



A comprehensive review of various approaches for treatment of tertiary wastewater with emerging contaminants: what do we know?

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Abstract In the last few decades, environmental contaminants (ECs) have been introduced into the environment at an alarming rate. There is a risk to human health and aquatic ecosystems from trace levels of emerging contaminants, including hospital wastewater (HPWW), cosmetics, personal care products, endocrine system disruptors, and their transformation products. Despite the fact that these pollutants have been introduced or detected relatively recently, information about their characteristics, actions, and impacts is limited, as are the technologies to eliminate them efficiently. A wastewater recycling system is capable of providing irrigation water for crops and municipal sewage treatment, so removing ECs before wastewater reuse is essential. Water treatment processes containing advanced ions of biotic origin and ECs of biotic origin are highly recommended for contaminants. This study introduces the fundamentals of the treatment of tertiary wastewater, including membranes, filtration, UV (ultraviolet) irradiation, ozonation, chlorination, advanced oxidation processes, activated carbon (AC), and algae. Next, a detailed description of recent developments and innovations in each component of the emerging contaminant removal process is provided.

Keywords Emerging contaminants · Advanced wastewater treatment · Membrane · UV irradiation · Ozonation · Chlorination · Advanced oxidation process · Activated carbon

Introduction

Water quality managers and environmental regulators have been increasingly concerned about emerging contaminants (ECs) identified in the marine ecosystem over the past two decades (Noguera-Oviedo & Aga, 2016). It has become increasingly common to detect ECs in surface water (Riva et al., 2019), such as hospital wastewater (HPWW) (Khan et al., 2021b), cosmetics and personal care items (Juliano & Magrini, 2017), disruptors of the endocrine system (Ng et al., 2021), and pesticides (Primel et al., 2017), which have been linked to adverse ecological impacts. An essential source of the introduction of ECs to aquatic environments is discharges emitted from the treatment of sewage. Management and control of these pollutants depend on the fate and removal of these pollutants in sewage treatment and the natural environment (Margot et al., 2015).

It has been reported that more than 200 different ECs are present in river water worldwide, typically in concentrations ranging from nanograms to micrograms per liter (Murray et al., 2010). In spite of their low concentrations, ECs can cause harmful effects on humans and aquatic organisms, such as changes in

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mineral composition, metabolic processes, and reproductive organs (Varsha et al., 2022). Several studies have demonstrated the dangers of continuous disposal into sewage treatment systems, such as the rapid rise in antibiotic-resistant genes among aquatic species; disruption of biodegradation processes in sewage treatment; and several studies demonstrating that continuous disposal into the sewage treatment system poses significant dangers. Despite this, the fate of some ECs and treatment technologies' effectiveness in removing them are not fully understood (Ahmed et al., 2021). Most ECs are eliminated through wastewater treatment through three main processes: volatilization, biodegradation, and sorption onto particulates (Rout et al., 2021).

It is essential, however, to identify the dominant removal pathways since different mechanisms may influence EC fates differently. The removal efficiency and dominant mechanisms of WWTPs have been contradictory despite several studies conducted on them. As a result of operational parameters (hydraulic residence time, sludge age), seasonal fluctuations of input loads, and seasonal fluctuations in input loads, the reported efficiency varies widely (Cao et al., 2017) (Fig. 1).

The purpose of this paper is to provide an overview of the recent technological advances in the treatment of wastewater that remove ECs. In

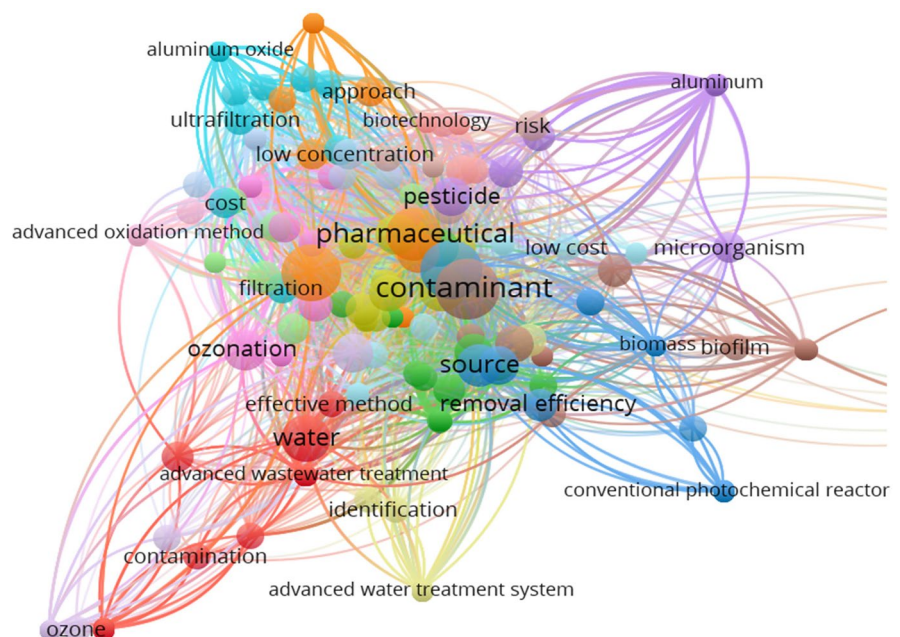
addition, each method's advantages and disadvantages is evaluated.

Emerging pollutants

Different sources of emerging contaminants (ECs) can be transported from urban and industrial sources to the ocean via multiple transport pathways. Urban, agricultural, and industrial pollution can result in the release of ECs into bodies of water (Geissen et al., 2015). In transporting ECs into water bodies, groundwater, surface water, soil, sediment, and ocean water can also carry these pollutants. Diverse sources contribute to the transport of ECs into the ocean after being discharged into sewage systems. These pollutants are a significant concern in water treatment plants since conventional treatment processes do not adequately eradicate them (Geissen et al., 2015). Inputs contaminated with these pollutants are difficult to remove. Lime softening or coagulation using alum or ferric sulfate can remove endocrine disrupting compounds by up to 20% (Westerhoff et al., 2005). Water effluents, whether they are partially or untreated, contain a variety of environmental pollutants which are released into aquatic environments (Häder et al., 2020).

Effluents from sewage treatment, water treatment, and wastewater treatment constitute point sources of

Fig. 1 Visualization network map of the keywords (i.e., “Emerging Contaminants,” wastewater, and “method for removing”) in the publications surveyed from the Web of Science published from 2016 to 2022: (a) Network visualization of terms related to wastewater treatment and Emerging Contaminants. Each node represents one keyword, and the lines connecting the nodes represent co-occurrence relationships. A larger node indicates a closer relationship between the keywords. The color of an element represents the cluster that it belongs to, and different colors differentiate different clusters



pollution (Parween et al., 2017). There are several mechanisms through which ECs are transported into water bodies, including runoff, erosion, or leaching. Upon reaching bodies of water, suspended solids or solutions can be used to transport them downstream. There is a relationship between the adsorption properties, polarity, persistence, and interactions between ECs and other environmental compartments when transported from diffusion sources to different water bodies (Atugoda et al., 2021). Based on degradation, sorption in sediments, and transport properties such as diffusion coefficients and conductivity, ECs in the water environment from different pollution sources are likely to have different fates in the water environment (Datta et al., 2018).

North America (Tran et al., 2018), Europe (Houtman, 2010), Asia (Lee et al., 2022), and Australia (Birch et al., 2015) exhibit different concentrations of pharmaceutical chemicals in surface water as a result of sewage and wastewater effluents. A wastewater treatment process can influence the concentration of these pollutants in bodies of water by determining how these compounds are disposed of (Jelic et al., 2011). In water bodies, EP concentrations can vary from a few nanograms to a few hundred grams per liter. In North America, Europe, Asia, and Australia, ibuprofen concentrations in freshwater rivers and canals range from 0 to 34 ng/L, 14 to 44 ng/L, and 28 to 360 ng/L, respectively (Ebele et al., 2017). Various regions apply different doses for treatment processes in different regions, and wastewater treatment plants vary in efficiency, which explains why they occur differently in surface water (Oosterhuis et al., 2013).

