellulosic materials have attracted significant attention in recent years as inexpensive adsorbents, demonstrating strong effectiveness in removing a wide range of pollutants with different structures. Typically, this type of biomass is derived from cultivated sources, agricultural and forestry residues, industrial by-products from these sectors, and even urban waste, and biomass was found to have a large number of applications in the energy sector, industry, manufacturing, and environment (Hoang et al., 2021; Chau et al., 2020; Anh Tuan, et al., 2020; Nguyen et al., 2021). Recent research has highlighted the potential of agricultural waste to function as biosorbents, offering a promising approach to mitigating environmental pollution (Chau et al., 2025; Hoang et al., 2018; Hoang and Pham, 2021). Reusing production residues—such as by-products and waste—not only enhances the economic value of raw materials but also lowers waste management costs, thereby increasing their importance as secondary resources. Various biomaterials, including lignin from black liquor, tea waste, olive stones, eucalyptus bark, corn cobs, bamboo chips, bagasse fly ash, and olive mill waste, have been explored for their ability to remove CECs from wastewater.

Biochar, a carbon-dense material, has attracted interest for its efficacy in removing contaminants from wastewater. Biochar, generated via the thermochemical conversion or co-thermochemical conversion of biomass and other wastes, has become popular owing to its cost-efficiency and adsorption capability (Le et al., 2023; Zhang et al., 2023; Sirohi et al., 2023; Hoang et al., 2024). Biomass typically undergoes pyrolysis to generate biochar from various feedstocks which include differing structural and chemical characteristics that directly influence its efficacy in pollutant removal Scrap (Jelita et al., 2022; Hoang et al., 2024). The composition of biochar sometimes contains partially carbonized fractions that can impact its adsorption capacity, depending on the feedstock type and processing conditions, therefore affecting its efficiency (Hoang et al., 2022; Lee et al., 2022). From an economic perspective, utilizing biochar, priced between 350 and 1200 USD per ton, presents a more cost-effective solution than AC, which ranges from 1100 to 1700 USD per ton, thereby significantly reducing wastewater treatment expenses and rendering it a feasible alternative in resource-constrained environments (Feizi et al., 2020). The fact shows that biochar has a large number of applications in energy production, construction, and the environment (Sudita et al., 2021; Rosalina and Febriadi, 2023). Biochar has demonstrated considerable effectiveness in adsorbing a range of organic and inorganic pollutants, thereby reinforcing its position as a sustainable adsorbent. Biochar derived from shells has been employed to adsorb volatile organic compounds (VOCs) such as nitrobenzene and trichloroethylene, illustrating its effectiveness in eliminating various ECs (Chen et al., 2011). The choice of feedstock significantly affects biochar's adsorption selectivity and treatment effectiveness, akin to AC, which is crucial for the elimination of ECs. For example, biochar generated from wood exhibited a sulfamethoxazole removal efficiency of 12%, while sugarcane-derived biochar achieved up to 21% (Yao et al., 2012). Biochar produced from rice straw and husks initially removed 11.6% of pollutants; however, its effectiveness rose to 30% after alkaline treatment, demonstrating that chemical alterations can improve its adsorption capabilities (Khan et al., 2022). The efficiencies of adsorption and regeneration are significantly influenced by the presence of carbon alongside nitrogen and phosphorus. Thermal and chemical modifications have been demonstrated to alter the structural and chemical properties of biochar, hence influencing its effectiveness in eliminating CECs, which warrants additional investigation. In the literature, biochar was successfully used in the sorption of dyes, pharmaceuticals, pesticides, benzene and nitrobenzene, heavy metals, and personal care products. Biochar has selectivity comparable to activated carbon and, in specific cases, surpasses activated carbon in the elimination of certain ECs, highlighting its potential as an alternative adsorbent (Mitchell et al., 2015). Therefore, further research is required to improve treatment methods that include the advantageous properties of biochar, guaranteeing optimal efficacy in diverse applications (Khan et al., 2022). **Table 3** delineates the efficacy of biochar in eliminating developing pollutants.

Table 3: Removal efficiency of ECs using biochar.

BC feedstock	Activation temperature, °C	EC	Removal efficiency, %	Notes	Reference
Brazilian pepper wood	NR	Sulfamethoxazole	4–12	T = 22 °C [C]0 = 10 mgL^{-1} 2 mgL^{-1} of absorbent	(Yao et al., 2012)
Hickory wood	450		0–12		
Sugarcane waste	600		19–21		
Bamboo	NR		5–12		
Arundo donax L.	NR	Sulfamethoxazole	25.5	[C]0 = 50 mgL^{-1} Ce = 50 mgL^{-1} pH = 5 7.14 gL^{-1} of absorbent	(Zheng et al., 2013).
Arundo donax L.	300–600		5–16		
Demineralized A. donax L.	300–600		8–17		
Graphite	NR		7		
Ash	NR		31		
Raw rice husk	450–500	Tetracycline	8.5	5 gL^{-1} of absorbent $[C]_0$ = 1 gL^{-1}	(Liu et al., 2012).
Acid rice husk	450–500		12		
Alkali rice husk	450–500		29		
Forest soil/sweet gum/oak	850	Tylosin	10	0.1 gmL^{-1} of absorbent $[C]_0$ = 250 mgL^{-1} Time: 239 h 10% amended of biochar	(Jeong et al., 2012)
Forest soil/yellow pine	900		10		
Cornfield/sweet gum/oak	850		10		
Cornfield/yellow pine	900		10		

Carbon nanotubes (CNTs), a distinct allotrope of carbon, exhibit diverse sorption properties influenced by their shape, size, internal architecture, sheet configuration, curvature, and synthesis technique, rendering them very adaptable adsorbents (Hoang et al., 2022). The effectiveness of ECs

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removal with CNTs is greatly affected by their surface area and functionalization. Single- and multi-walled carbon nanotubes have significant disparities in their sorption efficiency, even when applied to the same pollutant, necessitating meticulous attention during selection. **Fig. 4** is a conceptual model that illustrates several changes of CNTs designed to promote pollutant removal in water treatment, emphasizing potential improvements via functionalization.

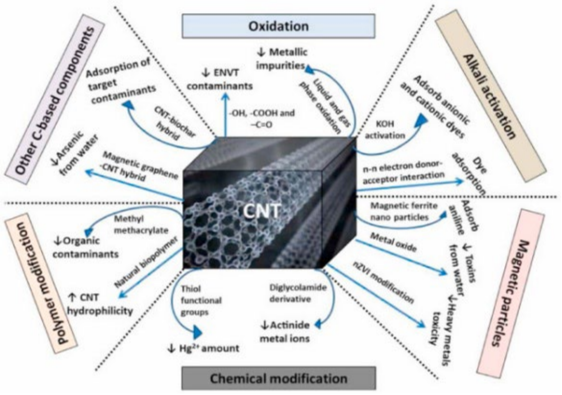

Figure 4: Diagram representing CNTs for CECs removal from water and wastewater (Khan et al., 2022)

The efficacy of carbon-based adsorbents, including CNTs, biochar, and AC, depends on their synthesis techniques. The effectiveness of CNTs in removing ECs is mostly dictated by their surface area, which may be modified through different fabrication techniques, hence affecting contaminant adsorption rates (Ji, et al., 2010). As a study reported a 92% efficacy in tetracycline elimination using single-walled nanotubes (SWNTs), but multi-walled nanotubes (MWNTs) achieved just 16% under identical conditions, indicating that structural differences significantly influence performance. Further research has shown the effectiveness of MWNTs in removing triclosan, ibuprofen, ciprofloxacin, and amoxicillin (Khan et al., 2022). SWNTs achieved complete norfloxacin removal, but multi-walled CNTs reached approximately 35% efficiency (Peng et al., 2012; Yang et al., 2012). Chemical treatments have been explored to enhance MWNTs by increasing their adsorption sites, hence improving removal efficiency. Nevertheless, molecular sieving effects in MWNTs have been recorded, but these structural characteristics do not invariably align with improved performance (Carabineiro et al., 2011). Owing to the scarcity of research, further experimental validation is necessary to determine definitive trends in CNT-based EC removal. Future research should focus on hybrid procedures that combine CNT adsorption properties with reactive nanomaterials, hence enhancing the potential for CNT-based pollution removal techniques. Integrating the adsorptive properties of CNTs with other reactive nanomaterials represents a promising research direction that still needs further exploration. For instance, embedding zero-valent iron nanoparticles onto CNT surfaces to enhance degradation processes, or combining CNTs with additional adsorption techniques, could open up entirely new avenues with significant application potential (Rodríguez-Narváez et al., 2017). A variety of other adsorbent materials have also been investigated for the removal of ECs, including zeolites, meso- and microporous materials, resins, and metal oxides. The structural characteristics of these adsorbents play a crucial role in determining their efficiency. The analysis examined Fe–Mn binary oxides for tetracycline removal: manganese oxide alone achieved over 98% removal, while iron oxide reached only 30% (Liu, et al., 2012). Similarly, combining aluminum oxide with CNTs significantly enhanced carbamazepine removal, increasing efficiency from 0 to 70% at a CNTs/Al_2O_3 ratio of 1:1. Other materials have also demonstrated effective EC removal, such as zeolite, pumice, and aluminum oxide. Additionally, molecularly imprinted polymers and other diverse materials have shown potential in eliminating a wide range of pharmaceutical compounds. **Table 4** provides a selected overview of studies reporting the removal of different ECs using CNTs.

