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REVIEW

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Mitigation Strategies for Emerging Environmental Contaminants: Pharmaceuticals and Related Personal Care Products

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Abstract
Pharmaceuticals and related personal care products, particularly, are a class of natural and man-made chemicals known as emerging environmental contaminants (EECs) that are being found in aquatic ecosystems more frequently all over the world. These substances, which include hormones, sunscreen agents, parabens, antibiotics, antidepressants, anti-inflammatories, and microplastics, come from a variety of sources, including home trash, municipal wastewater, pharmaceutical company effluents, and agricultural runoff. Because of their persistence, bioactivity, and resistance to standard wastewater treatment techniques, PPCPs pose serious dangers even when they are present in trace amounts, usually in the microgram to nanogram per litre range. Endocrine disruption, antibiotic resistance, bioaccumulation in aquatic organisms, and the environmental sources, destiny, and ecological and human health implications of the major PPCP groups are all categorized and highlighted in this review. The study talks about the problems with regular wastewater treatment plants and looks at new treatment methods that could better remove PPCP, like membrane filtration, advanced oxidation processes (AOPs), electrochemical techniques, and constructed wetlands, to reduce the lasting effects of PPCP pollution in order to lessen the long-term effects of PPCP contamination.

Keywords: Emerging environmental contaminants; Wastewater treatment; Advanced oxidation processes (AOPs); Membrane filtration; Endocrine disruption; Antibiotic resistance

Introduction

Emerging environmental contaminants (EECs), also referred to as emerging organic contaminants, are a class of natural and synthetic chemicals and their byproducts that are found in water bodies all over the world but are not yet being monitored in the environment. However, they have a great potential to negatively impact human health and ecosystems (Geissen et al., 2015). Emerging environmental contaminants can be categorized into a number of groups according to their chemical characteristics and origins. These consist of chemicals such as pesticides, flame retardants, endocrine-disrupting chemicals (EDCs), medicines, related personal care products (PCPs), artificial sweeteners, nanomaterials, and microplastics (Bhagat et al., 2024). Emerging environmental contaminants reach the environment from various sources such as industrial and pharmaceutical wastes, municipal wastewater, agricultural practices, and various human activities. Trace levels of EECs are found, usually in the range of micrograms to nanograms per liter (Murray et al., 2010). These pollutants have drawn more attention recently due to their mobility, persistence, and as-yet-unknown toxicological effects. Pharmaceuticals and related personal care products are considered to be the source of pharmaceutical contaminants in the environment. Although these pollutants are not new to our environment, their biotransformation, metabolite, by-product generation, and other effects can make them persistent (Grajales et al., 2017). While allied personal care products, such as moisturizers, lipsticks, shampoos, hair colors, deodorants, and toothpastes, are used to enhance everyday living, pharmaceuticals are largely used to prevent or treat disease in humans and animals. Because PPCPs are still a global issue, it is imperative that effective treatment solutions be continuously researched and developed to lessen their negative effects on ecosystems and human health.

The goal of this review study is to categorize and identify the main classes of pharmaceuticals and related personal care products that add Emerging Contaminants to wastewater and to evaluate the efficacy of different treatment technologies. The negative effects of these EECs on humans, ecosystems, and the environment are also covered.

Pharmaceuticals and related personal care products (PPCPs)

Drugs or other pharmaceutical chemicals that are discharged into the environment and have the potential to endanger both human health and the ecosystem are known as pharmaceutical emerging contaminants (PECs). The combined source of pharmaceutical pollutants in the environment is thought to be pharmaceuticals and related personal care products. Because of the extensive use of pharmaceuticals in both human and veterinary medicine, pharmaceutical emerging contaminants (PECs), such as active pharmaceutical ingredients (APIs) and their metabolites, are being found in the environment more frequently. Antibiotics, analgesics, steroids, antidepressants, cosmetics, and disinfectants are examples of common PPCPs that are released into the environment through everyday use and disposal (Daughton et al., 1999).