Hospital wastewater (HPWW)

SARS-CoV-2-containing humans (Zahmatkesh et al., 2022a, b, c, d, e) and feces (Zahmatkesh et al., 2022a, b, c, d, e) are being increasingly (Zahmatkesh et al., 2022a, b, c, d, e) and rapidly contaminated with HPWWs as an ecological contaminant (Zahmatkesh et al., 2022a, b, c, d, e). Among these are antibiotics, legal and illegal drugs, analgesics, steroids, beta-blockers, etc. Among their most common sources are wastewater effluents, sludge, sediment, natural waters, drinking water, and groundwater (Jiang et al., 2013). The persistence of these compounds in the body is due to their specific mechanism of action. The purpose of these substances is to promote the

development of antibiotic-resistant genes in soil bacteria (Serwecińska, 2020). The bioaccumulation of active pharmaceutical ingredients (APIs) and their biotransformation products is causing significant consequences for the environment. The APIs and their biotransformation products are mostly unknown (Pranker, 2007). In spite of the fact that these compounds have been entering the environment for many years, the adverse effects of these compounds on aquatic organisms have only recently been investigated. Pseudo-persistent pollutants are pollutants that are continuously released in low concentrations into the environment (Abdel-Shafy & Mansour, 2016). Various pharmaceuticals have been found at low concentrations in aquatic systems, ranging from ng L^{-1} to low g L^{-1} (Jones et al., 2001). Pharmaceutical agents have a significant ecological impact on terrestrial and aquatic life forms, but little is known about their ecotoxicological effects, and it is impossible to comprehensively study their ecological impacts. Aquatic organisms are a critical target as they live in constant contact with wastewater remnants (Bhattacharya & Khare, 2022).

Cosmetics and personal care items

In addition to prescription and non-prescribed pharmaceuticals for veterinary and human use, cosmetics and personal care products also contain active and inert elements for individual care. Cosmetic products, hormones, steroids, perfumes, shampoos, and engineered hormones are some examples of personal care and cosmetics products (Gogoi et al., 2018). The most common cosmetics and personal care products in groundwater and other aquatic environments contain UV filters, which have estrogenic activity (Brausch & Rand, 2011). Whether in their natural form or transformed biologically, cosmetics and personal care products are discharged into the wastewater and directed toward wastewater treatment plants (Yang et al., 2017). A cosmetic or personal care product's metabolites and their conversion to CO_2 and water are likely to occur in WWTPs, mixed with receiving water bodies, or mineralized and sorbable to solids, such as sludge or biosolids, mainly if the compounds or the biologically moderated transformation products are lipophilic (Lishman et al., 2006).

Disruptors of the endocrine system

The function of the body will be altered when an endocrine disruptor enters the body and either copies or obstructs hormones (Green et al., 2021). According to the Environmental Protection Agency (EPA), an external agent disrupts the endocrine system by altering the synthesis, distribution, transmission, binding, function, or displacement of hormones necessary to maintain homeostasis, development, sexual function, and mental health (McCuin & Clancy, 2003). According to general consensus, estrogenic drugs are those that mimic or alter the effects of natural estrogens, androgenic drugs (which copy or obstruct natural testosterone), and thyroidal drugs (which cause direct or indirect effects on the thyroid) (Marazuela et al., 2020). Natural and engineered agents are impairing the endocrine system due to human activities, creatures, and industries. These agents end up in soil, surface water, and groundwater via sewage treatment systems. Research has primarily focused on estrogenic compounds. Disruptors of the endocrine system can be found in wastewater in low concentrations (ng L^{-1} or $\mu\text{g L}^{-1}$) (Archer et al., 2017). Due to the fact that it is unclear how these compounds will affect humans in the long term, they are of profound concern.

The impact of emerging contaminants on the environment and human health

Humans and animals are affected by emerging pollutants (EPs) released by wastewater effluents that mimic, block, or disrupt hormone functions, affecting the endocrine systems (Kasonga et al., 2021). It has been shown that EPs in effluents are carcinogenic and non-carcinogenic and can adversely affect aquatic life and human health at a trace concentration (Vasilachi et al., 2021). It is usually the case that ecological risk assessment is performed by comparing a substance's concentration in various environmental compartments with the levels below which organisms are not adversely or unacceptably affected. International and national environmental regulations already regulate certain chemicals based on their numerical toxicity values that have non-cancerous effects on humans and animals (Fuhrman et al., 2015). Assessing the ecological and human health risks associated with EPs in water can be helpful using a multi-scale framework rather than exposure to single chemicals.

Multiple stressors can be considered in this framework, including chemicals, physical agents, and biological agents, both acute (short-term) and chronic (long-term) risks (Reid et al., 2019; Sonawane et al., 2022).

Water bodies can be contaminated by HPWW, cosmetics, and endocrine disruptors, and these contaminants can persist far beyond what is acceptable. ECs will probably be incorporated into crops irrigated with contaminated water because of their widespread presence in water and pose a health risk when consumed. In addition to harming marine and land-based wildlife, ECs can also have a detrimental impact on people and communities (Luque-Espinar et al., 2015). ECs also negatively impact the environment, as summarized in Table 1. Endocrine disrupting chemicals are responsible for a variety of hormonal and reproductive abnormalities in animals and people. During pregnancy and after delivery, exposure to these chemicals can cause permanent, sometimes irreversible effects on child development. The effects are irreversible during development (Sifakis et al., 2017). A critical issue is the management of ECs in water resources, particularly in ecologically sensitive areas and areas with rapid population growth. ECs in the natural environment have different ecological effects compared to those in laboratories (Geissen et al., 2015). In an environment where ECs are present, various factors may influence their bioavailability, including pH, soil and water composition, and ionizable compounds. Developing a system-wide abatement framework combining structural and non-structural strategies (source-transfer-fate levels) is essential (Geissen et al., 2015).

Emerging pollutants in sewage

An overview of the sources and concentrations

Many municipal wastewater treatment plants (WWTP) cannot handle complex pharmaceuticals (Liu et al., 2017). During construction and updates, the primary objective was to eliminate substances and microbes that regularly accumulate at WWTPs readily biodegradable or moderately biodegradable in terms of carbon, phosphorus, and nitrogen. Through the discharge of shower wastes, PCPs (e.g., perfumes) are released into aquatic systems alongside human pharmaceuticals (Al-Baldawi et al., 2021).

Table 1 Emerging contaminants (HPWW, cosmetics and personal care products, and disruptors of the endocrine system)

Emerging contaminants (HPWW, cosmetics and personal care products, and disruptors of the endocrine system)	Effects adverse to health or aquatic life	References
Penicillin, sulfonamides, tetracyclines (antibiotics)	It results in bacterial pathogen resistance, which affects the higher food chain and alters the structure of microbial communities in nature	Pailler et al. (2009)
Roxithromycin, clarithromycin, tylosin	Inhibition of <i>Pseudokirchneriella subcapitata</i> growth	Yang et al. (2008)
Caffeine	Goldfish <i>Carassius auratus</i> endocrine disruption	Arfanis et al. (2017)
Diclofenac	<i>Oncorhynchus mykiss</i> : alterations to the renal system and gills	Smiljanić et al. (2020)
Carbamazepine	<i>Oncorhynchus mykiss</i> under oxidative stress	Sun et al. (2013)
Gemfibrozil	<i>Anabaena</i> sp. growth inhibition	Farzaneh et al. (2020)
Propranolol	An evaluation of the effectiveness of control methods for Japanese medaka <i>Oryzias latipes</i>	Zhang et al. (2008)
HHCB	Goldfish <i>Carassius auratus</i> under oxidative stress	Murray et al. (2010)
Fragrances	A carcinogen that damages the nervous system of rodents, easily absorbed by human skin, and can be fatal to humans	Gogoi et al. (2018)
Triclosan and triclocarban	<i>Pseudokirchneriella subcapitata</i> growth inhibition	Jagini et al. (2019)
Bisphenol A	Researchers have shown that it increases the risk of breast cancer in humans due to estrogenic effects in rats. Furthermore, it has been reported that it causes feminizing effects in men due to its anti-androgen properties	Tang et al. (2022)
Estrone and 17-β estradiol (steroidal estrogens) and 17-α ethynylestradiol (synthetic contraceptive)—contained in contraceptive pills	Identifies non-targets as estrogen hormones in fishes	Borrull et al. (2020)
Preservatives, i.e., parabens (alkyl-hydroxybenzoate)—used for anti-microbiological preservatives in cosmetics, toiletries, and even foods	Activates estrogenically weakly	Bolong et al. (2009)
Disinfectants/antiseptics, i.e., triclosan—used in toothpaste, hand soaps, acne cream	It causes microbial resistance and acts as a toxic or biocidal agent	Bueno et al. (2012)

Several nations have reported PhACs and PCPs in WWTPs in amounts ranging from ng L⁻¹ to µg L⁻¹, including the USA, Japan, UK, Finland, and Spain. In March 2015, 1814 consumer nanomaterials products were included in an inventory (K’oreje et al., 2018). Although these products are seldom detected, they can adversely affect the environment. Some ECs are presented in Table 2 as amounts in different environmental media. Conventional sewage treatment methods such as sedimentation, flocculation, and active sludge are not as effective at removing ECs as they once were (Ahmed et al., 2017).