Table 4: Removal efficiency of ECs using CNTs

CNT Type	EC	Removal efficiency, %	Notes	Reference
MWNT	Amoxicillin	>90	MWCNT (50 mg) pH = 4	(Mohammadi et al., 2015)
MWNT	Ciprofloxacin	67.5	Temp = 25 °C pH = 5	(Carabineiro et al., 2012)
SWNT	Ibuprofen/Triclosan	100	100 mgL^{-1} absorbent $[C]_0$ = 2 mg mg^{-1}	(Cho et al., 2011)
MWNT		100		
Oxidized MWNT		97–100		
SWNT	Tetracycline	92	$[C]_0$ = 0.19 mmolL^{-1}	(Ji, et al., 2010)
MWNT		16.5	pH = 5; 0.25 gL-^{1} absorbent	
Hydroxylized MWNT	Ofloxacin/Norfloxacin	11–99	$[OFL]_0$ = 0.7 gL^{-1} $[NOR]_0$ = 60 mgL^{-1} pH = 7 75 mgL^{-1} absorbent	(Peng et al., 2012)
Carboxylized MWNT		7–63		
Multi-walled graphite		5–70		
15 nm-ID CNT		11–99		
30 nm-ID CNT		7–63		
50 nm-ID CNT		5–50		
Hydroxylized SWNT		11–99		
Carboxylized SWNT		17–100		
Purified SWNT		17–100		
MWNT	Norfloxacin	35	0.5 gL^{-1} absorbent	(Yang et al., 2012)
			$[C]_0$ = 100 mgL^{-1}	
			T = 27 °C; pH = 5.4	

4. Membrane Technology For Cec Treatment

Membrane technologies are emerging as efficient solutions for several applications in water treatment, gas purification, and waste recycling. For wastewater treatment, membrane technology is a key phase-change mechanism widely employed for the removal of ECs. Membranes are fabricated from various materials with unique filtering characteristics (e.g., pore size, surface charge, and hydrophobicity) that influence their effectiveness in pollutant retention (Simmons et al., 2011). These membranes function by selective permeability, permitting some molecules to traverse while inhibiting others, thus guaranteeing optimal separation efficacy. Membrane separation techniques operate by applying hydrostatic pressure to facilitate the movement of water and low molecular weight solutes, while concurrently excluding suspended particles and larger molecules. Notable membrane filtration techniques include ultrafiltration (UF), nanofiltration (NF), microfiltration (MF), forward osmosis (FO), and reverse osmosis (RO). Each approach has distinct operational features and application domains, guaranteeing versatility for various environmental pollutants. **Fig. 5** illustrates several membrane types, their associated pore size ranges, and the common water pollutants they remove (Meng et al., 2015).

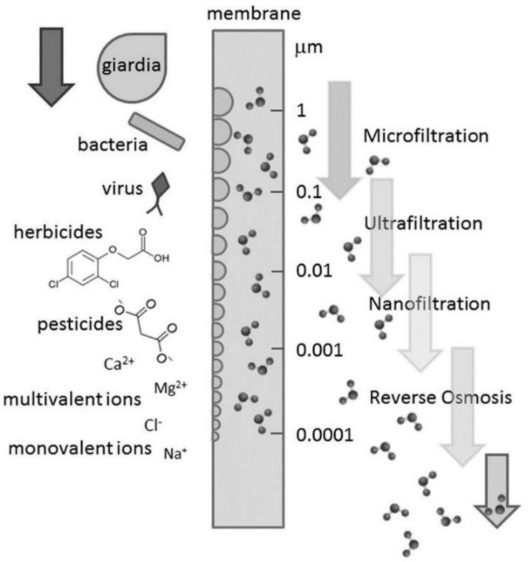

Figure 5: Membrane types, pore size ranges, and representative ECs removed (Meng et al., 2015).

A primary benefit of forward osmosis (FO) is its reduced energy consumption compared to other separation methods like reverse osmosis (RO). The forward osmosis method relies on a concentrated draw solution with a substantial osmotic gradient to enable water movement across a semipermeable membrane. This inherent osmotic mechanism diminishes the necessity for external pressure, hence enhancing energy efficiency (Johnson et al., 2018). The intricate relationships among these parameters and membrane materials influence separation efficiency, necessitating a comprehensive examination for enhanced pollutant elimination. A thorough understanding of these characteristics is essential for improving membrane-based pollutant retention in water treatment. Previous research has examined medication retention efficacy using forward osmosis membranes (Cao et al., 2020). Ciprofloxacin, sulfamethoxazole, acetaminophen, and carbamazepine were assessed in both solitary and combinatorial scenarios. A 0.1 mol/L NaCl solution served as the draw solute, demonstrating that retention rates correlated with molecular weight. Ciprofloxacin revealed the highest retention rate at 94.8%, whereas acetaminophen displayed the lowest at 29.1%, indicating that bigger molecules are maintained more effectively. Furthermore, in binary combinations, different chemicals influenced retention behavior. Sulfamethoxazole, exhibiting a negative charge at pH of 7, showed considerable retention due to electrostatic attraction to the negatively charged membrane, which became positive at pH of 5. This underscores the significance of electrostatic interactions in influencing retention rates across varying pH settings. Conversely, ciprofloxacin with a positive charge at pH 5 demonstrated reduced electrostatic interactions. The influence of pH on drug-membrane interactions highlights the complexity of charge-dependent separation mechanisms. **Fig. 6** summarizes the elimination procedure for ciprofloxacin and sulfamethoxazole (Cao et al., 2020).

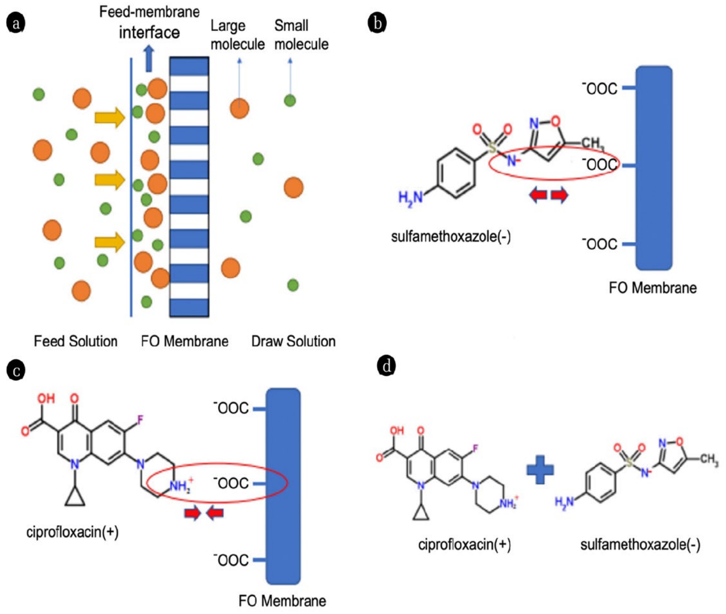

Figure 6: Various mechanisms on FO separation of binary trace pharmaceuticals: (a) collision between pharmaceutical molecules without charge; (b) repulsion between pharmaceutical molecule and membrane with the same charge; (c) attraction between pharmaceutical molecule and membrane with opposite charge; (d) attraction between pharmaceutical molecules with opposite charge (Cao et al., 2020).

Carbamazepine was removed from wastewater using a submerged membrane bioreactor that combined membrane filtration with activated sludge biodegradation (Cao et al., 2020). The removal efficiency for chemical oxygen demand ranged from 94.8% to 97.5%, while NH^{4+}-N exhibited a clearance rate of 93.6% to 99.4%. The elevated removal efficiencies underscore the effectiveness of integrated biological and membrane-based treatment methodologies. Carbamazepine was eliminated with an efficiency between 88.2% and 94.5%. Increased carbamazepine concentrations correlated with enhanced chemical oxygen demand and NH^{4+}-N removal; however, high levels adversely impacted both processes due to microbial suppression (Yao et al., 2020). The inhibitory impact is due to harmful interactions between the medication and microbial communities, requiring optimal concentration thresholds for treatment. The degradation of carbamazepine primarily resulted from oxidation, hydroxylation, and decarboxylation, with a specific bacterial species playing a crucial role. Research on the filtration of medical radioactive liquid waste indicated that pH exerted no significant influence on external concentration polarization (Lee et al., 2018). This indicates that additional physicochemical features, including ionic strength and membrane charge characteristics, may exert a more significant influence on filtration efficacy. Iodine was identified as the primary contaminant of concern in the management of radioactive liquid waste. FO achieved removal rates of up to 99.3%, successfully eliminating both natural and radioactive iodine. The efficacy of removal was primarily influenced by electrostatic repulsion at elevated pH levels, which hindered iodine-membrane interactions. Moreover, alterations in membrane surface characteristics and operating parameters affect the efficacy of iodine rejection, rendering forward osmosis a viable option for the treatment of radioactive wastewater.

Multiple factors influence pesticide retention in reverse osmosis (RO) membranes, such as molecular weight, steric hindrance, electrostatic interactions, and hydrophobicity (Ates et al., 2022). These factors collectively determine the efficiency and selectivity of membrane separation, impacting the removal rates of diverse contaminants. Notwithstanding its relatively low molecular weight, tributyl phosphate demonstrated strong rejection rates of 98–99% across three distinct RO membranes, which displayed similar NaCl rejection values (99.0–99.8%), indicating that removal was influenced by size exclusion and other mechanisms. The high rejection rates suggest that additional interactions, such as electrostatic repulsion and hydrophobic interactions, play a critical role in separation. Conversely, flutriafol, possessing a somewhat greater molecular weight and projection area, exhibited a reduced NaCl rejection rate of 99.0%, indicating that elements beyond steric exclusion substantially influenced its retention. The discrepancy in removal efficiency highlights the complexity of molecular transport mechanisms within the membrane matrix. Dicofol, the most substantial pesticide analyzed, exhibited significant rejection efficiency, underscoring the preeminent influence of size exclusion. The correlation between molecular size and rejection efficiency emphasizes the dominant role of steric hindrance in RO membrane performance. Pesticide retention in reverse osmosis membranes arises from a complicated interaction of several factors influencing their removal efficiency. Understanding these intricate interactions is essential for optimizing membrane design and operational parameters for enhanced contaminant removal.