Pharmaceuticals can be divided into a number of types or categories based on the pathology they are meant to address or their use as cures or remedies. They are classified as antidepressants, antibiotics, antivirals, anticoagulants, cardiovascular drugs, analgesics, and anti-inflammatory drugs (Feng et al., 2013). Allied personal care products, such as moisturizers, lipsticks, shampoos, hair colors, deodorants, and toothpaste, are used to enhance everyday living, while pharmaceuticals are used primarily to prevent or treat human and animal diseases. Antiseptics, fragrances, galaxolide, pesticides, preservatives, diethyl phthalate ultraviolet (UV) filters, and disinfection pollutants like triclosan (TCS) and triclocarban are the most likely new contaminants to appear in PCPs. Due to the widespread use of PCPs, these pollutants are being released into the environment at a growing rate every day (Kim et al., 2016). PPCPs produce pharmacologically active pollutants that are resistant to degradation and persistent in aqueous systems (Chen et al., 2014). Degradation of the environment is caused by a variety of sources, including pharmaceutical company industrial discharges, hospital effluents, agricultural runoffs containing pesticides and fertilizers, and human and animal waste from homes and sewers (Gojkovic et al., 2019; Hollman et al., 2020). The presence of PPCPs in water sources has sparked worries around the world because of the potential harm they could do to the environment, human health, and animal health (Moreira et al., 2022). Some documented impacts of PPCPs on living organisms include increased feminization and masculinization in fish populations, cancer, reproductive issues, and neurological damage (Agunbiade et al., 2016). When released into a water stream, PPCP effluent can have genotoxic, mutagenic, and ecotoxicological effects on humans, animals, and plants (Jukosky et al., 2008). Conventional wastewater treatment facilities are unable to effectively remove most emerging pollutants (Morin Crini et al., 2022), but alternative techniques such as advanced oxidation processes (AOPs) and nanotechnology hold promise for their rehabilitation.

Classification of PPCPs as emerging environmental contaminants

The classification of PPCPs as emerging environmental contaminants (EECs) is based on their chemical makeup and sources (fig. 1). Antibiotics, analgesics, antidepressants, hormones, and cosmetic chemicals are among the subgroups of pharmaceuticals and allied personal care products (PPCPs), which constitute a substantial category of newly discovered environmental pollutants. These compounds are introduced into the environment via human and animal excretion, improper disposal methods, and discharges from manufacturing processes. Because PPCPs are physiologically active, even trace amounts of them can have an impact on aquatic life (Daughton *et al.*, 1999). They are becoming a greater concern in environmental monitoring and risk assessment due to their tenacity and extensive use.

Pharmaceutical contaminants

Antibiotics

Antibiotics are commonly used antimicrobial medicines that treat human and animal diseases and encourage livestock growth (Bhushan *et al.*, 2020). Their global consumption has risen by 30% in recent decades (Tiwari *et al.*, 2017), leading to their frequent detection in the environment, particularly tetracyclines, quinolones, macrolides, and sulfonamides. Antibiotics function as pseudo-persistent contaminants as a result of insufficient removal in wastewater treatment, which encourages the spread of antibiotic resistance genes (ARGs), which present major concerns to public health (Tiwari *et al.*, 2017). If not properly managed, over 90% of ingested antibiotics are excreted and can contaminate water systems (Dolliver *et al.*, 2008). Hospitals, veterinary clinics, pharmaceutical companies, animal husbandries, and aquaculture are examples of common suppliers. Antibiotics can contribute to resistant bacteria in soil and water, even at low concentrations; hence, efficient removal technologies are required (Sodhi *et al.*, 2021).

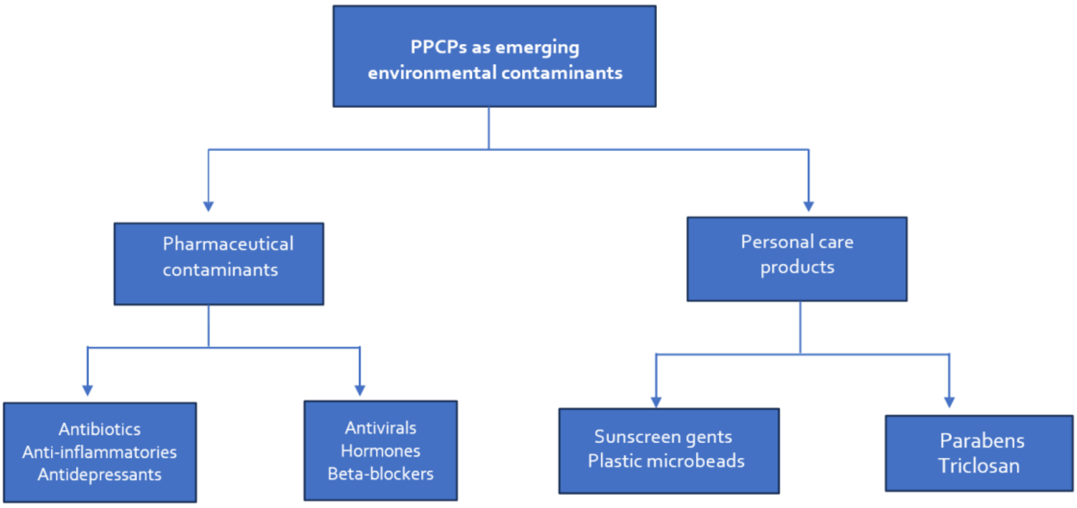

Fig. 1. Classification of pharmaceuticals and related personal care products as emerging environmental contaminants (Dey *et al.*, 2019).