Wastewater EP fate and transportation

As emerging pollutants enter the environment, their behavior is influenced by their physical and chemical

properties, including their solvability, vapor pressure, and charge. It depends on the properties of the pollutants that are released into watersheds on whether they enter the groundwater through leaching, are carried to water bodies by rainfall, or can be absorbed by the soil (Khan et al., 2022a, b). Transporting EPs from watersheds to bodies of water may result in their degradation. Furthermore, several processes are involved in the degradation of ECs once they are introduced into the environment, including biological degradation, chemical degradation, and photochemical degradation (Gimeno et al., 2016). Parameter sensitivity analysis can identify the significance of these processes in modeling (Gan et al., 2014). By using a set of mathematical equations, one can incorporate these processes into fate and transport modeling. The modeling of EP fate and transport provides an

Table 2 Different environmental samples were tested for the presence of some emerging contaminants

HPWW, cosmetics and personal care products, and disruptors of the endocrine system as emerging contaminants	Effluents treated	Water on the surface	Ground and drinking water
Analgesics and anti-inflammatory	55–60 µg/L	4–6 µg/L	8.5–0.12
Lipid regulators	4–5 µg/L	0.1–0.3 µg/L	7.5–0.17
β blockers	8–10 µg/L	1–2.5 µg/L	0.27
Antibiotics	5–6 µg/L	1.8–2 µg/L	0.2
Antiepileptic drugs	20–22 µg/L	1.5–1.9 µg/L	1.1–0.05
Estrone (E1)	0.15 ng/L	0.1–17.5 ng/L	13–80, 0.2–2.1
Estrone and 17-β estradiol (steroidal estrogens)	0.1–650 ng/L	0.05–6.5 ng/L	-
Estriol (E3)	4–7.8 ng/L	0.9–2.6 ng/L	3–1410, 0.5–44
Bisphenol A	5–260 ng/L	0.4–260 ng/L	-

effective method for identifying EP behavior and fate in soil, sediment, and aquatic systems. By modeling the fate and distribution of EPs, emerging chemicals within watersheds can be identified, and the concentrations of EPs within these watersheds can be quantified (Locatelli et al., 2019). It is crucial to have accurate modeling results for EP fate and transport from a variety of perspectives. Ecological risk assessment tools can be developed based on the findings in order to prevent the risks associated with EPs from affecting aquatic life and human health. These findings may likewise be applied to developing environmental policies and regulations that can be used to mitigate the risks associated with EPs and to control their release into water bodies (Jones, 2001). As a result, EP management in aquatic environments will become more challenging. It is possible to calibrate and validate existing fate and transport models using data and information collected from existing surveillance activities of EPs. Alternatively, the modeling results may assist in identifying target pollutants in the marine ecosystem and improving existing assessment methods (Datta et al., 2018).

The traditional wastewater treatment system includes several biological and physicochemical treatment phases, including initial, secondary, and advanced treatment. During the initial treatment, settleable solids, plastics, oils, and fats, as well as sand and grit, are separated. Filtration and sedimentation are typically used in municipal sewage treatment systems. The secondary treatment method, which generally relies on the degradation of organic substances or nutrients by microorganisms (aerobic or anaerobic),

can differ significantly from one method to another (Zahmatkesh et al., 2022a, b, c, d, e). Among the various biological treatment methods used in MWWTPs, the most common is the use of activated sludge (CAS) (Zahmatkesh & Pirouzi, 2020). It is one of several methods, including fixed bed bioreactors (FBR), membrane bioreactors (MBR), and moving bed bio-film reactors (MBBR). By forming biological floc using dissolved oxygen and dissolved oxygen, activated sludge plants remove organic matter and nitrogen from wastewater (Zahmatkesh et al., 2022a, b, c, d, e). As a final step, precipitation and filtration are used to remove phosphorous from the water during advanced treatment (Zahmatkesh et al., 2022a, b, c, d, e). Municipal wastewater treatment effluent is sometimes disinfected by UV rays or chlorination prior to discharge into the water supply. However, these treatments alone cannot ensure that all ECs have been removed. Many cosmetics and personal care products are resistant to biodegradation, such as diclofenac and carbamazepine. The most common activated sludge method is not effective in removing all cosmetics and personal care products (Chopra & Kumar, 2018).

In addition, ECs are capable of undergoing biological, chemical, and photochemical degradation, which can result in their transformation into toxic forms (Yap et al., 2019). As a result of partial oxidation, cosmetics and personal care generate transformation products (TPs) that are significantly more toxic than acyclovir as a result of partial oxidation, such as carboxy-acyclovir, the two TPs of acyclovir that are significantly more toxic than acyclovir, and N-(4-carbamoyl-2-imino-5-oxoimidazolidin)-formamido-N-methoxyacetic acid (COFA), the two TPs

of the antiviral drug. The number of disinfection byproducts (DBPs) has increased to more than 600 as of today. The formation of DBPs occurs when BOD, COD, and TSS in water react with disinfectants such as ozone and chlorine (Li & Mitch, 2018).

Membrane bioreactor

A comparison of EPs and conventional activated sludge systems has revealed that EPs have low removal efficiencies under anaerobic conditions coupled with MBR. Anaerobic digestion of sludge under thermophilic and mesophilic conditions resulted in a removal efficiency of over 99% for sulfamethoxazole (SMX) (Zahmatkesh & Sillanpää, 2022; Zahmatkesh et al., 2022a, b, c, d, e). Under anoxic and aerobic conditions, Li et al. (2011) found SMX removal efficiency to be 65%. Under anaerobic conditions, cellulose was used as a primary substrate for reducing ethinylestradiol, progesterone, and metoprolol tartrate levels significantly. The combining anaerobic pretreatment with aerobic treatment may be beneficial for optimal EP removal (Li et al., 2011; Zahmatkesh et al., 2022f).

Membrane

Phase separation occurs through selective movement of components through membranes, which block the flow of components through them. Based on their behavior, membranes can be classified as anisotropic or isotropic based on the nature of their behavior (Zhao & Zhang, 2020). In terms of wastewater treatment, there are four major categories: microfiltration (MF), ultrafiltration (UF), nanofiltration, and reverse osmosis. Separation is accomplished by hydraulic pressure in these processes. Membranes have the following characteristics: A pressure of 1–3 bars is required for the membrane of the MF. There is a required UF pressure of 2–5 bars, and this membrane has microporous, asymmetric characteristics, with particle sizes ranging from 0.15 to 5×10^{-2} μm . Pressures used in NF range from 5 to 15 bars, and the type of membrane used is a tight-porous, asymmetric, thin-film composite, with particle sizes ranging from 5×10^{-2} μm to 5×10^{-3} μm . In contrast, the pressure for RO is 15–75 bars, and the particle size range is 5×10^{-3} μm to 10^{-4} μm . The RO process can separate monovalent ions up to 99.5% of the time, unlike other

membrane separation processes based on pressure, which cannot separate small particles like bacteria (Zahmatkesh et al., 2022a, b, c, d, e, g).