The consistent removal across varying operational conditions signifies the robustness of RO membranes in mitigating the presence of ECs. The principal removal method was size exclusion, due to triclosan's considerable molecular weight and Stokes radius. Additionally, hydrophobic interactions between triclosan and membrane material could contribute to the enhanced retention efficiency. The removal of CECs was assessed utilizing a pressure-driven RO system at varying flux and recovery rates (Farrokh Shad et al., 2019). This approach allowed for a comprehensive evaluation of the effectiveness of RO membranes under practical operational conditions, ensuring the applicability of the findings to real-world scenarios. The research demonstrated that RO efficiently eliminated CECs, especially those with molecular weights exceeding 200 g/mol. The significant rejection of larger molecular weight compounds underscores the importance of steric exclusion in EC removal. Compounds having molecular weights between 100 and 560 g/mol demonstrated high rejection rates, whereas those below 300 g/mol showed diminished removal efficiency. The observed variations in rejection rates suggest that molecular structure, charge distribution, and membrane surface properties collectively influence separation performance. Elevated influent concentrations and pre-membrane pressures resulted in enhanced retention rates. Higher contaminant concentrations likely increase mass transfer resistance, thereby enhancing the effectiveness of the separation process. Negatively charged CECs were eliminated more effectively than neutral or positively charged counterparts, with total elimination surpassing 90%. The strong electrostatic interactions between negatively charged species and the charged membrane surface likely contribute to this enhanced removal efficiency. A comparative investigation of ibuprofen, carbamazepine, and triclosan elimination under varying water quality circumstances demonstrated an escalating retention rate during the RO process. The variability in the removal of ibuprofen and carbamazepine was mostly ascribed to variances in their molecular characteristics and the prevailing separation methods. The structural complexity of these pharmaceuticals influences their transport behavior within the membrane, affecting overall rejection rates. An optimization using factorial design at an initial concentration of 500 μg/L, pre-membrane pressure of 16 bar, and pH 10 achieved maximum removal efficiencies of 98.9%, 97.5%, and 99.0% for ibuprofen, carbamazepine, and triclosan, respectively (Liu et al., 2023). The high efficiency observed under these conditions demonstrates the potential for fine-tuning operational parameters to enhance CEC removal. A new reverse osmosis membrane including titania nanotubes was assessed for the removal of bisphenol A and caffeine at low concentrations ([94]. Incorporating nanomaterials into membrane structures enhances permeability while maintaining high rejection rates, offering an effective solution for addressing ECs. The study employed a thin-film nanocomposite membrane incorporating 0.01% titania nanotubes, resulting in improved permeability (50 L/m².h.bar for bisphenol A, 49 L/m².h.bar for caffeine) and elevated rejection rates (89.0% for bisphenol A, 97.9% for caffeine). The integration of nanomaterials improved the membrane's surface properties, thereby enhancing separation performance. Enhanced surface wettability and diminished surface roughness resulted in elevated water permeability and improved pollutant rejection. The increased hydrophilicity of the membrane contributed to reduced fouling potential, further improving its long-term operational efficiency. The membrane demonstrated significant antifouling properties owing to its improved hydrophilicity (Ahmad et al., 2022). These findings underscore the promising role of nanocomposite membranes in advanced water treatment applications.

Microfiltration (MF) is extensively utilized because it functions effectively at atmospheric pressure. The ability to operate under lower pressure conditions makes microfiltration a cost-effective and energy-efficient solution for water treatment applications. Nonetheless, microfiltration (MF) is inadequate for the removal of pollutants smaller than 1 μm, including dissolved solids, hence constraining its efficacy in addressing ECs (Rodríguez-Narváez et al., 2017). This limitation necessitates the integration of additional treatment technologies to ensure comprehensive EC removal. A previous study indicated that polyethersulfone microfiltration effectively eliminated 17β-estradiol from water (Niavarani et al., 2021). The successful removal of this endocrine-disrupting chemical highlights the potential of microfiltration for selective pollutant removal. The functionalization of membranes with hydrophilic amide groups markedly enhanced wettability, resulting in increased 17β-estradiol removal efficiency. Improved wettability reduces the likelihood of membrane fouling, thereby extending the operational lifespan of the filtration system. Hydrophobic ceramic microfiltration membranes derived from chromium-rich tannery waste demonstrated atrazine removal efficiency over 95% (Mukherjee et al., 2019). The high efficiency of these ceramic membranes suggests their applicability in treating pesticide-contaminated water sources. Investigations using ibuprofen as a model chemical demonstrated that retention rates in sericin-coated hollow fiber microfiltration membranes were influenced by feed flow rates (Verma and Subbiah, 2019). The relationship between flow rate and retention efficiency highlights the importance of optimizing process parameters for effective pollutant removal. Complete removal of ibuprofen was accomplished at reduced flow rates (5 L/h and 10 L/h) for designated filtered solution quantities (1750 mL and 750 mL, respectively). The increased residence time at lower flow rates allowed for enhanced interactions between ibuprofen molecules and the membrane surface. At elevated flow rates of 15 L/h and 20 L/h, the removal efficiency diminished due to reduced residence durations, which limited interactions between drug molecules and the membrane surface. These observations suggest that optimizing hydraulic conditions can significantly enhance pollutant retention in microfiltration systems. A separate study investigated the influence of membrane hydrophilicity on the efficacy of pollutant removal (Yun et al., 2023). These results reinforce the significance of material selection in optimizing microfiltration membrane performance for the removal of ECs.

Ultrafiltration (UF) has been widely applied to remove a broad range of ECs due to its smaller pore size compared to MF, typically ranging from 0.001 to 0.1 μm. However, its removal performance varies considerably depending on both the membrane material and the specific type of contaminant (Heo et al., 2012). For instance, studies on bisphenol A removal using UF membranes made of polysulfone and polyvinylidene showed differing efficiencies: the polysulfone membrane achieved about

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75% removal, while the polyvinylidene membrane reached up to 98% under experimental conditions (Heo et al., 2012; Melo-Guimarães et al., 2013). In another study, evaluated two phthalate acid derivatives—bis(2-ethylhexyl)phthalate and butylbenzyl phthalate—using a polyvinylidene fluoride UF membrane (100 kDa pore size), obtaining removal rates of 15% and 78%, respectively (Melo-Guimarães et al., 2013). In general, UF is more effective at removing polar, highly water-soluble ECs than non-polar, poorly soluble ones. Compounds such as hormone derivatives and organic acid-type contaminants (e.g., estrone, EE2, E2, diclofenac, and ketoprofen) tend to exhibit high removal efficiencies, whereas less polar substances like phthalate esters are removed less effectively (Melo-Guimarães et al., 2013).

Nanofiltration (NF) is an effective technique for removing ECs due to its relatively small pore size, typically between 10 and 100 Å. An additional advantage of NF is its operation at comparatively low feeding water pressures, which can reduce operational costs. Compared to UF, NF generally demonstrates higher removal efficiencies for certain contaminants (Lidén and Persson, 2015). For example, caffeine removal using UF ranges from 2–21%, whereas NF achieves significantly higher efficiencies of 46–84%, with a similar trend observed for ketorolac tromethamine (Rodríguez-Narváez et al., 2017). The performance of NF membranes is influenced by factors such as membrane properties and solution chemistry. At low pH, hydrophobic interactions dominate, resulting in high retention of sulfamethoxazole. As pH increases, electrostatic repulsion becomes more significant, enhancing the rejection of both compounds (Shah et al., 2022). Feed water pH also plays a critical role in NF performance. Studies on aromatic amine pollutants have shown that solute rejection varies with pH in both freshwater and brackish water systems. For example, NaCl rejection increases with pH due to stronger electrostatic exclusion caused by membrane charge, while lower rejection occurs under acidic conditions. Interestingly, the rejection behavior of aromatic amines does not always follow the same trend as simple electrolytes, indicating more complex separation mechanisms in NF compared to RO (Shah et al., 2022). In the case of ibuprofen enantiomers, both membrane surfaces and system components (e.g., stainless steel equipment) contribute to adsorption at pH values below the compound's pKa. Up to 23% of ibuprofen adsorption was observed on equipment surfaces, largely driven by the S-enantiomer, with further adsorption occurring on the membrane. This behavior follows the Freundlich and Langmuir isotherms for the equipment and the membrane, respectively. At pH of 4, NF retention ranged from 34.5% to 49.5%, with higher rejection of S-ibuprofen compared to the R-form. As pH increases, retention improves while adsorption effects diminish (Kim et al., 2024).

Membrane-based processes, including forward osmosis (FO), reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF), are increasingly recognized as effective approaches for maintaining water quality. The adsorption of CECs onto membranes is strongly influenced by their physicochemical characteristics, with hydrophobic interactions playing a dominant role, especially neutral compounds. Properties such as molecular weight and hydrophobicity are generally associated with improved rejection and adsorption performance. In addition, water quality parameters, including pH and solute concentration, significantly affect membrane efficiency and fouling behavior. Membrane characteristics and operational factors — such as draw solution selection and microbial activity — also play important roles in determining CEC removal and fouling dynamics. These interrelated factors underscore the importance of careful system design and optimization of operating conditions (Rodríguez-Narváez et al., 2017). Among these technologies, FO and RO have demonstrated particularly high efficiencies in removing a wide range of ECs. For instance, carbamazepine has been removed with efficiencies between 80% and 99%, while similar removal rates have been reported for caffeine using FO processes. Overall, only a limited number of ECs, such as acetaminophen, exhibit removal efficiencies below 50% when treated with FO or RO (Rodríguez-Narváez et al., 2017). Although the underlying mechanisms are not yet fully understood, some studies suggest that ionic contaminants tend to have a stronger affinity for membrane surfaces, leading to higher removal efficiencies compared to neutral compounds. This limited understanding highlights the need for further research, particularly in structure–response relationships of ECs across membranes with varying chemical compositions and physical properties, to better elucidate separation mechanisms and improve process performance (Kim et al., 2024).

5. BIOLOGICAL PROCESSES

Biological treatment is considered an eco-friendly method for wastewater treatment since it uses microorganisms instead of chemicals. Biological treatment approaches are essential for the degradation of ECs, with activated sludge systems being widely acknowledged for their effectiveness. Depending on the kind of pollutant, either aerobic or anaerobic treatment processes may be utilized, frequently in conjunction with tertiary treatment approaches (Zengel and Michel, 2013). While activated sludge is the predominant biological system employed, alternative biological methods such as soil filtration and biofiltration have been explored with encouraging results. The prevailing terminal electron-accepting conditions determine the efficacy of aerobic vs anaerobic routes. It was indicated that benzotriazoles undergo more efficient degradation under aerobic circumstances by natural attenuation mechanisms, whereas particular electron acceptors in the environment can influence biodegradability (Rodríguez-Narváez et al., 2017).

The research examined the removal of 39 common CECs via biological treatment in a wastewater treatment plant and an UF system (Ferreiro et al., 2020). No significant association was seen between ammonium concentration and CEC profiles in the influent. The degradation kinetics and biodegradability of specific chemicals determined their removal rates, with substances such as genistein, methylparaben, progesterone, testosterone, caffeine, and acetaminophen attaining elimination rates exceeding 99.5%. In contrast, irbesartan, carbamazepine, diuron, and phenytoin demonstrated clearance rates under 20.0%. Wastewater with CEC values surpassing 1500 ng/L obtained removal efficiencies exceeding 80% (Ferreiro et al., 2020). The study investigated the function of soil microorganisms in the breakdown of endocrine disruptors, revealing that estradiol derivatives were more efficiently destroyed than ibuprofen and triclosan (Carr et al., 2011). The researchers determined that saturated soil conditions facilitated biodegradation more effectively than unsaturated circumstances. A compelling biological method entails biofiltration with Daphnia magna as the degrading agent (Matamoros et al., 2012).