Anti-inflammatories

Due to their extensive usage in treating pain and fever, analgesics and anti- inflammatory medications are among the most prevalent pharmaceutical pollutants (PCs) in wastewater (Batt *et al.*, 2007). These include the commonly used and generally accessible medications diclofenac, ibuprofen, and paracetamol (Kumar *et al.*, 2019). A significant class of these substances, non-steroidal anti-inflammatory medicines (NSAIDs), are present in trace concentrations in drinking water, soil, and even Antarctic ice (Tyumina *et al.*, 2020). Improved wastewater treatment and regulation are desperately needed, as evidenced by their persistence and capacity to induce endocrine disruption, DNA damage, and alterations in gene expression.

Antidepressants

Antidepressants are important pharmaceutical pollutants in aquatic ecosystems because they are chemically persistent and highly accessible (60–100%). They are used to treat depression, anxiety, and chronic pain (Bhushan *et al.*, 2020). Their widespread use and excretion in water create ecotoxicological hazards for aquatic life, influencing development, behaviour, and reproduction. They may also have an effect on human health(Fitzgerald & Watson, 2019). According to Morin-Crini *et al.* (2022), conventional wastewater treatment procedures frequently fail to remove these contaminants. According to Hollman *et al.* (2020), advanced removal methods, including electrochemical oxidation (which removes over 99% of venlafaxine) and biodegradation with activated sludge (which removes 90% of sertraline in 0.25 hours), have demonstrated encouraging outcomes.

Antivirals

Antiviral medications, which are used to treat illnesses such as COVID-19, hepatitis, influenza, and HIV, are becoming environmental pollutants because of their extensive release and persistence through human excretion, inappropriate disposal, and pharmaceutical effluents (Jain *et al.*, 2013). Concerns regarding antiviral resistance and the ecotoxicological effects on aquatic species like fish and algae are raised by their high bioactivity and resistance to breakdown in traditional wastewater treatment (Wallace *et al.*, 2023). These substances have the ability to upset microbial communities and cause gram-positive and gram-negative bacteria to become resistant to antibiotics, which emphasizes the necessity of better removal techniques in wastewater treatment facilities (Daughton & Ternes, 1999).

Hormones

Estrone, estradiol, and estriol are examples of both natural and synthetic hormones that are widely utilized in medical, animal husbandry, and agriculture to treat cancer, hormonal imbalances, and contraception. Endocrine-disrupting chemicals (EDCs) are frequently discovered in drinking water, surface water, and groundwater due to their persistence and the inability of wastewater treatment plants to fully eliminate them. (Pironti *et al*., 2021). Hormones can disrupt the endocrine systems of both humans and wildlife once they are in the environment, resulting in conditions like endometriosis, thyroid dysfunction, and infertility (Wee *et al*., 2019). There is a serious ecological and public health risk associated with their widespread release through home sewage, industrial waste, and livestock effluents.

Beta-blockers

Although beta blockers like propranolol, atenolol, and metoprolol are frequently used to treat cardiovascular conditions, their persistence and inability to be completely eliminated by traditional wastewater treatment facilities have made them environmental pollutants. These medications are eliminated in their active state and found in sediments and surface waters, where they can be found in amounts of up to 86 ng/g in places affected by effluent (Yi *et al*., 2020). Aquatic organisms' heart rate, reproduction, and behaviour can all be impacted by beta blockers' disruption of endocrine functioning, which could result in ecological imbalances. Their bioaccumulation potential and stability underscore the pressing need for better treatment technology and appropriate disposal methods.

Allied personal care products

Sunscreen agents

UV filters, sometimes referred to as sunscreen agents, are utilized in non-cosmetic and personal care items to protect users from damaging ultraviolet radiation. These filters, which can be either organic or inorganic, get into aquatic ecosystems through things like washing clothes, swimming, and releasing wastewater (Ramos *et al*., 2016). EHMC, OC, and benzophenone derivatives are examples of organic UV filters that are persistent, difficult to remove by wastewater treatment, and have been connected to reproductive harm, coral bleaching, and endocrine disruption in aquatic animals. Even though they are good UV blockers, inorganic filters like TiO_2 and ZnO nanoparticles can produce reactive oxygen species (ROS) when exposed to UV light, which can damage marine life (Ahmad *et al*., 2024). Their long-term ecological impact is still a rising concern, as their environmental behaviour is controlled by elements including pH and salinity.