Activated sludge

A GC–MS/MS analysis of endocrine system as emerging contaminants using activated sludge was conducted in Germany, Canada, and Brazil in 1999 (Ohoro et al., 2019). Estrone (E1) was removed 83% of the time, 17 β -estradiol (E2) was removed 99.9% of the time, and 17 α -ethinylestradiol (EE2) was removed 78% of the time (Elias et al., 2021). According to a yeast estrogen screen (YES) bioassay conducted in Sweden, activated sludge results in 81% of estrogenic endocrine system as emerging contaminants, indicating that activated sludge is a more effective method than other methods. The activated sludge process appears to degrade E1 and E2 by approximately 90%, while EE2 degradation occurs slower (Mohapatra & Kirpalani, 2019). Dubey et al., 2022 found that endocrine system as emerging contaminant removal efficiency in aerobic conditions is more significant than in anaerobic conditions. It has been reported that an activated sludge process has a 90 to 99% efficiency in removing endocrine system as emerging contaminants (Dubey et al., 2022). According to Suzuki and Maruyama (2006), activated sludge was initially able to absorb E1 and E2 at a high rate. In a matter of hours, the same was capable of biodegrading them, thereby removing estrogens without dissolved organic carbon (DOC) decomposition or nitrification (Suzuki & Maruyama, 2006). Additionally, this study showed that activated sludge activity decreases significantly at low temperatures. As a result of the biotransformation of E2 into E1, E1 concentrations were found to exceed those in influent in some cases, which is explained by the biotransformation of E2 into E1. In 24 h, activated sludge from WWTPs mineralized 70–80% of the added E2 to CO₂. In contrast, EE2 mineralized 25–75 times less than E2. The nitrification of activated sludge was also found to degenerate EE2 entirely in 6 days (Ren et al., 2007). On a large pilot scale in Paris, France, micrograin activated carbon (GAC) was used as a tertiary treatment technique. Several studies have shown that GAC reduces BOD (3–84%), COD (21–48%), and DOC (13–44%) and removes PPHs (60–80%), PCPs, artificial sweeteners,

pesticides, etc. There are many advantages to this method compared to powdered activated carbon, such as improved treatment wastewater efficiency and more convenient handling (Nguyen et al., 2021).

Activated carbon

The adsorption of activated carbon can remove many hydrophobic and charged pharmaceuticals from water (Zahmatkesh et al., 2022a, b, c, d, e). This process is characterized primarily by the following steps: The solute is transported to the active sites by a static film covering the adsorbent (Duan et al., 2021); adsorbates are transported through the film (Piai et al., 2019); adsorbates are transported through the permeable system (Koutník et al., 2020); and adsorbates are transported through the porous fabric (Mohan et al., 2006). Several factors can influence the sorption performance of activated carbon adsorbent frameworks, including adsorbent properties, permeability, and polarity. A number of factors may play a significant role in the antibiotic sorption process, including the initial concentration of the compound chosen, the temperature, pH, and the presence of a wide range of other species (Zheng et al., 2019). The van der Waals interaction between molecules is one of the most efficient methods for removing antibiotics and other organic compounds from activated carbon. In addition to eliminating ionic or polar antibiotics, activated carbon's surface charge group can be used to remove ionic and polar antibiotics (Xiang et al., 2019).

The adsorption of a few ECs, especially nonpolar contaminants with $\text{Log KOW} > 2$, can be enhanced by powdered activated carbon (PAC) or granular activated carbon (GAC). In order to achieve better removal rates, PACs must be measured, or GAC must be recovered and substituted (Cheng et al., 2021). For endocrine disrupting compounds, Snyder et al. found that PAC could be removed with an incubation period of 4 h with a concentration of 5 mg/L1 and an incubation period of 4 h (Snyder et al., 2007). In 2022, only nine of 66 cosmetics and personal care products were removed with less than 50% efficiency when PAC was applied at a concentration of 5 mg/L1 and a contact time of 5 h (Kumar et al., 2022). In addition to the need to dispose of PAC either by land disposal or other solid management methods, one must also take into account the inevitable issue of carbon

redemption and disposition. In addition, the use of GAC for thermal recovery may create more ecological danger than the presence of ECs because it uses an enormous amount of energy (Kanhar et al., 2020).

Advanced oxidation process (AOPS)

The use of AOPs with or after oxidative biological treatment is suitable due to the fact that oxidative biological treatment has many advantages but may not be able to remove certain biorefractory compounds (M'Arimi et al., 2020). An oxidative debasement process occurs when an oxidant is directly exposed to a substance or a second species, such as hydroxyl radicals (OH^-), is formed. The term "AOPs" refers to procedures that can produce hydroxyl radicals as a result of their procedure (Khan et al., 2022a, b). UV radiation is usually the starting point for generating hydroxyl radicals (Song et al., 2019). It can be achieved by various methods, including photocatalysis with titanium dioxide, electrooxidation using diamond electrodes doped with boron, or directly with hydrogen peroxide. Several AOPs, such as Ozone/ H_2O_2 and UV/Ozone, stimulate radical hydroxyl production. Sewage treatment strategies based on AOPs are very innovative. Although HO^- is a powerful oxidizer, it is not a specific catalyst and oxidizes organic matter extensively (Zahmatkesh et al., 2022a, b, c, d, e). A significant advantage of this property is its ability to strafe organic compounds at a rate of $106\text{--}109 \text{ M}^{-1} \text{ S}^{-1}$ (Gogoi et al., 2018).

By utilizing different methods for creating hydroxyl radicals, the AOPs are better suited to a wide range of treatment needs, which enhances their adaptability. Economic constraints are one of the most significant disadvantages of this process (Giannakis et al., 2021). An environmentally friendly way to save energy is to use solar energy for oxidation. A solar photocatalysis investigation has been carried out using heterogeneous materials, including TiO_2 , ozonation, and a solar Fenton reaction (with Fe (III)). A higher degradation rate is observed for photocatalytic ozonation in comparison to photocatalytic oxidation. There has been research on several AOPs, including ozone (O_3), hydrogen peroxide (H_2O_2), photolysis using UV, Fenton reagents (homogeneous), semiconductors (heterogeneous), and ultrasound (sonolysis) (Gimeno et al., 2016).

Ozonation

The use of ozone treatment systems involves the conversion of microbes and certain chemicals into oxygen via a reaction with ozone, a powerful disinfectant, and oxidizing agent. The removal efficiency of ozonation was >90% for aromatic compounds that contain a high concentration of electrons (e.g., sulfamethoxazoles), deprotonated amine compounds (e.g., trimethoprim), and non-aromatic alkenes, which are highly reactive as well as highly reactive (Premjit et al., 2022). Various antibiotics have been shown to have greater sensitivity to ozone treatment, including fluoroquinolones, macrolides, and sulfonamides (Pazda et al., 2019). However, hydroxyl groups significantly alter N4-acetyl sulfamethoxazole, cephalexin, and penicillin. Additionally, ozone alters antimicrobials' bactericidal properties by changing their functional groups, such as dimethyl-amino groups and N-etheroxime, the aniline part of sulfonamides (Le-Minh et al., 2010).

Chlorination

It is possible to inactivate functional groups in chemical compounds by substituting or adding chlorine. Chlorine, on the other hand, has the ability to oxidize or disintegrate substances such as antibiotics. It is necessary to have enough free chlorine and contact time for chlorination to remove antibiotics from drinking water effectively (Stolte et al., 2008). There was a reduction in antibiotic levels in drinking water after a chlorine amount of 1.2 mg L⁻¹, an incubation period of 1 day, and a reduction of tetracyclines by >99%, trimethoprim by 42%, sulfonamides by 50–80%, fluoroquinolones by 30–40%, and macrolides by less than 10% (Michael et al., 2013). After 10 days, they were removed entirely. For sulfamethoxazole, trimethoprim, and erythromycin in river water, 90 to >99% expulsions were achieved at chlorine amounts of 3.5–3.8 mg L⁻¹ (Sivaranjane & Kumar, 2021).

In spite of the fact that certain antibiotics are more resistant to chlorination than others, free chlorine appears to degenerate slower than others. Additionally, increased organic matter in the water should lead to a higher concentration and contact time. In order of decreasing reactivity, sulfadimethoxine is the least reactive, followed by sulfathiazole and

sulfamethazine, then sulfamerazine and sulfamethoxazole, and finally sulfamethizole. By chlorination, sulfonamides cannot be expelled by a pH greater than 8 (alkaline). In water, Huber et al. (2005) found that ClO₂ reacts rapidly with antibiotics such as sulfonamides and macrolides. It is a source of concern that the chlorination treatment is responsible for toxic byproducts produced by chlorine reacting with organic matter (Huber et al., 2005).