Anaerobic treatment has been utilized for the removal of endocrine disruptors, attaining removal efficiencies of 60–90% for both natural and synthetic estrogens, along with nonylphenol derivatives, under mesophilic and thermophilic settings (Paterakis et al., 2012). A significant constraint of biological treatment approaches is the challenge of detecting and quantifying ECs in intricate wastewater matrices, highlighting the need for improvements in analytical techniques (Rodríguez-Narváez et al., 2017). In the majority of traditional wastewater treatment facilities, biological processes are essential for the breakdown of pharmaceuticals. Anaerobic treatment methods are suggested as economical, low-energy solutions because of their capacity to manage high organic loads (Khadir et al., 2020). Research on the anaerobic breakdown of sulfamethoxazole-laden wastewater is limited, and the long-term cost-effectiveness of up-flow anaerobic sludge systems is still questionable. **Table 6** delineates the effectiveness of biological mechanisms in eliminating CECs.

Table 6: Removal efficiency of ECs using biological processes

Type	System	EC	Removal efficiency, %	Reference
Anaerobic digestion	Activated Sludge	Estrone	79	(Paterakis, et al., 2012)
		Estriol	45	
		Estrone-3-Sulfate	36	
		17β-Ethinyl estradiol	34	
		Mono- and diethoxylated nonylphenol	88	
		Polyethoxylated Nonylphenols	66	
Aerobic and anaerobic	Activated Sludge	Bezafibrate	19–80	(Sui et al., 2011)

Table 6(Cont.): Removal efficiency of ECs using biological processes

		Caffeine	78–100	
		N,*N*-diethyl-meta-toluamide	23–30	
		Trimethoprim	38–55	
		Naproxen	97–100	
Aerobic	Soil Filtration	Estrogens	26	(Carr et al., 2011)
		17β-Estradiol	99	
		17β-Ethinyl estradiol	27	
		Triclosan	90	
		Ibuprofen	18	
Aerobic	Biological Filtration	Cashmeran	68	(Matamoros et al., 2012)
		Ibuprofen	86	
		Benzothiazole, 2-(methylthio)-	66	
		Tributyl phosphate	22	
		Methyl dihydrojasmonate	97	
		Tri(2-chloroethyl) phosphate	2	
		Diazone	8	
		Caffeine	49	
		Galaxolide	89	
		Tonalide	90	
		Terbutryn	94	
		Carbamazepine	5	
		Naproxen	72	
		Oxybenzone	89	
		Triclosan	87	
		Ketoprofen	99	
		Diclofenac	93	
Aerobic	Activated sludge	Salicylic acid	97	(Melo-Guimarães et al., 2013)
		Naproxen	75	
		Diclofenac	75	
		Gemfibrozil	70	
		Ibuprofen	83	
		2,4-D	>60	
		Carbamazepine	9	
		Ketoprofen	71	
		DEHP	46	
		4-Nonylphenol	53	
		Buthylbenzylphthalate	72	
		Bisphenol-A	84	
		Triclosan	41	
		Estrone	>95	
		EE2	>93	
		17β-Ethinyl estradiol	>96	

6. ADVANCED OXIDATION PROCESSES

Advanced oxidation processes (AOPs) offer a novel solution for water treatment, characterized by their high efficacy, wide applicability, and capacity to transform pollutants into non-toxic byproducts. These techniques produce hydroxyl radicals (-OH) and, in certain instances, sulfate radicals, referred to as HR-AOPs and SR-AOPs, respectively. These radicals exhibit great reactivity and can decompose a broad range of water contaminants (Deng and Ezyske, 2011). **Fig. 7** depicts the diverse AOP methodologies employed for the degradation of contaminants. The Fenton reaction (Fe^{2+}/H_2O_2) is among the earliest and most well-investigated techniques for the production of hydroxyl radicals (Fenton, 1894).

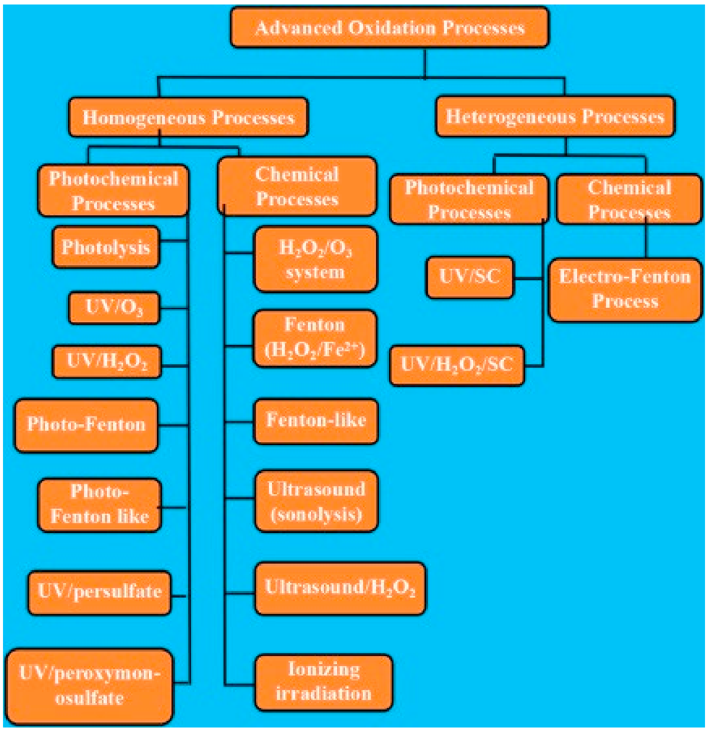

Figure 7: Types of advanced oxidation processes widely applied for water and wastewater treatments.

Photolytic therapies employing UV light have been extensively investigated for the degradation of chlorinated and nitrated aromatics, phenols, halogenated aliphatics, and other industrial effluents. The styudy examined the photodegradation of contaminants of emerging concern, including benzotriazole, chlorophene, N, N-diethyl-m-toluamide, methylindole, and nortriptyline HCl, under 254 nm ultraviolet light (Benítez et al., 2013). Their findings demonstrated first-order kinetics, with degradation rates affected by molecule structure and starting pH conditions. The degradation hierarchy was determined as CF > ML > BZ > NH > DT, with corresponding rate constants of 0.094, 0.397, 0.063, 0.197, and 0.153 min^{-1}, respectively, at a pH of 7. Analysis investigated the photolytic degradation of pharmaceutical pollutants, including acetaminophen, ibuprofen, diclofenac, and sulfamethoxazole, using UV-LED irradiation (E Eskandarian et al., 2016). Shorter wavelengths demonstrated greater efficacy, adhering to the hierarchy UV-C > UV-B > UV-A. At natural pH levels, the degradation efficiencies for SMX, DCF, IBP, and ACT at 365 nm UV-A were 6%, 20%, 20%, and 20%, respectively, after a period of 180 minutes. Analysis investigated the photodegradation of amoxicillin as well as ampicillin in river water, emphasizing their vulnerability to UV degradation in environmental settings (Arsand et al., 2018). The UV/H_2O_2 technique has been thoroughly reported for the elimination of organic pollutants from water environments. Researchers investigated the elimination of estrogens, specifically estrone (E_1), β-estradiol (E_2), and 17α-ethinylestradiol (EE_2), using UV/H_2O_2 treatment in aqueous solutions (Cédat et al., 2016). The findings indicated that UV/H_2O_2 markedly improved the breakdown of these estrogens, which were initially at a concentration of 5 µM. At neutral pH, almost 90% of the target estrogens were removed at a H_2O_2 concentration of 90 mg/L with an energy dosage of 1000 mJ/cm^2. Evaluated the efficacy of removing pharmaceutical contaminants, including diclofenac, sulfamethoxazole, carbamazepine, and trimethoprim, by UV and UV/H_2O_2 treatments (Alharbi et al., 2017). Their research indicated that DCF (5 mg/L) and SMX (5 mg/L) exhibited significant susceptibility to UV irradiation at natural pH, resulting in destruction within 8 minutes under a low-pressure mercury UV lamp (254 nm). Garcia-Segura et al. [118] examined electrochemical AOPs employing boron-doped diamond electrodes for the degradation of 29 pharmaceuticals and pesticides, such as ibuprofen and metolachlor, in secondary effluents at microgram per liter (µg/L) concentrations. The nearly full mineralization of pollutants was accomplished by the production of hydroxyl radicals (•OH) at the boron-doped diamond surface. At pH of 3, total elimination of ibuprofen and metolachlor was accomplished with a continuous current of 98 or 196 A/m^2 during a duration of 24 hours. The degradation efficiency at pH of 7 was reduced under the same conditions. utilized boron-doped diamond electrodes for the electrocatalytic degradation of bisphenol A, nonylphenol, and triclosan (Barrios et al., 2016). At a current density of 28.5 mA/cm^2, degradation efficiencies of 51%, 69%, and 63% were attained for BPA (194.3 ng/L), nonylphenol (1583 ng/L), and triclosan (1193 ng/L), respectively, at pH of 6.6 during a duration of 180 minutes.

7. RISK ASSESSMENT AND MANAGEMENT OF CECS

CECs present considerable risks to human health and the environment. The most successful strategy for alleviating these hazards entails the establishment of environmental standards and the execution of thorough risk assessments. Water quality standards have been defined for pesticides. Nonetheless, numerous obstacles endure in CEC risk management due to inadequate regulatory frameworks and monitoring. The absence of national chemical rules hinders effective control actions, leading to variations in pollutant prioritization and risk assessment. Furthermore, the restricted availability of resources and technical infrastructure hinders the effective management of CECs. Notwithstanding their global importance, existing environmental quality and industrial discharge regulations insufficiently address CECs. Mitigating CEC pollution necessitates immediate legislative action, targeted regulatory measures, and augmented research efforts. Essential actions encompass establishing pollutant thresholds, executing focused monitoring initiatives, and amalgamating scientific research with technological advancements for the concurrent treatment of CECs and traditional pollutants. Addressing CEC pollution is a complex issue that links with social and economic development, the sustainability of the environment, and public health. A sustained, methodical strategy is essential for enhancing environmental quality and realizing a holistic green transition in economic and social domains.