Triclosan

A lipid-soluble, broad-spectrum antimicrobial, triclosan (TCS) is found in many household goods, medical equipment, and personal care products like toothpaste, soaps, deodorants, and shampoos. TCS is an important developing pollutant because of its tenacity and extensive use. During wastewater treatment, it can produce more toxic chlorinated byproducts, increasing the risks to the environment and human health (Yueh *et al*., 2016). TCS disrupts endocrine systems, inhibits growth, and hinders reproduction, particularly in fish and invertebrates, all of which have an impact on aquatic ecology. Due to inadequate removal in treatment plants, it is frequently found in domestic sewage and contributes to antibiotic resistance. The range of concentrations in sediment and water is µg/L to ng/L (Dhillon *et al*., 2015).

Parabens

Because of their antibacterial qualities and chemical stability, parabens are synthetic preservatives that are frequently found in food, medicine, and cosmetics. Methylparaben, ethyl paraben, propylparaben, butylparaben, and benzyl paraben are common varieties. Parabens are currently regarded as emergent environmental contaminants because of their extensive use, tenacity, and possible health hazards. There are worries regarding their endocrine-disrupting effects and connections to reproductive and developmental problems because they can penetrate human skin and have been found in a variety of human tissues and fluids, including breast tissue and urine. Because parabens cannot be completely eliminated by conventional wastewater treatment facilities, they are frequently found in aquatic settings, where methylparaben concentrations can reach 56.7 µg/L (Zolfaghari *et al*., 2022). These results underline how urgently better regulations and cutting-edge treatment methods are needed.

Plastic microbeads

Plastic microbeads, which are synthetic polymer particles consisting of polyethylene (PE), polypropylene (PP), or PET and are usually smaller than 5 mm, are frequently found in personal care products including toothpaste, cleansers, and scrubs. They are meant to be washed off, but they frequently evade wastewater treatment and end up in aquatic habitats where marine life confuses them for food. Additionally, microbeads have the ability to absorb pollutants such as POPs and heavy metals, making them more harmful when consumed by aquatic life and perhaps making their way into the human food chain. Countries like the U.S., U.K., and Canada have prohibited their usage in rinse-off cosmetics due to health and environmental concerns (Kershaw, 2016), which has led to a move toward biodegradable substitutes.

Origins and pathways of pharmaceuticals and related personal care products (PPCPs)

After a consumer product is used and consumed, the constituent chemicals and their metabolites might enter the environment through a number of paths, as illustrated in Fig. 2. Landfills, wastewater treatment plants, and sewage treatment plants (STPs) are the primary sources of PPCP contamination that are tracked worldwide (Daughton and Ternes, 1999). The extensive use of pharmaceuticals and personal care products (PPCPs) in agriculture, human and veterinary medicine, and personal care is the main way that these substances enter the environment.

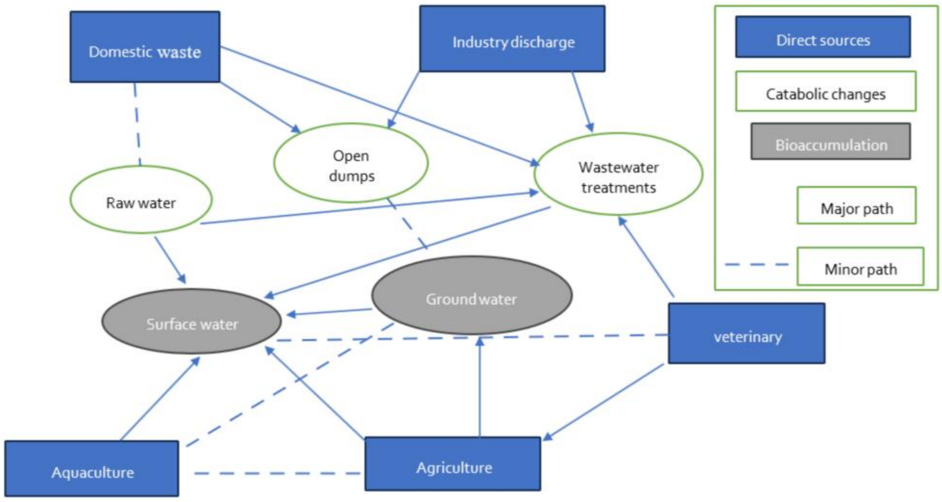

Fig. 2. Origin and pathways of pharmaceuticals and personal care products (PPCPs) in the environment (Chen et al., 2014)