Ultraviolet (UV) irradiation

Organic matter in water can be degraded using UV radiation. Several variables influence the efficiency of the removal of DOC, including an incubation period, dosage, and amount, as well as the molecules' quantum yields that administer degradation and UV absorption. In addition, UV light radiation also possesses germicidal properties and can be utilized as a wastewater disinfectant because of its germicidal properties (Sichel et al., 2011). As a result of an appropriate dose of UV radiation, wastewater can be treated effectively as a bactericide and virucide without creating byproducts. Several pharmaceuticals, including EDCs and PCPs, are absorbed by UV rays and used for the removal of micropollutants and for microbial purification. During UV treatment, the chromophores in these compounds are transformed, resulting in the removal of micropollutants. Despite its advantages in treating PCPs, UV radiation is, to some degree, more costly when compared to conventional treatment methods because it oxidizes the organic compounds more quickly, with hydrogen peroxide in the mixture (Ahmed et al., 2017).

Trends, challenges, and future research needs

Despite the fact that no process can effectively remove every single EC under normal operating conditions, prudent treatment techniques must be applied to ensure that they are effectively removed. The effectiveness of current treatment methods, such as chemical and biological methods, membrane filtration, and adsorption, lacks sufficient data to assess their effectiveness. Nevertheless, different antibiotics have been described subjectively by utilizing some essential molecular and physicochemical characteristics in order to determine their susceptibility to some

removal processes. It is possible to quantify ECs by developing advanced analytical instruments. It has been crucial to detect and find effective removal strategies for potential ECs in today's complex world, so finding solutions should be an essential component of the solution.

As a result of a lack of knowledge, many ECs are not reported or detected. Persistent transformation products are still unknown after treating ECs that can pose a higher environmental risk. In the absence of ECs, it does not mean that there will be no toxicants. Additionally, ecotoxicological agents behave differently in natural habitats and exhibit distinct toxicological characteristics that conventional lab tests cannot predict. New ecotoxicity testing protocols will need to be developed in order to determine the effects of exotoxins using different organisms with suitable endpoints. Further and deeper studies are needed to fill knowledge gaps regarding ECs conducted under conventional and tertiary sewage treatment processes. Future research should examine the methods used to treat sewage biomass, the fate of these pollutants, and their conversion into toxic metabolites or compounds that retain their pharmacological properties. The removal of ECs should be performed using a combination of more effective methods than a specific or traditional method. Furthermore, future research should define and govern all operational variables of treatment plants in order to facilitate later correlations or analyses.

Conclusion

Although EC parameters are generally at ng L^{-1} levels, there is still a lack of knowledge regarding their environmental and health effects, mainly because additive effects have not been evaluated. It is easier to detect ECs in natural specimens with persistently enhanced assay methods, which has contributed to an increase in ECs within the natural environment. Since ECs dissolve quickly without evaporating under standard temperatures and pressures, they are common in the environment as long as temperatures and pressures are standard. Even so, there is little information about their behavior and biodegradability in water, despite the fact that most people dispose of antibiotics and their byproducts in municipal

sewage systems. Researchers should develop models and frameworks based on risk-based screening approaches to reduce the risks associated with ECs and their sources, fates, and behaviors. Additionally, it is crucial to focus studies on the occurrence, fate, and treatment of human-derived metabolites within wastewater treatment plants.

In terms of removing pathogens as well as emerging contaminants, chlorination and ozonation appear to be the best disinfection methods. Therefore, it is necessary to conduct further research to identify the potential toxic properties of disinfection byproducts compared to their parent compounds, as well as the possible synergic effects of cocktails of disinfection byproducts, even at trace levels of concentration. Due to its efficiency, simplicity, and efficiency on an industrial scale and for economic reasons, countries have been using ozonation and adsorption on activated carbon for about 10 years. In addition to being easy to integrate into existing treatment facilities, these technologies are also cost-effective. As a result of current research efforts, some biological approaches are available, such as constructed wetlands, biomembrane reactors, biotechnology, and enzymatic degradation. As a final solution, advanced oxidation processes contribute significantly to the sustainability of wastewater treatment facilities due to their efficiency and simplicity. They can also improve existing procedures by integrating them as primary, secondary, and tertiary treatment processes.

General information

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References

Abdel-Shafy, H. I., & Mansour, M. S. (2016). A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. *Egyptian Journal of Petroleum*, 25(1), 107–123.

Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., Thomaidis, N. S., & Xu, J. (2017). Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: A critical review. *Journal of Hazardous Materials*, 323, 274–298.

Ahmed, S., Mofijur, M., Nuzhat, S., Chowdhury, A. T., Rafa, N., Uddin, M. A., Inayat, A., Mahlia, T., Ong, H. C., & Chia, W. Y. (2021). Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *Journal of Hazardous Materials*, 416, 125912.

Al-Baldawi, I. A., Mohammed, A. A., Mutar, Z. H., Abdullah, S. R. S., Jasim, S. S., & Almansoori, A. F. (2021). Application of phytotechnology in alleviating pharmaceuticals and personal care products (PPCPs) in wastewater: Source, impacts, treatment, mechanisms, fate, and SWOT analysis. *Journal of Cleaner Production*, 319, 128584.

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*, 174, 437–446.

Arfanis, M. K., Adamou, P., Moustakas, N. G., Triantis, T. M., Kontos, A. G., & Falaras, P. (2017). Photocatalytic degradation of salicylic acid and caffeine emerging contaminants using titania nanotubes. *Chemical Engineering Journal*, 310, 525–536.

Atugoda, T., Vithanage, M., Wijesekara, H., Bolan, N., Sarmah, A. K., Bank, M. S., You, S., & Ok, Y. S. (2021). Interactions between microplastics, pharmaceuticals and personal care products: Implications for vector transport. *Environment International*, 149, 106367.

Bhattacharya, A., & Khare, S. (2022). Ecological and toxicological manifestations of microplastics: Current scenario, research gaps, and possible alleviation measures. *Journal of Environmental Science and Health, Part C*, 38(1), 1–20.

Birch, G., Drage, D., Thompson, K., Eaglesham, G., & Mueller, J. (2015). Emerging contaminants (pharmaceuticals, personal care products, a food additive and pesticides) in waters of

Sydney estuary, Australia. *Marine Pollution Bulletin*, 97(1–2), 56–66.

Bolong, N., Ismail, A., Salim, M. R., & Matsuura, T. (2009). A review of the effects of emerging contaminants in wastewater and options for their removal. *Desalination*, 239(1–3), 229–246.

Borrull, J., Colom, A., Fabregas, J., Borrull, F., & Pocurull, E. (2020). Liquid chromatography tandem mass spectrometry determination of 34 priority and emerging pollutants in water from the influent and effluent of a drinking water treatment plant. *Journal of Chromatography A*, 1621, 461090.

Brausch, J. M., & Rand, G. M. (2011). A review of personal care products in the aquatic environment: Environmental concentrations and toxicity. *Chemosphere*, 82(11), 1518–1532.

Bueno, M. M., Gomez, M., Herrera, S., Hernando, M., Agüera, A., & Fernández-Alba, A. (2012). Occurrence and persistence of organic emerging contaminants and priority pollutants in five sewage treatment plants of Spain: Two years pilot survey monitoring. *Environmental Pollution*, 164, 267–273.

Cao, Y., van Loosdrecht, M., & Daigger, G. T. (2017). Mainstream partial nitrification–anammox in municipal wastewater treatment: Status, bottlenecks, and further studies. *Applied Microbiology and Biotechnology*, 101(4), 1365–1383.

Cheng, N., Wang, B., Wu, P., Lee, X., Xing, Y., Chen, M., & Gao, B. (2021). Adsorption of emerging contaminants from water and wastewater by modified biochar: A review. *Environmental Pollution*, 273, 116448.

Chopra, S., & Kumar, D. (2018). Pharmaceuticals and personal care products (PPCPs) as emerging environmental pollutants: Toxicity and risk assessment. *Advances in animal biotechnology and its applications* (pp. 337–353). Springer.