AOPs are at a pivotal point, offering potential for future applications. Although many AOPs are economically viable to execute, their operational costs, encompassing chemical and energy usage, remain elevated. The generation of disinfection by-products in specific AOPs generates apprehensions among researchers and regulatory agencies, hindering their broad implementation. The efficient management of residual oxidants, including H_2O_2, persulfate, and peroxymonosulfate, as well as the recovery of photocatalysts, continues to pose a considerable challenge. Optimizing reactor design is a crucial element frequently overlooked in studies on AOP-based wastewater treatment. Achieving consistent irradiation and mitigating mass transfer restrictions in ozone-based systems are crucial for enhancing process efficiency. Lowering treatment expenses will improve the viability of AOPs in the water treatment sector. The use of renewable energy sources, like solar photocatalysis, constitutes a sustainable method for decreasing operational expenses. Furthermore, utilizing AOPs as a pre-treatment measure to augment the biodegradability of refractory pollutants can boost their eventual degradation in standard wastewater treatment systems. The advancement of economical, stable, and reusable catalytic materials will augment the economic feasibility of advanced oxidation processes in environmental applications.

Overseeing traditional biological degradation processes requires meticulous management of the biosolids produced by activated sludge systems. The complex composition of the biosolids matrix and the absence of analytical techniques for the extraction, separation, and characterization of ECs in this medium have created a substantial knowledge gap concerning the presence of these pollutants. Prior studies have shown that hydrophobic and persistent ECs, including flame retardants, polybrominated diphenyl ethers, and antimicrobial compounds, can persist in biosolids after biological treatment (Noguera-Oviedo et al., 2016). Conventional biosolid processing generally entails dewatering and volume reduction, rendering these residues a significant source of ECs in the environment, since they can progressively leach and pollute soil and aquatic systems post-disposal. Additional investigation into the identification and measurement of metabolites and transformation products is highly significant. Biological degradation can result in the creation of transformation products that may maintain residual bioactivity or, in certain instances, demonstrate increased toxicity compared to the parent chemicals. The discharge of these derivatives into the environment during processing steps is a significant concern, as certain byproducts may remain undetected owing to conjugation mechanisms, which can subsequently be reversed under environmental conditions, resulting in the formation of stable compounds with increased ecotoxicity. Biological treatment, especially at elevated temperatures and prolonged hydraulic retention times, has been associated with the heightened production of perfluoroalkyl acid derivatives, such as perfluorooctanoic acid and perfluorooctanesulfonic acid, in comparison to chemically assisted primary treatment. Therefore, in addition to quantifying parent chemicals, it is crucial to assess the toxicity and residual bioactivity of the treated effluent. Future research in membrane technology should prioritize the advancement of surface modifications to improve selectivity and fouling resistance, investigate innovative materials and nanotechnology applications for membrane fabrication, optimize operational conditions to increase energy efficiency, and evaluate the long-term environmental sustainability of membrane-based water purification systems. A thorough investigation of environmental and economic impacts via lifecycle assessment studies is essential to evaluate the viability of membrane-based treatment methods relative to traditional treatments. A comprehensive study of the economic feasibility of membrane technologies will yield insights into their enduring impacts on resource management, energy utilization, and waste production. Furthermore, analyzing the impact of improvements in membrane technology on regulatory rules and compliance frameworks is crucial. Evaluating the probable influence of technological advancement on regulatory standards will enable the foresight and adjustment of future regulations. Ongoing research and innovation in these domains will further improve the sustainability and efficacy of membrane-based technology in tackling the issues presented by ECs in aquatic environments.

8. CONCLUSIONS

The progression of wastewater treatment via innovative and enhanced methods has become a vital focus in water resource management. The incorporation of wastewater treatment into sanitation policies and economic frameworks is progressing rapidly. The reclamation and reuse of treated wastewater are becoming significant, with numerous new strategies involving risk-based management and the application of decision support systems alongside the most advanced technology being investigated. The features of wastewater might differ based on factors such as source, geographic location, and seasonal variations. Due to the swift advancement of novel treatment techniques, there is an urgent requirement for sustainable solutions that guarantee long-term wastewater management while reducing operational expenses. Improving the efficacy of certain treatment systems for the elimination of ECs from industrial and municipal wastewater is a primary objective. A variety of treatment methods, encompassing biological, advanced oxidation, and physicochemical processes, are accessible. Nonetheless, these approaches encounter obstacles with economic viability, environmental sustainability, and the creation of novel ECs, some of which may produce transformation products with greater toxicity than their precursor molecules. Thus, the implementation of integrated treatment methods seems to be the most efficacious method for addressing the constraints linked to single-treatment modalities. Notwithstanding their potential, phase-change techniques for wastewater treatment, such as electrocoagulation removal, are still underexploited. Nonetheless, these methods may still function as effective pre-concentration techniques prior to their incorporation into multi-step treatment processes to improve pollutant removal efficiency. Future synergistic strategies focused on creating autonomous and resilient treatment options for the reduction or elimination of newly recognized environmental contaminants may be crucial for maintaining water quality and safeguarding ecosystems.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

While preparing this manuscript, the authors employed ChatGPT to enhance the readability and improve the grammatical accuracy of certain sections and sentences. The use of ChatGPT is only to assist in the refinement of the text and language; we do not use ChatGPT to supplant any essential tasks.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Ahmad, N. A., Goh, P. S., Azman, N., Ismail, A. F., Hasbullah, H., Hashim, N., et al., 2022. Enhanced removal of endocrine-disrupting compounds from wastewater using reverse osmosis membrane with titania nanotube-constructed nanochannels. Membranes, 12, 958. https://doi.org/10.3390/membranes12100958

Ahmed, M. J., and Theydan, S. K., 2012. Adsorption of cephalexin onto activated carbons from Albizia lebbeck seed pods by microwave-induced KOH and K_2CO_3 activations. Chemical Engineering Journal, Pp. 211–212, 200–207. https://doi.org/10.1016/j.cej.2012.09.089

Alharbi, S. K., Kang, J., Nghiem, L. D., van de Merwe, J. P., Leusch, F. D. L., and Price, W. E., 2017. Photolysis and UV/H_2O_2 of diclofenac, sulfamethoxazole, carbamazepine, and trimethoprim: Identification of their major degradation products by ESI–LC–MS and assessment of the toxicity of reaction mixtures. Process Safety and Environmental Protection, 112, 222–234. https://doi.org/10.1016/j.psep.2017.07.015.

AL-Othman, Z. A., Ali, R., and Naushad, M., 2012. Hexavalent chromium removal from aqueous medium by activated carbon prepared from peanut shell: Adsorption kinetics, equilibrium and thermodynamic studies. Chemical Engineering Journal, 184, Pp. 238–247. https://doi.org/10.1016/j.cej.2012.01.048

Anh Tuan, H., Minh Quang, C., and Quang Binh, L., 2020. Parameters affecting fiber quality and productivity of coir spinning machines. Journal of Mechanical Engineering Research and Developments, 43, Pp. 122–145.

Antunes, E., Vuppaladadiyam, A. K., Sarmah, A. K., Varsha, S. S. V., Pant, K. K., Tiwari, B., et al., 2021. Application of biochar for emerging contaminant mitigation. In Advances in Environmental Pollution Management, Pp. 65–91. https://doi.org/10.1016/bs.apmp.2021.08.003

Archer, E, Petrie, B., Kasprzyk-Hordern, B., Wolfaardt, G.M., 2017. The fate of pharmaceuticals and personal care products (PPCPs), endocrine disrupting contaminants (EDCs), metabolites and illicit drugs in a WWTW and environmental waters. Chemosphere 2017;174: Pp. 437–46. https://doi.org/10.1016/j.chemosphere.2017.01.101.

Arsand, J. B., Hoff, R. B., Jank, L., Meirelles, L. N., Díaz-Cruz, M. S., Pizzolato, T. M., et al., 2018. Transformation products of amoxicillin and ampicillin after photolysis in aqueous matrices: Identification and kinetics. Science of the Total Environment, 642, Pp. 954–967. https://doi.org/10.1016/j.scitotenv.2018.06.122.

Ates, N., Uzal, N., Yetis, U., and Dilek, F. B., 2022. Removal of pesticides from secondary treated urban wastewater by reverse osmosis. Environmental Science and Pollution Research, 30, Pp. 8732–8745. https://doi.org/10.1007/s11356-022-20077-5.

Baccar, R., Sarrà, M., Bouzid, J., Feki, M., and Blánquez, P., 2012. Removal of pharmaceutical compounds by activated carbon prepared from agricultural by-product. Chemical Engineering Journal, 211–212, Pp. 310–317. https://doi.org/10.1016/j.cej.2012.09.099

Bagnis, S., Boxall, A., Gachanja, A., Fitzsimons, M., Murigi, M., Snape, J., et al.,

2020. Characterization of the Nairobi River catchment impact zone and occurrence of pharmaceuticals: Implications for an impact zone inclusive environmental risk assessment. Science of the Total Environment, 703, 134925. https://doi.org/10.1016/j.scitotenv.2019.134925.

Barrios, J. A., Cano, A., Becerril, J. E., and Jiménez, B., 2016. Influence of solids on the removal of emerging pollutants in electrooxidation of municipal sludge with boron-doped diamond electrodes. Journal of Electroanalytical Chemistry, 776, Pp. 148–151. https://doi.org/10.1016/j.jelechem.2016.07.018

Benítez, F. J., Acero, J. L., Real, F. J., Roldán, G., and Rodríguez, E., 2013. Photolysis of model emerging contaminants in ultra-pure water: Kinetics, by-products formation and degradation pathways. Water Research, 47(3), Pp. 870–880. https://doi.org/10.1016/j.watres.2012.11.016.

Bernal-Romero del Hombre Bueno, M. de los Á., Boluda-Botella, N., and Prats-Rico, D., 2019. Removal of emerging pollutants in water treatment plants: Adsorption of methyl and propylparaben onto powdered activated carbon. Adsorption, 25, Pp. 983–999. https://doi.org/10.1007/s10450-019-00120-7

Bilal, M., Adeel, M., Rasheed, T., Zhao, Y., and Iqbal, H. M. N., 2019. Emerging contaminants of high concern and their enzyme-assisted biodegradation – A review. Environment International, 124, Pp. 336–353. https://doi.org/10.1016/j.envint.2019.01.011.

Borgert, C. J., Quill, T. F., McCarty, L. S., and Mason, A. M., 2004. Can mode of action predict mixture toxicity for risk assessment? Toxicology and Applied Pharmacology, 201, Pp. 85–96. https://doi.org/10.1016/j.taap.2004.05.005.

Cabrita, I., Ruiz, B., Mestre, A. S., Fonseca, I. M., Carvalho, A. P., and Ania, C. O., 2010. Removal of an analgesic using activated carbons prepared from urban and industrial residues. Chemical Engineering Journal, 163, Pp. 249–255. https://doi.org/10.1016/j.cej.2010.07.058

Cao, D.-Q., Yang, X.-X., Yang, W.-Y., Wang, Q.-H., and Hao, X.-D., 2020. Separation of trace pharmaceuticals individually and in combination via forward osmosis. Science of the Total Environment, 718, 137366. https://doi.org/10.1016/j.scitotenv.2020.137366.