Industrial discharges

Industrial effluents, especially from pharmaceutical manufacturing facilities, are one of the main ways that PPCPs enter aquatic systems. If not properly controlled, industrial procedures used in the synthesis, formulation, and packing of pharmaceutical substances can discharge significant amounts of active pharmaceutical ingredients (APIs) into adjacent water bodies. According to studies, these facilities' effluents frequently contain significant levels of unmetabolized medicines and the products of their transformation, which might linger in the environment and endanger aquatic life (Ziylan-Yavas et al., 2022). Particularly because of their regular detection and resistance to traditional treatment methods, some PPCPs, including carbamazepine, sulfamethoxazole, and diclofenac, have been suggested as markers of raw wastewater pollution in urban surface waters (Ziylan-Yavas et al., 2022). This emphasizes how important it is to have strong pre-treatment procedures in place at the source in order to lower the loads of pollutants from industrial discharges.

Domestic and municipal waste

Untreated or inadequately treated household and municipal wastewater discharge is a major source of PPCPs in the environment. These substances are released into residential sewage as a result of routine human activities such as the use of soaps, detergents, cosmetics, and pharmaceuticals. PPCPs enter wastewater treatment plants (WWTPs) after being flushed down toilets or drains, and many of these facilities lack the necessary equipment to adequately remove these micro-contaminants. As a result, large amounts of PPCPs are released into surface waters after passing through these systems (Kallenborn et al., 2017). This problem is especially noticeable in isolated or underdeveloped areas, including the Arctic regions, where advanced wastewater treatment equipment is frequently non-existent or very limited. PPCP concentrations in these regions can rise to levels that have an impact on aquatic life, interfere with endocrine functions, and fuel the emergence of antibiotic resistance. Urban population growth around the world makes this problem worse, necessitating immediate investment in cutting-edge wastewater treatment equipment capable of managing the intricate removal of PPCP.

Veterinary pharmaceuticals

Another significant source of PPCPs in the environment is veterinary medicines, which are mostly used in pest control and animal husbandry. To maintain health and increase output, livestock are frequently given antibiotics, growth boosters, and antiparasitic. A sizable amount of these medications is eliminated unmetabolized and then ends up in the environment as manure. A range of PPCPs are introduced into the soil and, via leaching and runoff, into adjacent water bodies when such manure is used as fertilizer on agricultural land (Daughton & Ternes, 1999). This process is additionally aided by WWTP-derived biosolids, which are frequently applied as soil supplements. These compounds may accumulate in soils as a result of long-term use, endangering the soil microbiota and possibly making their way into the food chain. Furthermore, using veterinary PPCPs in aquaculture raises additional environmental concerns, especially in freshwater and coastal systems where drug residues can build up and have an impact on creatures that are not the intended target.

Agricultural waste

Animal manure and sewage sludge (biosolids) are the main ways that PPCPs get into the environment in agricultural settings. Veterinary medications are frequently given to livestock, including cattle, pigs, and poultry, for the purposes of parasite control, growth enhancement, and disease prevention. Many of these medications stay active in manure after being eliminated unmetabolized (Kümmerer, 2009). Applying this manure to agricultural areas, particularly during rainfall or irrigation events, serves as a route for the entry of pharmaceuticals into the soil and, eventually, into adjacent water bodies through leaching and surface runoff. Additionally, because these biosolids frequently contain traces of veterinary and human medications that were not entirely eliminated during wastewater treatment, using treated sewage sludge as a soil amendment can lead to PPCP contamination. Long-term PPCP buildup in agricultural soils can change microbial ecosystems, encourage the emergence of antibiotic-resistant genes (ARGs), and endanger groundwater quality and terrestrial species.

Conjectures behind release and movement of PPCPs

Following are some generally acknowledged theories about the release and movement of PPCPs: (Ebele et al., 2017)

Metabolic Incompleteness and Excretion in Human Therapy: During therapy, pharmaceuticals that are absorbed by the living body are not fully broken down and are then expelled, contaminating sewage systems and septic tanks. For example, the human body does not react at all to methotrexate.

Limitations of Wastewater Treatment: These pollutants cannot be removed by sewage treatment plants, and when the recovered water is utilized for irrigation and the dried organic sludge is converted to manure, significant proportions of these compounds dissolve and bio adsorb.