Datta, A. R., Kang, Q., Chen, B., & Ye, X. (2018). Fate and transport modelling of emerging pollutants from watersheds to oceans: A review. *Advances in Marine Biology*, 81, 97–128.

Duan, J., Ji, H., Xu, T., Pan, F., Liu, X., Liu, W., & Zhao, D. (2021). Simultaneous adsorption of uranium (VI) and 2-chlorophenol by activated carbon fiber supported/modified titanate nanotubes (TNTs/ACF): Effectiveness and synergistic effects. *Chemical Engineering Journal*, 406, 126752.

Dubey, M., Rajpal, A., Vellanki, B. P., & Kazmi, A. A. (2022). Occurrence, removal, and mass balance of contaminants of emerging concern in biological nutrient removal-based sewage treatment plants: Role of redox conditions in biotransformation and sorption. *Science of the Total Environment*, 808, 152131.

Ebele, A. J., Abdallah, M. A. -E., & Harrad, S. (2017). Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerging Contaminants*, 3(1), 1–16.

Elias, K. D., Ejidike, I. P., Mtunzi, F. M., & Pakade, V. E. (2021). Endocrine disruptors-(estrone and β -estradiol) removal from water by nutshell activated carbon: Kinetic, isotherms and thermodynamic studies. *Chemical Thermodynamics and Thermal Analysis*, 3, 100013.

Farzaneh, H., Loganathan, K., Saththasivam, J., & McKay, G. (2020). Ozone and ozone/hydrogen peroxide

- treatment to remove gemfibrozil and ibuprofen from treated sewage effluent: Factors influencing bromate formation. *Emerging Contaminants*, 6, 225–234.
- Fuhrman, V. F., Tal, A., & Arnon, S. (2015). Why endocrine disrupting chemicals (EDCs) challenge traditional risk assessment and how to respond. *Journal of Hazardous Materials*, 286, 589–611.
- Gan, Y., Duan, Q., Gong, W., Tong, C., Sun, Y., Chu, W., Ye, A., Miao, C., & Di, Z. (2014). A comprehensive evaluation of various sensitivity analysis methods: A case study with a hydrological model. *Environmental Modelling & Software*, 51, 269–285.
- Geissen, V., Mol, H., Klumpp, E., Umlauf, G., Nadal, M., Van der Ploeg, M., Van de Zee, S. E., & Ritsema, C. J. (2015). Emerging pollutants in the environment: A challenge for water resource management. *International Soil and Water Conservation Research*, 3(1), 57–65.
- Giannakis, S., Lin, K. -Y. A., & Ghanbari, F. (2021). A review of the recent advances on the treatment of industrial wastewaters by Sulfate Radical-based Advanced Oxidation Processes (SR-AOPs). *Chemical Engineering Journal*, 406, 127083.
- Gimeno, O., García-Araya, J., Beltrán, F., Rivas, F., & Espejo, A. (2016). Removal of emerging contaminants from a primary effluent of municipal wastewater by means of sequential biological degradation-solar photocatalytic oxidation processes. *Chemical Engineering Journal*, 290, 12–20.
- Gogoi, A., Mazumder, P., Tyagi, V. K., Chaminda, G. T., An, A. K., & Kumar, M. (2018). Occurrence and fate of emerging contaminants in water environment: A review. *Groundwater for Sustainable Development*, 6, 169–180.
- Green, M. P., Harvey, A. J., Finger, B. J., & Tarulli, G. A. (2021). Endocrine disrupting chemicals: Impacts on human fertility and fecundity during the peri-conception period. *Environmental Research*, 194, 110694.
- Häder, D. -P., Banaszak, A. T., Villafañe, V. E., Narvarte, M. A., González, R. A., & Helbling, E. W. (2020). Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications. *Science of the Total Environment*, 713, 136586.
- Houtman, C. J. (2010). Emerging contaminants in surface waters and their relevance for the production of drinking water in Europe. *Journal of Integrative Environmental Sciences*, 7(4), 271–295.
- Huber, M. M., Korhonen, S., Ternes, T. A., & Von Gunten, U. (2005). Oxidation of pharmaceuticals during water treatment with chlorine dioxide. *Water Research*, 39(15), 3607–3617.
- Jagini, S., Konda, S., Bhagawan, D., & Himabindu, V. (2019). Emerging contaminant (triclosan) identification and its treatment: A review. *SN Applied Sciences*, 1(6), 1–15.
- Jelic, A., Gros, M., Ginebreda, A., Cespedes-Sánchez, R., Ventura, F., Petrovic, M., & Barcelo, D. (2011). Occurrence, partition and removal of pharmaceuticals in sewage water and sludge during wastewater treatment. *Water Research*, 45(3), 1165–1176.
- Jiang, J. -Q., Zhou, Z., & Sharma, V. (2013). Occurrence, transportation, monitoring and treatment of emerging micro-pollutants in waste water—A review from global views. *Microchemical Journal*, 110, 292–300.
- Jones, O., Voulvoulis, N., & Lester, J. (2001). Human pharmaceuticals in the aquatic environment a review. *Environmental Technology*, 22(12), 1383–1394.
- Jones, R. N. (2001). An environmental risk assessment/management framework for climate change impact assessments. *Natural Hazards*, 23(2), 197–230.
- Juliano, C., & Magrini, G. A. (2017). Cosmetic ingredients as emerging pollutants of environmental and health concern. A mini-review. *Cosmetics*, 4(2), 11.
- K'oreje, K. O., Kandie, F. J., Vergeynst, L., Abira, M. A., Van Langenhove, H., Okoth, M., & Demeestere, K. (2018). Occurrence, fate and removal of pharmaceuticals, personal care products and pesticides in wastewater stabilization ponds and receiving rivers in the Nzoia Basin, Kenya. *Science of the Total Environment*, 637, 336–348.
- Kanhar, A. H., Chen, S., & Wang, F. (2020). Incineration fly ash and its treatment to possible utilization: A review. *Energies*, 13(24), 6681.
- Kasonga, T. K., Coetzee, M. A., Kamika, I., Ngole-Jeme, V. M., & Momba, M. N. B. (2021). Endocrine-disruptive chemicals as contaminants of emerging concern in wastewater and surface water: A review. *Journal of Environmental Management*, 277, 111485.
- Khan, A., Mahmood, H., Yasin, S., Moniruzzaman, M., & Iqbal, T. (2022a). A comprehensive overview of advanced oxidation process assisted mono-ethanolamine degradation in aqueous phase: Current advances and future challenges. *Journal of Environmental Chemical Engineering*, 108078.
- Khan, M. T., Shah, I. A., Ihsanullah, I., Naushad, M., Ali, S., Shah, S. H. A., & Mohammad, A. W. (2021b). Hospital wastewater as a source of environmental contamination: An overview of management practices, environmental risks, and treatment processes. *Journal of Water Process Engineering*, 41, 101990.
- Khan, S., Naushad, M., Govarthan, M., Iqbal, J., & Alfadul, S. M. (2022b). Emerging contaminants of high concern for the environment: Current trends and future research. *Environmental Research*, 207, 112609.
- Koutník, I., Vráblová, M., & Bednárek, J. (2020). Reynoutria japonica, an invasive herb as a source of activated carbon for the removal of xenobiotics from water. *Bioresource Technology*, 309, 123315.
- Kumar, R., Qureshi, M., Vishwakarma, D. K., Al-Ansari, N., Kuriqi, A., Elbeltagi, A., & Saraswat, A. (2022). A review on emerging water contaminants and the application of sustainable removal technologies. *Case Studies in Chemical and Environmental Engineering*, 6, 100219.
- Le-Minh, N., Khan, S., Drewes, J., & Stuetz, R. (2010). Fate of antibiotics during municipal water recycling treatment processes. *Water Research*, 44(15), 4295–4323.
- Lee, T. H., Chuah, J., & Snyder, S. A. (2022). Occurrence of emerging contaminants in southeast Asian environments: Present status, challenges, and future prospects. *ACS ES&T Water*.
- Li, X. -F., & Mitch, W. A. (2018). Drinking water disinfection byproducts (DBPs) and human health effects: Multidisciplinary challenges and opportunities. *Environmental Science & Technology*, 52(4), 1681–1689.
- Li, X., Hai, F. I., & Nghiem, L. D. (2011). Simultaneous activated carbon adsorption within a membrane bioreactor for an enhanced micropollutant removal. *Bioresource Technology*, 102(9), 5319–5324.
- Lishman, L., Smyth, S. A., Sarafin, K., Kleywegt, S., Toito, J., Peart, T., Lee, B., Servos, M., Beland, M., & Seto, P.