Carabineiro, S. A. C., Thavorn-Amornsri, T., Pereira, M. F. R., and Figueiredo, J. L., 2011. Adsorption of ciprofloxacin on surface-modified carbon materials. Water Research, 45, Pp. 4583–4591. https://doi.org/10.1016/j.watres.2011.06.008.

Carabineiro, S. A. C., Thavorn-Amornsri, T., Pereira, M. F. R., Serp, P., and Figueiredo, J. L., 2012. Comparison between activated carbon, carbon xerogel and carbon nanotubes for the adsorption of the antibiotic ciprofloxacin. Catalysis Today, 186, Pp. 29–34. https://doi.org/10.1016/j.cattod.2011.08.020.

Carr, D. L., Morse, A. N., Zak, J. C., and Anderson, T. A., 2011. Biological degradation of common pharmaceuticals and personal care products in soils with high water content. Water, Air, and Soil Pollution, 217, Pp. 127–134. https://doi.org/10.1007/s11270-010-0573-z.

Cédat, B., de Brauer, C., Métivier, H., Dumont, N., and Tutundjan, R., 2016. Are UV photolysis and UV/H_2O_2 process efficient to treat estrogens in waters? Chemical and biological assessment at pilot scale. Water Research, 100, Pp. 357–366. https://doi.org/10.1016/j.watres.2016.05.040

Chang, B.-V., Liu, J.-H., and Liao, C.-S., 2014. Aerobic degradation of bisphenol-A and its derivatives in river sediment. Environmental Technology, 35, Pp. 416–424. https://doi.org/10.1080/09593330.2013.831111

Chau, M. Q., Nguyen, D. C., Hoang, A. T., Tran, Q. V., and Pham, V. V., 2020. A numeral simulation determining optimal ignition timing advance of SI engines using 2,5-dimethylfuran–gasoline blends. International Journal of Advanced Science and Engineering Information Technology, 10, Pp. 1933–1938. https://doi.org/10.18517/ijaseit.10.5.13051.

Chau, M. Q., Truong, T. T., Hoang, A. T., and Le, T. H., 2025. Oil spill cleanup by raw cellulose-based absorbents: A green and sustainable approach. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 47, Pp. 8269–8282. https://doi.org/10.1080/15567036.2021.1928798

Chen, B., Chen, Z., and Lv, S., 2011. A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. Bioresource Technology, 102, Pp. 716–723. https://doi.org/10.1016/j.biortech.2010.08.067.

Chen, M., Qiang, L., Pan, X., Fang, S., Han, Y., and Zhu, L., 2015. In vivo and in vitro isomer-specific biotransformation of perfluorooctane sulfonamide in common carp (Cyprinus carpio). Environmental Science and Technology, 49, Pp., 13817–13824. https://doi.org/10.1021/acs.est.5b00488.

Cho, H.-H., Huang, H., and Schwab, K., 2011. Effects of solution chemistry on the adsorption of ibuprofen and triclosan onto carbon nanotubes. Langmuir, 27, Pp. 12960–12967. https://doi.org/10.1021/la202459g

Cleuvers, M., 2003. Aquatic ecotoxicity of pharmaceuticals including the assessment of combination effects. Toxicology Letters, 142, Pp. 185–194. https://doi.org/10.1016/S0378-4274(03)00068-7.

Corsini, E., Luebke, R. W., Germolec, D. R., and DeWitt, J. C., 2014. Perfluorinated compounds: Emerging POPs with potential immunotoxicity. Toxicology Letters, 230, Pp. 263–270. https://doi.org/10.1016/j.toxlet.2014.01.038.

de Andrade, J. R., Oliveira, M. F., da Silva, M. G. C., and Vieira, M. G. A., 2018. Adsorption of pharmaceuticals from water and wastewater using nonconventional low-cost materials: A review. Industrial and Engineering Chemistry Research, 57, Pp. 3103–3127. https://doi.org/10.1021/acs.iecr.7b05137

Deng, Y., and Ezyske, C. M., 2011. Sulfate radical-advanced oxidation process (SR-AOP) for simultaneous removal of refractory organic contaminants and ammonia in landfill leachate. Water Research, 45(19), Pp. 6189–6194. https://doi.org/10.1016/j.watres.2011.09.015

E Eskandarian, M. R., Choi, H., Fazli, M., and Rasoulifard, M. H., 2016. Effect of UV-LED wavelengths on direct photolytic and TiO_2 photocatalytic degradation of emerging contaminants in water. Chemical Engineering Journal, 300, Pp. 414–422. https://doi.org/10.1016/j.cej.2016.05.049.

Enyoh, C. E., Verla, A. W., Qingyue, W., Ohiagu, F. O., Chowdhury, A. H., Enyoh, E. C., et al., 2020. An overview of emerging pollutants in air: Method of analysis and potential public health concern from human environmental exposure. Trends in Environmental Analytical Chemistry, 28, e00107. https://doi.org/10.1016/j.teac.2020.e00107

Farrokh Shad, M., Juby, G. J. G., Delagah, S., and Sharbatmaleki, M., 2019. Evaluating occurrence of contaminants of emerging concerns in MF/RO treatment of primary effluent for water reuse – Pilot study. Journal of Water Reuse and Desalination, 9, Pp. 350–371. https://doi.org/10.2166/wrd.2019.004.

Feizi, F., Reguyal, F., Antoniou, N., Zabaniotou, A., and Sarmah, A. K., 2020. Environmental remediation in circular economy: End of life tyre magnetic pyrochars for adsorptive removal of pharmaceuticals from aqueous solution. Science of the Total Environment, 739, 139855. https://doi.org/10.1016/j.scitotenv.2020.139855.

Fenton, H. J. H., 1894. LXXIII.—Oxidation of tartaric acid in presence of iron. Journal of the Chemical Society, Transactions, 65, Pp. 899–910.

Ferreiro, C., Gómez-Motos, I., Lombraña, J. I., de Luis, A., Villota, N., Ros, O., et al., 2020. Contaminants of emerging concern removal in an effluent of wastewater treatment plant under biological and continuous mode ultrafiltration treatment. Sustainability, 12(2), Pp. 725. https://doi.org/10.3390/su12020725

Gani, K. M., Hlongwa, N., Abunama, T., Kumari, S., and Bux, F., 2021. Emerging contaminants in South African water environment: A critical review of their occurrence, sources and ecotoxicological risks. Chemosphere, 269, Pp. 128737. https://doi.org/10.1016/j.chemosphere.2020.128737.

García-Fernández, A. J., Espín, S., Gómez-Ramírez, P., Sánchez-Virosta, P., and Navas, I., 2021. Water quality and contaminants of emerging concern (CECs). In Chemometrics, Cheminformatics and Aquatic Toxicology, Pp. 1–21.

García-Segura, S., Keller, J., Brillas, E., and Radjenović, J., 2015. Removal of organic contaminants from secondary effluent by anodic oxidation with a boron-doped diamond anode as tertiary treatment. Journal of Hazardous Materials, 283, Pp. 551–557. https://doi.org/10.1016/j.jhazmat.2014.10.003

Golovko, O., Örn, S., Sörengård, M., Frieberg, K., Nassazzi, W., Lai, F. Y., et al., 2021. Occurrence and removal of chemicals of emerging concern in wastewater treatment plants and their impact on receiving water systems. Science of the Total Environment, 754, 142122. https://doi.org/10.1016/j.scitotenv.2020.142122.

Gumbi, B. P., Moodley, B., Birungi, G., and Ndungu, P. G., 2017. Detection and quantification of acidic drug residues in South African surface water using gas chromatography-mass spectrometry. Chemosphere, 168, Pp. 1042–1050. https://doi.org/10.1016/j.chemosphere.2016.10.105.

Heo, J., Flora, J. R. V., Her, N., Park, Y. G., Cho, J., Son, A., et al., 2012. Removal of bisphenol A and 17β-estradiol in single-walled carbon nanotubes–ultrafiltration (SWNTs–UF) membrane systems. Separation and Purification Technology, 90, Pp. 39–52. https://doi.org/10.1016/j.seppur.2012.02.007

Hoang, A. T., and Pham, X. D., 2021. An investigation of remediation and recovery of oil spill and toxic heavy metal from maritime pollution by a new absorbent material. Journal of Marine Engineering and Technology, 20, Pp. 159–169. https://doi.org/10.1080/20464177.2018.1544401

Hoang, A. T., Goldfarb, J. L., Foley, A. M., Lichtfouse, E., Kumar, M., Xiao, L., et al., 2022. Production of biochar from crop residues and its application for anaerobic digestion. Bioresource Technology, 363, 127970. https://doi.org/10.1016/j.biortech.2022.127970.

Hoang, A. T., Kumar, S., Lichtfouse, E., Cheng, C. K., Varma, R. S., Senthilkumar, N., et 2022. Remediation of heavy metal polluted waters using activated carbon from lignocellulosic biomass: An update of recent trends. Chemosphere, 302, 134825. https://doi.org/10.1016/j.chemosphere.2022.134825.

Hoang, A. T., Le, V. V., Al-Tawaha, A. R. M. S., Nguyen, D. N., Noor, M. M. et al., 2018). An absorption capacity investigation of new absorbent based on polyurethane foams and rice straw for oil spill cleanup. Petroleum Science and Technology, 36, Pp. 361–370. https://doi.org/10.1080/10916466.2018.1425722

Hoang, A. T., Nguyen, T. H., and Nguyen, H. P., 2024. Scrap tire pyrolysis as a potential strategy for waste management pathway: A review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46, Pp. 6305–6322. https://doi.org/10.1080/15567036.2020.1745336

Hoang, A. T., Nguyen, T. H., and Nguyen, H. P., 2024. Scrap tire pyrolysis as a potential strategy for waste management pathway: A review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46, Pp. 6305–6322. https://doi.org/10.1080/15567036.2020.1745336.

Hoang, A. T., Nguyen, X. P., Duong, X. Q., and Huynh, T. T., 2021. Sorbent-based devices for the removal of spilled oil from water: A review. Environmental Science and Pollution Research, 28, Pp. 28876–28910. https://doi.org/10.1007/s11356-021-13775-z.