Direct Industrial Emissions: A direct and verifiable source of PPCPs is manufacturers of consumer goods.

Despite being used as fertilizer, the treated effluent sludge from STP is dumped straight into freshwater ecosystems, damaging the water and soil.

Runoff from Veterinary and Aquaculture Pharmaceuticals: Chemicals from veterinary drugs used in animal husbandry often leak into groundwater through the excrement of animals. It is possible for chemicals used in aquaculture to immediately reach surface waters.

Domestic Use of Personal Care Products: Washing, cleaning, and bathing activities from homes and

businesses can easily release externally applied consumer goods into sewers.

Inappropriate Pharmaceutical Waste Disposal: Solid wastes dumped in landfills sometimes contain discarded goods and expired prescriptions, which are a long-term source of primary PPCPs, along with their bio-transformed derivatives that dissolve in the leachate and easily contaminate groundwater.

Environmental risks with pharmaceuticals and allied personal care products

The metabolites of several PPCPs have been found to be more hazardous in the environment than the parent compounds themselves, and they are all produced in vast quantities all over the world, each with a distinct physiological effect. PPCPs' physiochemical characteristics enable their persistence in an aquatic environment. It is very concerning because traditional wastewater treatment methods are unable to remove the chemicals. Serious risks can arise from prolonged exposure and the synergistic action of multiple PPCPs occurring in low quantities in the same ecosystem. Because they live in an environment where PPCP toxins are most mobile, fish are most sensitive to these pollutants (Li, 2014). Chronic side effects, such as diclofenac's projected direct negative effects on fish organs, may reduce survival chances and result in unsuccessful reproduction. Additionally, adverse effects on algae must be ignored. Phototrophic organisms and algae control the water's cycle of nutrients and energy. Because of this, their activity is essential to the overall health of the ecosystem. Algal chloroplasts have been shown to suffer significant harm when carbamazepine and diclofenac are together. (Vannini et al., 2011). Hormones in aquatic environments have the potential to interfere with the endocrine system's function, which can upset the homeostasis of species that are not their intended targets. The emergence of antibiotic tolerance in naturally occurring bacteria is a significant worry regarding PPCP contamination, especially by antibiotics. Furthermore, it has been noted that ciprofloxacin is hazardous to green algae.

Mitigation strategies of pharmaceuticals and allied personal care products

Over the time, a number of wastewater treatment technologies have been created (Table 1.) Chemical treatments require sophisticated oxidation processes, biological methods rely on the biodegradation of contaminants by specific bacteria in specially built treatment chambers or reactors, and physical treatment uses absorbents.

Table 1. Mitigation treatment, mechanism, and advantages of PPCP contaminated wastewater (Kumar *et al.*, 2022)

Mitigation treatment	Mechanism	Advantages
Conventional WWTPs	Sedimentation and microbial degradation	Reliable and affordable for the elimination of general pollutants
Advanced Oxidation Processes	Hydroxyl radicals (O_3, UV/H_2O_2, etc.) are produced.	Broad-spectrum efficacy against different PPCPs
Membrane Filtration	Physical separation depending on size via tiny membrane pores	Compact design, wide PPCP removal
Activated Carbon Adsorption	Adsorption on the surface of carbon	Affordable and environmentally friendly
Constructed Wetlands	Plant absorption, sorption, and biodegradation	Affordable and environmentally friendly
Advanced Biological Treatment	Utilizing biofilm procedures and prolonging retention periods	More effective elimination of PPCP than conventional WWTPs
Electrochemical Methods	Pollutant oxidation caused by applied electric current	Effective PPCP degradation without the use of chemicals
Photocatalysis	UV-activated catalysts to break down contaminants, such as TiO_2	PPCPs are broken down into nontoxic products
Ion Exchange Resins	Charged ion exchange with particular PPCPs	High selectivity for the elimination of certain compounds

Advanced wastewater treatment technologies

To address the growing environmental problems related to pharmaceuticals and allied personal care products (PPCPs) in wastewater, a range of treatment technologies have been developed and put into use. While conventional WWTPs are mainly intended to remove pathogens, nutrients, and bulk organic matter, they are frequently insufficient to remove trace contaminants, including pharmaceuticals and personal care products (PPCPs). Advanced treatment technologies that can more efficiently remove or degrade PPCPs are becoming more and more popular as worries about their persistence and ecotoxicological impacts increase. The next part describes the methods, benefits, and drawbacks of many cutting- edge strategies for improved PPCP elimination that are presently being investigated and put into practice.