- (2006). Occurrence and reductions of pharmaceuticals and personal care products and estrogens by municipal wastewater treatment plants in Ontario, Canada. *Science of the Total Environment*, 367(2–3), 544–558.
- Liu, H. -Q., Lam, J. C., Li, W. -W., Yu, H. -Q., & Lam, P. K. (2017). Spatial distribution and removal performance of pharmaceuticals in municipal wastewater treatment plants in China. *Science of the Total Environment*, 586, 1162–1169.
- Locatelli, L., Binning, P. J., Sanchez-Vila, X., Søndergaard, G. L., Rosenberg, L., & Bjerg, P. L. (2019). A simple contaminant fate and transport modelling tool for management and risk assessment of groundwater pollution from contaminated sites. *Journal of Contaminant Hydrology*, 221, 35–49.
- Luque-Espinar, J. A., Navas, N., Chica-Olmo, M., Cantarero-Malagón, S., & Chica-Rivas, L. (2015). Seasonal occurrence and distribution of a group of ECs in the water resources of Granada city metropolitan areas (South of Spain): Pollution of raw drinking water. *Journal of Hydrology*, 531, 612–625.
- M'Arimi, M., Mecha, C., Kiprop, A., & Ramkat, R. (2020). Recent trends in applications of advanced oxidation processes (AOPs) in bioenergy production. *Renewable and Sustainable Energy Reviews*, 121, 109669.
- Marazuela, M., Giustina, A., & Puig-Domingo, M. (2020). Endocrine and metabolic aspects of the COVID-19 pandemic. *Reviews in Endocrine and Metabolic Disorders*, 21(4), 495–507.
- Margot, J., Rossi, L., Barry, D. A., & Holliger, C. (2015). A review of the fate of micropollutants in wastewater treatment plants. *Wiley Interdisciplinary Reviews: Water*, 2(5), 457–487.
- McCuin, R. M., & Clancy, J. L. (2003). Modifications to United States Environmental Protection Agency methods 1622 and 1623 for detection of *Cryptosporidium* oocysts and *Giardia* cysts in water. *Applied and Environmental Microbiology*, 69(1), 267–274.
- Michael, I., Rizzo, L., McArdell, C., Manaia, C., Merlin, C., Schwartz, T., Dagot, C., & Fatta-Kassinos, D. (2013). Urban wastewater treatment plants as hotspots for the release of antibiotics in the environment: A review. *Water Research*, 47(3), 957–995.
- Mohan, D., Singh, K. P., & Singh, V. K. (2006). Trivalent chromium removal from wastewater using low cost activated carbon derived from agricultural waste material and activated carbon fabric cloth. *Journal of Hazardous Materials*, 135(1–3), 280–295.
- Mohapatra, D. P., & Kirpalani, D. M. (2019). Advancement in treatment of wastewater: Fate of emerging contaminants. *The Canadian Journal of Chemical Engineering*, 97(10), 2621–2631.
- Murray, K. E., Thomas, S. M., & Bodour, A. A. (2010). Prioritizing research for trace pollutants and emerging contaminants in the freshwater environment. *Environmental Pollution*, 158(12), 3462–3471.
- Ng, B., Quinete, N., Maldonado, S., Lugo, K., Purrinos, J., Briceño, H., & Gardinali, P. (2021). Understanding the occurrence and distribution of emerging pollutants and endocrine disruptors in sensitive coastal South Florida Ecosystems. *Science of the Total Environment*, 757, 143720.
- Nguyen, P., Carvalho, G., Reis, M. A., & Oehmen, A. (2021). A review of the biotransformations of priority pharmaceuticals in biological wastewater treatment processes. *Water Research*, 188, 116446.
- Noguera-Oviedo, K., & Aga, D. S. (2016). Lessons learned from more than two decades of research on emerging contaminants in the environment. *Journal of Hazardous Materials*, 316, 242–251.
- Ohoro, C., Adeniji, A., Okoh, A., & Okoh, O. (2019). Distribution and chemical analysis of pharmaceuticals and personal care products (PPCPs) in the environmental systems: A review. *International Journal of Environmental Research and Public Health*, 16(17), 3026.
- Oosterhuis, M., Sacher, F., & Ter Laak, T. L. (2013). Prediction of concentration levels of metformin and other high consumption pharmaceuticals in wastewater and regional surface water based on sales data. *Science of the Total Environment*, 442, 380–388.
- Pailier, J. -Y., Krein, A., Pfister, L., Hoffmann, L., & Guignard, C. (2009). Solid phase extraction coupled to liquid chromatography-tandem mass spectrometry analysis of sulfonamides, tetracyclines, analgesics and hormones in surface water and wastewater in Luxembourg. *Science of the Total Environment*, 407(16), 4736–4743.
- Parween, M., Ramanathan, A., & Raju, N. (2017). Waste water management and water quality of river Yamuna in the megacity of Delhi. *International Journal of Environmental Science and Technology*, 14(10), 2109–2124.
- Pazda, M., Kumirska, J., Stepnowski, P., & Mulkiewicz, E. (2019). Antibiotic resistance genes identified in wastewater treatment plant systems—A review. *Science of the Total Environment*, 697, 134023.
- Piai, L., Dykstra, J. E., Adishakti, M. G., Blokland, M., Langenhoff, A. A., & van der Wal, A. (2019). Diffusion of hydrophilic organic micropollutants in granular activated carbon with different pore sizes. *Water Research*, 162, 518–527.
- Pranker, R. J. (2007). Critical compilation of pKa values for pharmaceutical substances. *Profiles of Drug Substances, Excipients and Related Methodology*, 33, 1–33.
- Premjit, Y., Sruthi, N., Pandiselvam, R., & Kothakota, A. (2022). Aqueous ozone: Chemistry, physiochemical properties, microbial inactivation, factors influencing antimicrobial effectiveness, and application in food. *Comprehensive Reviews in Food Science and Food Safety*, 21(2), 1054–1085.
- Primel, E. G., Caldas, S. S., Marube, L. C., & Escarrone, A. L. V. (2017). An overview of advances in dispersive liquid-liquid microextraction for the extraction of pesticides and emerging contaminants from environmental samples. *Trends in Environmental Analytical Chemistry*, 14, 1–18.
- Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T., Kidd, K. A., MacCormack, T. J., Olden, J. D., & Ormerod, S. J. (2019). Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, 94(3), 849–873.
- Ren, Y. -X., Nakano, K., Nomura, M., Chiba, N., & Nishimura, O. (2007). Effects of bacterial activity on estrogen removal in nitrifying activated sludge. *Water Research*, 41(14), 3089–3096.
- Riva, F., Zuccato, E., Davoli, E., Fattore, E., & Castiglioni, S. (2019). Risk assessment of a mixture of emerging contaminants in surface water in a highly urbanized area in Italy. *Journal of Hazardous Materials*, 361, 103–110.