Hoang, A. T., Nižetić, S., Cheng, C. K., Luque, R., Thomas, S., Banh, T. L., et al., 2022. Heavy metal removal by biomass-derived carbon nanotubes as a greener environmental remediation: A comprehensive review. Chemosphere, 287, 131959. https://doi.org/10.1016/j.chemosphere.2021.131959

Hoang, A. T., Nizetic, S., Ong, H. C., Chong, C. T., Atabani, A. E., and Pham, V. V., 2021. Acid-based lignocellulosic biomass biorefinery for bioenergy production: Advantages, application constraints, and perspectives. Journal of Environmental Management, 296, 113194. https://doi.org/10.1016/j.jenvman.2021.113194.

Hsieh, S., Lin, P.-Y., Lin, I.-H., Beck, D. E., and Lin, C.-H., 2023. Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022. Heliyon, 9, e13976.

Huynh, D. N. L., Nguyen, X. P., Pham, N. D. K., Le, T. T., Tran, X. T., Saengsupavanich, C., and Hoang, A. T., 2026. Booms and skimmers for oil spill recovery: Perspective analysis from lab scale to practical applications. Marine Pollution Bulletin, 224, 119128. https://doi.org/10.1016/j.marpolbul.2025.119128.

Israel Dikobe, P., Tekere, M., Masindi, V., and Foteinis, S., 2024. Occurrence, persistence, and removal of contaminants of emerging concern through drinking water treatment processes: A case study in South Africa. Environmental Nanotechnology, Monitoring & Management, 22, 100997. https://doi.org/10.1016/j.enmm.2024.100997.

Jacob, R. S., Santos, L. V. de S., de Souza, A. F. R., and Lange, L. C., 2016. A toxicity assessment of 30 pharmaceuticals using Aliivibrio fischeri: A comparison of the acute effects of different formulations. Environmental Technology, 37, Pp. 2760–2767. https://doi.org/10.1080/09593330.2016.1164249

Jelita, R., Jefriadi, Irawan, C., Putra, M. D., Hafiz, M., Anggreini, I., et al., 2022. Palm oil shell pyrolysis: Temperature effect, kinetics, and thermodynamics study. International Journal of Advanced Science and Engineering Information Technology, 12, Pp. 2513–2518. https://doi.org/10.18517/ijaseit.12.6.16088

Jeong, C. Y., Wang, J. J., Dodla, S. K., Eberhardt, T. L., and Groom, L., 2012. Effect of biochar amendment on tylosin adsorption–desorption and transport in two different soils. Journal of Environmental Quality, 41, Pp. 1185–1192. https://doi.org/10.2134/JEQ2011.0166.

Ji, L., Chen, W., Bi, J., Zheng, S., Xu, Z., Zhu, D., et al., 2010. Adsorption of tetracycline on single-walled and multi-walled carbon nanotubes as affected by aqueous solution chemistry. Environmental Toxicology and Chemistry, 29, Pp. 2713–2719. https://doi.org/10.1002/etc.350

Ji, L., Chen, W., Bi, J., Zheng, S., Xu, Z., Zhu, D., et al., 2010. Adsorption of tetracycline on single-walled and multi-walled carbon nanotubes as affected by aqueous solution chemistry. Environmental Toxicology and Chemistry, 29, Pp. 2713–2719. https://doi.org/10.1002/etc.350

Johnson, D. J., Suwaileh, W. A., Mohammed, A. W., and Hilal, N., 2018. Osmotic's potential: An overview of draw solutes for forward osmosis. Desalination, 434, Pp. 100–120. https://doi.org/10.1016/j.desal.2017.09.017.

Kar, S., Roy, K., and Leszczynski, J., 2018. Impact of pharmaceuticals on the environment: Risk assessment using QSAR modeling approach. In Computational Toxicology: Methods and Applications, Pp. 395–443. Springer. https://doi.org/10.1007/978-1-4939-7899-1_19.

Khadir, A., Mollahosseini, A., Negarestani, M., and Mardy, A., 2020. Anaerobic biotechnology for the treatment of pharmaceutical compounds and hospital wastewaters. In Methods in Bioremediation of Water and Wastewater Pollution Pp. 61–84.

Khan, S., Naushad, M., Govarthanan, M., Iqbal, J., and Alfadul, S. M., 2022. Emerging contaminants of high concern for the environment: Current trends and future research. Environmental Research, 207, 112609. https://doi.org/10.1016/j.envres.2021.112609

Kim, S., Jun, B.-M., Jung, B., Park, C. M., Jang, M., Nam, S.-N., et al., 2024. Removal of contaminants of emerging concern by membranes in water and wastewater: An updated review. Environmental Engineering Research, 30, 240103–0. https://doi.org/10.4491/eer.2024.103

Kleywegt, S., Pileggi, V., Yang, P., Hao, C., Zhao, X., Rocks, C., et al., 2011. Pharmaceuticals, hormones and bisphenol A in untreated source and finished drinking water in Ontario, Canada—Occurrence and treatment efficiency. Science of the Total Environment, 409, Pp. 1481–1488. https://doi.org/10.1016/j.scitotenv.2011.01.010.

Le, A. T., Pandey, A., Sirohi, R., Sharma, P., Chen, W.-H., Pham, N. D. K., and others. (2023). Precise prediction of biochar yield and proximate analysis by modern machine learning and SHapley additive exPlanations. Energy and Fuels, 37, 17310–17327. https://doi.org/10.1021/acs.energyfuels.3c02868.

Lee, K.-T., Tsai, J.-Y., Hoang, A. T., Chen, W.-H., Gunarathne, D. S., Tran, K.-Q., et al., 2022. Energy-saving drying strategy of spent coffee grounds for co-firing fuel by adding biochar for carbon sequestration to approach net zero. Fuel, 326, 124984. https://doi.org/10.1016/j.fuel.2022.124984.

Lee, S., Kim, Y., Park, J., Shon, H. K., and Hong, S., 2018. Treatment of medical radioactive liquid waste using forward osmosis (FO) membrane process. Journal of Membrane Science, 556, Pp. 238–247. https://doi.org/10.1016/j.memsci.2018.04.008.

Lidén, A., and Persson, K. M., 2015. Comparison between ultrafiltration and nanofiltration hollow-fiber membranes for removal of natural organic matter – a pilot study. Journal of Water Supply: Research and Technology—AQUA. https://doi.org/10.2166/aqua.2015.065

Liu, H., Yang, Y., Kang, J., Fan, M., and Qu, J., 2012. Removal of tetracycline from water by Fe-Mn binary oxide. Journal of Environmental Sciences, 24, Pp. 242–247. https://doi.org/10.1016/S1001-0742(11)60763-8

Liu, J., Duan, L., Gao, Q., Zhao, Y., and Gao, F., 2023. Removal of typical PPCPs by reverse osmosis membranes: Optimization of treatment process by factorial design. Membranes, 13, 355. https://doi.org/10.3390/membranes13030355.

Liu, N., Jin, X., Feng, C., Wang, Z., Wu, F., Johnson, A. C., et al., 2020. Ecological risk assessment of fifty pharmaceuticals and personal care products (PPCPs) in Chinese surface waters: A proposed multiple-level system. Environment International, 136, 105454. https://doi.org/10.1016/j.envint.2019.105454

Liu, P., Liu, W. J., Jiang, H., Chen, J. J., Li, W. W., and Yu, H. Q., 2012. Modification of bio-char derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. Bioresource Technology, 121, Pp.235–240. https://doi.org/10.1016/j.biortech.2012.06.085.

Matamoros, V., Sala, L., and Salvadó, V., 2012. Evaluation of a biologically-based filtration water reclamation plant for removing emerging contaminants: A pilot plant study. Bioresource Technology, 104, Pp. 243–249. https://doi.org/10.1016/j.biortech.2011.11.036 [107] Paterakis, N., Chiu, T. Y., Koh, Y. K. K., Lester, J. N., McAdam, E. J., Scrimshaw, M. D., et al., 2012. The effectiveness of anaerobic digestion in removing estrogens and nonylphenol ethoxylates. Journal of Hazardous Materials, Pp. 199–200, 88–95. https://doi.org/10.1016/j.jhazmat.2011.10.075.

Maurer-Jones, M. A., Gunsolus, I. L., Murphy, C. J., and Haynes, C. L., 2013. Toxicity of engineered nanoparticles in the environment. Analytical Chemistry, 85, Pp. 3036–3049.

Melo-Guimarães, A., Torner-Morales, F. J., Durán-Álvarez, J. C., and Jiménez-Cisneros, B. E., 2013. Removal and fate of emerging contaminants combining biological, flocculation and membrane treatments. Water Science and Technology, 67(4), Pp. 877–885. https://doi.org/10.2166/wst.2012.640.

Melo-Guimarães, A., Torner-Morales, F. J., Durán-Álvarez, J. C., and Jiménez-Cisneros, B. E., 2013. Removal and fate of emerging contaminants combining biological, flocculation and membrane treatments. Water Science and Technology, 67(4), Pp. 877–885. https://doi.org/10.2166/wst.2012.640

Meng, S., Greenlee, L. F., Shen, Y. R., and Wang, E., 2015. Basic science of water: Challenges and current status towards a molecular picture. Nano Research, 8, Pp. 3085–3110. https://doi.org/10.1007/s12274-015-0822-y.

Mestre, A. S., Campinas, M., Viegas, R. M. C., Mesquita, E., Carvalho, A. P., and Rosa, M. J., 2022. Activated carbons in full-scale advanced wastewater treatment. Advanced Materials for Sustainable Environmental Remediation, Pp. 433–475.

Mestre, A. S., Campinas, M., Viegas, R. M. C., Mesquita, E., Carvalho, A. P., and Rosa, M. J., 2022. Activated carbons in full-scale advanced wastewater treatment. In Advanced Materials for Sustainable Environmental Remediation, Pp. 433–475. Elsevier. https://doi.org/10.1016/B978-0-323-90485-8.00001-1.

Metzger, S., Alt, K., and Benstöm, F., 2019. Aktivkohleeinsatz auf kommunalen Kläranlagen zur Spurenstoffentfernung: Verfahrensvarianten, Reinigungsleistung und betriebliche Aspekte. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V. (DWA).

Mitchell, S. M., Subbiah, M., Ullman, J. L., Frear, C., and Call, D. R., 2015. Evaluation of 27 different biochars for potential sequestration of antibiotic residues in food animal production environments. Journal of Environmental Chemical Engineering, 3, Pp. 162–169. https://doi.org/10.1016/j.jece.2014.11.012.