Conventional wastewater treatment plants (WWTPs)

Traditional wastewater treatment facilities are made to filter out common contaminants from industrial and municipal wastewater, including nutrients, organic debris, and suspended particulates. Aeration, microbial degradation, sedimentation, and other physical, chemical, and biological processes are frequently combined in these systems**.** Conventional WWTPs mostly use biologically degrading mechanisms like activated sludge and physical processes like sedimentation. These devices are extensively used and reasonably priced, although they are not very effective at eliminating PPCPs. Numerous PPCPs can flow past these treatment systems unchanged, leading to their ongoing discharge into surface waters, especially those that are hydrophilic, chemically stable, or biologically inert (Kaswan *et al.*, 2023). In order to handle these new contaminants, it is imperative to include more specific treatment steps.

Advanced Oxidation Processes (AOPs)

By producing extremely reactive species, primarily hydroxyl radicals (OH), Advanced Oxidation Processes (AOPs) are a class of chemical treatment techniques intended to eliminate organic contaminants, especially PPCPs, from water. PPCPs are among the many organic micropollutants that can be broken down by the extremely reactive hydroxyl radicals (OH) produced by AOPs, a class of chemical treatment technologies. Combinations of ozone (O_3), ultraviolet (UV) light, and hydrogen peroxide (H_2O_2) are common AOPs. These radicals damage PPCPs' molecular structure, changing them into less harmful or non-toxic byproducts. Although AOPs have demonstrated excellent removal efficiency for persistent pharmaceuticals, the procedure can be expensive, energy-intensive, and lead to the creation of transformation byproducts that could be hazardous (Kaswan *et al*., 2023).

Membrane filtration

Membrane filtration is a technology that physically separates contaminants from water by forcing it through semi-permeable membranes having incredibly small pore sizes. Commonly used techniques for the separation of pharmaceuticals and allied personal care products (PPCPs) are reverse osmosis (RO) and nanofiltration (NF), which are based on the molecular size and charge. Numerous hydrophilic and hydrophobic PPCPs can be effectively removed using these techniques. Despite their effectiveness, membrane filtration systems have a number of drawbacks, such as high energy requirements, membrane fouling, high operating costs, and the production of a concentrated waste stream that needs to be disposed of carefully (Kaswan *et al*., 2023).

Activated carbon adsorption

A popular technique for eliminating organic micropollutants from water, such as pharmaceuticals and allied personal care products (PPCPs), is activated carbon adsorption. This method uses activated carbon, either in granular activated carbon (GAC) or powdered activated carbon (PAC), to adsorb pollutants onto its surface due to its porous structure and huge surface area. This process depends on impurities adhering to the carbon material's porous surface. Contaminants, primarily hydrophobic compounds, are drawn to and stick to the surface of the carbon particles when contaminated water comes into contact with them. Van der Waals forces, hydrophobic interactions, and electrostatic interactions are the main forces causing this adsorption. Integrating it into current treatment systems is quite simple. But over time, carbon saturation calls for regular replacement or regeneration, which raises operating expenses (Kaswan *et al*., 2023).

Constructed wetlands

Constructed wetlands (CWs) are designed environments that treat wastewater using a mix of biological, chemical, and physical processes. Though they are constructed and run to treat particular contaminants, such as medications and personal care items (PPCPs), these systems replicate the processes of natural wetlands. In CWs, water runs through a vegetated region where microbes, plants, and soil collaborate to eliminate contaminants**.** Constructed wetlands remediate wastewater by using natural processes such as sorption, microbial decomposition, and plant uptake. These technologies provide a low-cost and environmentally friendly substitute for PPCP removal, especially in decentralized or rural locations. Despite being energy-efficient and low-maintenance, CWs' performance can vary depending on a number of variables, including temperature, vegetation type, and hydraulic loading rate. In order to attain the best possible treatment efficiency, they also need a lot of acreage (Kaswan *et al*., 2023).

Electrochemical method

Advanced treatment techniques known as electrochemical methods use electrical energy to propel chemical reactions that break down or eliminate contaminants from water, such as pharmaceuticals and personal care products (PPCPs). By applying an electric current to water, these techniques enable oxidation or reduction reactions that eliminate pollutants without the use of extra chemicals. Using electric current to create redox reactions that break down organic contaminants in water is known as electrochemical oxidation. These systems can target a variety of PPCPs and don't need the addition of further chemicals. However, their actual application is limited by problems including electrode degradation and high operating expenses, and they are frequently energy intensive. However, because of their high oxidative potential and minimal secondary pollutants, electrochemical techniques are seen as promising (Zhang *et al*., 2022).