- Rout, P. R., Zhang, T. C., Bhunia, P., & Surampalli, R. Y. (2021). Treatment technologies for emerging contaminants in wastewater treatment plants: A review. *Science of the Total Environment*, 753, 141990.
- Serwecińska, L. (2020). Antimicrobials and antibiotic-resistant bacteria: A risk to the environment and to public health. *Water*, 12(12), 3313.
- Sichel, C., Garcia, C., & Andre, K. (2011). Feasibility studies: UV/chlorine advanced oxidation treatment for the removal of emerging contaminants. *Water Research*, 45(19), 6371–6380.
- Sifakis, S., Androusoyopoulos, V. P., Tsatsakis, A. M., & Spanidos, D. A. (2017). Human exposure to endocrine disrupting chemicals: Effects on the male and female reproductive systems. *Environmental Toxicology and Pharmacology*, 51, 56–70.
- Sivaranjane, R., & Kumar, P. S. (2021). A review on remedial measures for effective separation of emerging contaminants from wastewater. *Environmental Technology & Innovation*, 23, 101741.
- Smiljanić, D., de Gennaro, B., Izzo, F., Langella, A., Daković, A., Germinario, C., Rottinghaus, G. E., Spasojević, M., & Mercurio, M. (2020). Removal of emerging contaminants from water by zeolite-rich composites: A first approach aiming at diclofenac and ketoprofen. *Microporous and Mesoporous Materials*, 298, 110057.
- Snyder, S. A., Adham, S., Redding, A. M., Cannon, F. S., DeCarolis, J., Oppenheimer, J., Wert, E. C., & Yoon, Y. (2007). Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals. *Desalination*, 202(1–3), 156–181.
- Sonawane, C., Alrubaie, A. J., Panchal, H., Chamkha, A. J., Jaber, M. M., Oza, A. D., Zahmatkesh, S., Burduhos-Nergis, D. D., & Burduhos-Nergis, D. P. (2022). Investigation on the impact of different absorber materials in solar still using CFD simulation economic and environmental analysis. *Water*, 14(19), 3031.
- Song, K., Mohseni, M., & Taghipour, F. (2019). Mechanisms investigation on bacterial inactivation through combinations of UV wavelengths. *Water Research*, 163, 114875.
- Stolte, S., Abdulkarim, S., Arning, J., Blomeyer-Nienstedt, A.-K., Bottin-Weber, U., Matzke, M., Ranke, J., Jastorff, B., & Thöming, J. (2008). Primary biodegradation of ionic liquid cations, identification of degradation products of 1-methyl-3-octylimidazolium chloride and electrochemical wastewater treatment of poorly biodegradable compounds. *Green Chemistry*, 10(2), 214–224.
- Sun, S.-P., Zeng, X., & Lemley, A. T. (2013). Nano-magnetite catalyzed heterogeneous Fenton-like degradation of emerging contaminants carbamazepine and ibuprofen in aqueous suspensions and montmorillonite clay slurries at neutral pH. *Journal of Molecular Catalysis a: Chemical*, 371, 94–103.
- Suzuki, Y., & Maruyama, T. (2006). Fate of natural estrogens in batch mixing experiments using municipal sewage and activated sludge. *Water Research*, 40(5), 1061–1069.
- Tang, Y., Li, Y., Zhan, L., Wu, D., Zhang, S., Pang, R., & Xie, B. (2022). Removal of emerging contaminants (bisphenol A and antibiotics) from kitchen wastewater by alkali-modified biochar. *Science of the Total Environment*, 805, 150158.
- Tran, N. H., Reinhard, M., & Gin, K. Y. -H. (2018). Occurrence and fate of emerging contaminants in municipal wastewater treatment plants from different geographical regions—a review. *Water Research*, 133, 182–207.
- Varsha, M., Kumar, P. S., & Rathi, B. S. (2022). A review on recent trends in the removal of emerging contaminants from aquatic environment using low-cost adsorbents. *Chemosphere*, 287, 132270.
- Vasilachi, I. C., Asiminicesei, D. M., Fertu, D. I., & Gavrilescu, M. (2021). Occurrence and fate of emerging pollutants in water environment and options for their removal. *Water*, 13(2), 181.
- Westerhoff, P., Yoon, Y., Snyder, S., & Wert, E. (2005). Fate of endocrine-disruptor, pharmaceutical, and personal care product chemicals during simulated drinking water treatment processes. *Environmental Science & Technology*, 39(17), 6649–6663.
- Xiang, Y., Xu, Z., Wei, Y., Zhou, Y., Yang, X., Yang, Y., Yang, J., Zhang, J., Luo, L., & Zhou, Z. (2019). Carbon-based materials as adsorbent for antibiotics removal: Mechanisms and influencing factors. *Journal of Environmental Management*, 237, 128–138.
- Yang, L. H., Ying, G. G., Su, H. C., Stauber, J. L., Adams, M. S., & Binet, M. T. (2008). Growth-inhibiting effects of 12 antibacterial agents and their mixtures on the freshwater microalga *Pseudokirchneriella subcapitata*. *Environmental Toxicology and Chemistry: An International Journal*, 27(5), 1201–1208.
- Yang, Y., Ok, Y. S., Kim, K. -H., Kwon, E. E., & Tsang, Y. F. (2017). Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review. *Science of the Total Environment*, 596, 303–320.
- Yap, H., Pang, Y., Lim, S., Abdullah, A., Ong, H., & Wu, C. -H. (2019). A comprehensive review on state-of-the-art photo-, sono-, and sonophotocatalytic treatments to degrade emerging contaminants. *International Journal of Environmental Science and Technology*, 16(1), 601–628.
- Zahmatkesh, S., & Pirouzi, A. (2020). Effects of the microalgae, sludge and activated carbon on the wastewater treatment with low organics (weak wastewater). *International Journal of Environmental Science and Technology*, 17(5), 2681–2688.
- Zahmatkesh, S., & Sillanpää, M. (2022). Review of method and a new tool for decline and inactive SARS-CoV-2 in wastewater treatment. *Cleaner Chemical Engineering*, 3, 100037.
- Zahmatkesh, S., Amesho, K. T., & Sillanpää, M. (2022a). A critical review on diverse technologies for advanced wastewater treatment during SARS-CoV-2 pandemic: What do we know? *Journal of Hazardous Materials Advances*, 7, 100121.
- Zahmatkesh, S., Amesho, K. T., Sillanpää, M., & Wang, C. (2022b). Integration of renewable energy in wastewater treatment during covid-19 pandemic: Challenges, opportunities, and progressive research trends. *Cleaner Chemical Engineering*, 3, 100036.
- Zahmatkesh, S., Far, S. S., & Sillanpää, M. (2022c). RSM-D-optimal modeling approach for COD removal from low strength wastewater by microalgae, sludge, and activated carbon—case study mashhad. *Journal of Hazardous Materials Advances*, 7, 100110.
- Zahmatkesh, S., Klemeš, J. J., Bokhari, A., Wang, C., Sillanpää, M., & Amesho, K. (2022d). Reducing chemical oxygen

- demand from low strength wastewater: A novel application of fuzzy logic based simulation in MATLAB. *Computers & Chemical Engineering*, 107944.
- Zahmatkesh, S., Klemeš, J. J., Bokhari, A., Wang, C., Sillanpää, M., Hasan, M., & Amesho, K. T. (2022e). Critical role of Hyssop plant in the possible transmission of SARS-CoV-2 in contaminated human feces and its implications for the prevention of the virus spread in sewage. *Chemosphere*, 305, 135247.
- Zahmatkesh, S., Rezakhani, Y., Arabi, A., Hasan, M., Ahmad, Z., Wang, C., Sillanpää, M., Al-Bahrani M., & Ghodrati I. (2022f). An approach to removing COD and BOD based on polycarbonate mixed matrix membranes that contain hydrous manganese oxide and silver nanoparticles: A novel application of artificial neural network based simulation in MATLAB. *Chemosphere*, 136304.
- Zahmatkesh, S., Sillanpää, M., Rezakhani, Y., & Wang, C. (2022g). Review of concerned SARS-CoV-2 variants like Alpha (B. 1.1. 7), Beta (B. 1.351), Gamma (P. 1), Delta (B. 1.617. 2), and Omicron (B. 1.1. 529), as well as novel methods for reducing and inactivating SARS-CoV-2 mutants in wastewater treatment facilities. *Journal of Hazardous Materials Advances*, 100140.
- Zhang, Z., Hibberd, A., & Zhou, J. L. (2008). Analysis of emerging contaminants in sewage effluent and river water: Comparison between spot and passive sampling. *Analytica Chimica Acta*, 607(1), 37–44.
- Zhao, Y. G., & Zhang, H. (2020). Phase separation in membrane biology: The interplay between membrane-bound organelles and membraneless condensates. *Developmental Cell*, 55(1), 30–44.
- Zheng, Y., Li, Q., Yuan, C., Tao, Q., Zhao, Y., Zhang, G., & Liu, J. (2019). Influence of temperature on adsorption selectivity: Coal-based activated carbon for CH₄ enrichment from coal mine methane. *Powder Technology*, 347, 42–49.

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