Mohammadi, A., Kazemipour, M., Ranjbar, H., Walker, R. B., and Ansari, M., 2015. Amoxicillin removal from aqueous media using multi-walled carbon nanotubes. Fullerenes, Nanotubes and Carbon Nanostructures, 23, Pp. 165–169. https://doi.org/10.1080/1536383X.2013.866944

Mukherjee, D., Kar, S., Mandal, A., Ghosh, S., and Majumdar, S., 2019. Immobilization of tannery industrial sludge in ceramic membrane preparation and hydrophobic surface modification for application in atrazine remediation from water. Journal of the European Ceramic Society, 39, Pp. 3235–3246. https://doi.org/10.1016/j.jeurceramsoc.2019.04.008.

Nguyen, X. P., Hoang, A. T., Ölçer, A. I., Engel, D., Pham, V. V., and Nayak, S. K., 2021. Biomass-derived 2,5-dimethylfuran as a promising alternative fuel: An application review on the compression and spark ignition engine. Fuel Processing Technology, 214, 106687. https://doi.org/10.1016/j.fuproc.2020.106687.

Niavarani, Z., Breite, D., Prager, A., Abel, B., and Schulze, A., 2021. Estradiol removal by adsorptive coating of a microfiltration membrane. Membranes, 11, 99. https://doi.org/10.3390/membranes11020099.

Noguera-Oviedo, K., and Aga, D. S., 2016. Lessons learned from more than two decades of research on emerging contaminants in the environment. Journal of Hazardous Materials, 316, Pp. 242–251. https://doi.org/10.1016/j.jhazmat.2016.04.058

Peng, H., Pan, B., Wu, M., Liu, Y., Zhang, D., and Xing, B., 2012. Adsorption of ofloxacin and norfloxacin on carbon nanotubes: Hydrophobicity- and structure-controlled process. Journal of Hazardous Materials, Pp. 233–234, 89–96. https://doi.org/10.1016/j.jhazmat.2012.06.058

Petrie, B., Barden, R., and Kasprzyk-Hordern, B., 2015. A review on emerging contaminants in wastewaters and the environment: Current knowledge, understudied areas and recommendations for future monitoring. Water Research, 72, Pp. 3–27. https://doi.org/10.1016/j.watres.2014.08.053

Rodríguez-Narváez, O. M., Peralta-Hernández, J. M., Goonetilleke, A., and Bandala, E. R., 2017. Treatment technologies for emerging contaminants in water: A review. Chemical Engineering Journal, 323, Pp. 361–380. https://doi.org/10.1016/j.cej.2017.04.106.

Rosalina, F., and Febriadi, I., 2023. A novel ameliorant biochar of areca nuts skin and sago bark waste for increasing soil chemical fertility. International Journal of Advanced Science and Engineering Information Technology, 13, Pp. 1184–1189. https://doi.org/10.18517/ijaseit.13.3.18315.

Ruiz, B., Cabrita, I., Mestre, A. S., Parra, J. B., Pires, J., Carvalho, A. P., et al., 2010. Surface heterogeneity effects of activated carbons on the kinetics of paracetamol removal from aqueous solution. Applied Surface Science, 256, Pp. 5171–5175. https://doi.org/10.1016/j.apsusc.2009.12.086

Shafi, M., Jan, R., and Gani, K. M., 2023. Selection of priority emerging contaminants in surface waters of India, Pakistan, Bangladesh, and Sri Lanka. Chemosphere, 341, 139976. https://doi.org/10.1016/j.chemosphere.2023.139976.

Shah, I. A., Ali, S., Yang, Z., Ihsanullah, I., and Huang, H., 2022. Effects of water matrix on the rejection of neutral pharmaceutically active compound by thin-film composite nanofiltration and reverse osmosis membranes. Chemosphere, 303, 135211. https://doi.org/10.1016/j.chemosphere.2022.135211.

Shehu, Z., Nyakairu, G. W. A., Tebandeke, E., and Odume, O. N., 2022. Overview of African water resources contamination by contaminants of emerging concern. Science of the Total Environment, 852, 158303. https://doi.org/10.1016/j.scitotenv.2022.158303

Simmons, F. J., Kuo, D. H.-W., and Xagoraraki, I., 2011. Removal of human enteric viruses by a full-scale membrane bioreactor during municipal wastewater processing. Water Research, 45, Pp. 2739–2750. https://doi.org/10.1016/j.watres.2011.02.001

Sirohi, R., Vivekanand, V., Pandey, A. K., Tarafdar, A., Awasthi, M. K., Shakya, A., et al., 2023. Emerging trends in role and significance of biochar in gaseous biofuels production. Environmental Technology and Innovation, 30, 103100. https://doi.org/10.1016/j.eti.2023.103100.

Sörengård, M., Campos-Pereira, H., Ullberg, M., Lai, F. Y., Golovko, O., and Ahrens, L., 2019. Mass loads, source apportionment, and risk estimation of organic micropollutants from hospital and municipal wastewater in recipient catchments. Chemosphere, 234, Pp. 931–941. https://doi.org/10.1016/j.chemosphere.2019.06.041.

Sotelo, J. L., Rodríguez, A. R., Mateos, M. M., Hernández, S. D., Torrellas, S. A., and Rodríguez, J. G., 2012. Adsorption of pharmaceutical compounds and an endocrine disruptor from aqueous solutions by carbon materials. Journal of Environmental Science and Health, Part B, 47, Pp. 640–652. https://doi.org/10.1080/03601234.2012.668462.

Sotelo, J. L., Rodríguez, A., Álvarez, S., and García, J., 2012. Removal of caffeine and diclofenac on activated carbon in fixed bed column. Chemical Engineering Research and Design, 90, Pp. 967–974. https://doi.org/10.1016/j.cherd.2011.10.012.

Sudita, I. D. N., Situmeang, Y. P., and Suarta, M., 2021. Compost and biochar characteristics test of some animal manure waste. International Journal of Advanced Science and Engineering Information Technology, 11, Pp. 266–271. https://doi.org/10.18517/ijaseit.11.1.11346.

Sui, Q., Huang, J., Deng, S., Chen, W., and Yu, G., 2011. Seasonal variation in the occurrence and removal of pharmaceuticals and personal care products in different biological wastewater treatment processes. Environmental Science and Technology, 45(8), Pp. 3341–3348. https://doi.org/10.1021/es200248d.

Tang, Y., Rong, J., Guan, X., Zha, S., Shi, W., Han, Y., et al., 2020. Immunotoxicity of microplastics and two persistent organic pollutants alone or in combination to a bivalve species. Environmental Pollution, 258, 113845. https://doi.org/10.1016/j.envpol.2019.113845.

Torres-Pérez, J., Gérente, C., and Andrès, Y., 2012. Sustainable activated carbons from agricultural residues dedicated to antibiotic removal by adsorption. Chinese Journal of Chemical Engineering, 20, Pp. 524–529. https://doi.org/10.1016/S1004-9541(11)60214-0

Tröger, R., Klöckner, P., Ahrens, L., and Wiberg, K., 2018. Micropollutants in drinking water from source to tap: Method development and application of a multiresidue screening method. Science of the Total Environment, 627, Pp. 1404–1432. https://doi.org/10.1016/j.scitotenv.2018.01.277.

Verma, V. K., and Subbiah, S., 2019. Sericin-coated polymeric microfiltration membrane for removal of drug-based micropollutants. Journal of Chemical Technology and Biotechnology, 94, Pp. 3625–3636. https://doi.org/10.1002/jctb.6168.

Viegas, R. M. C., Ribeiro, R., Rosa, M. J., Campinas, M., Mesquita, E., and Silva, C., 2021. Controlo de contaminantes de interesse emergente em ETA e ETAR.

Yang, J., Zhao, Y., Li, M., Du, M., Li, X., and Li, Y., 2019. A review of a class of emerging contaminants: The classification, distribution, intensity of consumption, synthesis routes, environmental effects and expectation of pollution abatement to organophosphate flame retardants (OPFRs). International Journal of Molecular Sciences, 20, Pp. 2874. https://doi.org/10.3390/ijms20122874

Yang, W., Lu, Y., Zheng, F., Xue, X., Li, N., and Liu, D., 2012. Adsorption behavior and mechanisms of norfloxacin onto porous resins and carbon nanotube. Chemical Engineering Journal, 179, Pp. 112–118. https://doi.org/10.1016/j.cej.2011.10.068

Yang, X., Flowers, R. C., Weinberg, H. S., and Singer, P. C., 2011. Occurrence and removal of pharmaceuticals and personal care products (PPCPs) in an advanced wastewater reclamation plant. Water Research, 45, Pp. 5218–5228. https://doi.org/10.1016/j.watres.2011.07.026

Yao, M., Duan, L., Wei, J., Qian, F., and Hermanowicz, S. W., 2020. Carbamazepine removal from wastewater and the degradation mechanism in a submerged forward osmotic membrane bioreactor. Bioresource Technology, 314, 123732. https://doi.org/10.1016/j.biortech.2020.123732.

Yao, Y., Gao, B., Chen, H., Jiang, L., Inyang, M., Zimmerman, A. R., et al., 2012. Adsorption of sulfamethoxazole on biochar and its impact on reclaimed water irrigation. Journal of Hazardous Materials, Pp. 209–210, 408–413. https://doi.org/10.1016/j.jhazmat.2012.01.046.

Yun, K. H., Sharma, K., Kim, H. U., and Bae, T.-H., 2023. Modification of a PES microfiltration membrane to enhance sterile filtration by inhibiting protein adsorption. Journal of Industrial and Engineering Chemistry, 123, Pp. 311–319. https://doi.org/10.1016/j.jiec.2023.03.048.

Zengel, S., and Michel, J., 2013. Deepwater Horizon spill: Salt marsh oiling conditions, treatment testing, and treatment history in northern Barataria Bay, Louisiana (Interim report, October 2011, NOAA Technical Memorandum NOS OR&R 42, 74. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Zhang, C., Chen, W.-H., Ho, S.-H., Hoang, A. T., and Zhang, Y., 2023. Tetracycline-adsorbed biochar for solid biofuel usage to achieve waste utilization for environmental sustainability. Environmental Research, 237, 116959. https://doi.org/10.1016/j.envres.2023.116959.

Zhang, Y., Geißen, S.-U., and Gal, C., 2008. Carbamazepine and diclofenac: Removal in wastewater treatment plants and occurrence in water bodies. Chemosphere, 73, Pp. 1151–1161. https://doi.org/10.1016/j.chemosphere.2008.07.086.

Zheng, H., Wang, Z., Zhao, J., Herbert, S., and Xing, B., 2013. Sorption of antibiotic sulfamethoxazole varies with biochars produced at different temperatures. Environmental Pollution, 181, Pp. 60–67. https://doi.org/10.1016/j.envpol.2013.05.056.

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