Photocatalysis

By using light-activated catalysts, usually titanium dioxide (TiO_2), photocatalysis produces reactive species that can convert PPCPs into innocuous byproducts. TiO_2 is photoactivated under UV light, which promotes the oxidative breakdown of pollutants. The low UV content of natural sunlight limits photocatalysis's effectiveness, and the expensive cost of catalysts and difficulties with catalyst recovery continue to be major obstacles to its widespread use (Kaswan *et al*., 2023; Zhang *et al*., 2022).

Source Management and Waste Reduction

Source control refers to the methods and measures used to minimize or completely stop the release of pharmaceuticals and personal care products (PPCPs) into the environment at the point of origin, as opposed to addressing contamination after it has begun. One of the best and most long-lasting strategies for dealing with PPCP pollution is this one. Source control stops the pollutants from getting into soils, water systems, and the air, where they could linger and negatively impact ecosystems and human health. To reduce the amount of PPCPs released into the environment, there are a few essential tactics:

Pharmaceutical Take-Back Programs

Encouraging pharmaceutical take-back programs is one of the best ways to lower PPCP contamination. By enabling customers to return unwanted or expired pharmaceuticals to approved facilities, these programs lessen the possibility of inappropriate disposal practices like flushing drugs down the toilet or throwing them in the trash. For example, National Prescription Drug Take-Back Days, which are regularly held by the Drug Enforcement Administration (DEA) in the United States, have been demonstrated to dramatically lower the quantity of pharmaceuticals that end up in the trash.

Public Awareness

The impact of PPCPs can be lessened by public education efforts that emphasize how to properly dispose of medications, including not flushing them down the toilet or throwing them in the trash. Customers can also receive education on how to select personal care items that are less harmful to the environment and contain fewer chemicals.

Regulatory Actions

Governments have the authority to impose laws that limit the use of dangerous chemicals in medications and personal hygiene products. For instance, in a number of nations, outlawing the use of specific dangerous chemicals, such as triclosan in soaps, has been shown to be a successful strategy (Dewitt *et al*., 2022).

Regulations and guidelines

Strong policy development and the application of efficient regulatory frameworks are necessary to reduce the environmental contamination caused by pharmaceuticals and personal care products (PPCPs). In contrast to traditional pollutants, PPCPs are bioactive, frequently persistent, and present in tiny amounts that can nonetheless have an impact on aquatic life and ecosystems. Therefore, developing legally enforceable regulations and tactics to regulate their release, use, disposal, and monitoring is a crucial task for governments, environmental agencies, and international organizations.

Wastewater regulations

In order to lower the concentration of PPCPs in aquatic ecosystems, stricter rules governing the release of residues from personal care and pharmaceutical products into water bodies are necessary. PPCPs in the aquatic environment are subject to monitoring and regulation under the European Union's Water Framework Directive (EC, 2020).

Pharmaceutical industry regulations

PPCP contamination can be considerably decreased by establishing clear regulations for the pharmaceutical industry, such as limiting the discharge of active pharmaceutical ingredients (APIs) into wastewater during production and guaranteeing appropriate waste disposal procedures (Müller *et al*.,2023).

Environmental risk assessment

A fundamental tool used by regulatory bodies to assess the possible ecological and environmental effects of chemicals, such as pharmaceuticals and personal care products (PPCPs), is Environmental Risk Assessment (ERA). To ascertain the possible impacts of pharmaceuticals and related personal care items on ecosystems, regulatory bodies are required to carry out thorough environmental risk assessments. Better management procedures and safer formulations for these chemicals can be developed with the help of these evaluations.

Conclusion

Pharmaceuticals and related personal care products (PPCPs) are widely used, persistent, and biologically active, making them important environmental contaminants. Found in trace concentrations in a variety of water bodies, these substances frequently evade traditional wastewater treatment systems and find their way into the environment through domestic waste, agricultural runoff, and industrial discharge. There are significant ecological and health dangers associated with PPCPs, such as hormones, UV filters, antibiotics, and microplastics. These risks include endocrine disruption, antibiotic resistance, and reproductive harm to aquatic creatures. Adsorption, membrane filtration, and AOPs are examples of advanced treatment methods that have the ability to effectively remove PPCP. Standardized rules, environmental risk assessments, and greater public awareness are still desperately needed, nevertheless. To maintain the preservation of ecosystems and public health, PPCP pollution must be addressed through an integrated strategy that includes policy creation, technical innovation, and continuing research.

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