Navigating Emerging Contaminants: An In-Depth Review of Sources, Risks, and Remediation Strategies

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Abstract

Water contamination through ECs is increasingly troublesome because of enhanced urbanization, industrialization, and agricultural practices. ECs are uncontrolled anthropogenic chemicals found primarily in airborne contaminants, soil, water, food, and human/animal tissues. This category includes a wide range of pollutants, consisting of pesticides, pharmaceuticals, pills, cosmetics, personal care products, surfactants, industrial chemical compounds, cleaning agents, food packaging substances, metalloids, food additives, nanomaterials, microplastics, rare earth elements and pathogens. The number one resources of ECs include household discharges, industrial wastewater, agricultural runoff, cattle and aquaculture operations, hospital effluents and landfill leachates. These contaminants can persist in the environment for prolonged intervals, inflicting adverse consequences to human health, flora and fauna and ecosystems. To cope with the challenges posed via ECs, numerous degradation and removal strategies have been investigated, such as physical, chemical, and organic methods. This review paper gives a comprehensive assessment of ECs, detailing their sources, regulatory status, and identity technologies. It also evaluates latest improvements in treatment technologies for EC elimination, highlighting the effectiveness and barriers of different physical, chemical, and biological strategies. By means of consolidating cutting-edge research, this paper objectives to enhance knowledge of EC management and offer insights into future studies to improve treatment tactics and mitigate the dangerous effects of these contaminants.

Keywords: Emerging Contaminants (ECs), Pollution, Water Pollution, Industrial wastewater, Toxicity

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6.2.3 Clay Minerals Assisted Adsorption

Due to varying levels of nitrogen, magnesium, iron and other minerals, clay minerals, which are composed of hydrated aluminium phyllosilicates and cations like iron, magnesium, alkali, and alkaline earth metals, show different removal efficiencies (Shahid et al., 2021). Studies conducted by Paolo et al. (2012) and Zhao et al. (2012) have demonstrated that modifying their cation exchange capacity and specific surface area can enhance their efficiency. Maraschi et al. (2014) showed that modified zeolites are able to achieve up to 99% removal of fluoroquinolones from water. Natural clay has shown to remove ECs such as amoxicillin and trimethoprim. Additionally, enrofloxacin and fluoroquinolone were also removed using zeolites (Maraschi et al. 2014). Wu et al. (2012) and Wu et al. (2010) used montmorillonite to adsorb ciprofloxacin and found removal efficiencies of 35% and 100% under various conditions. Fischer et al. (2020) demonstrated effective adsorption of 21 different ECs on the surfaces of several zeolite-based adsorbents. Other studies reported high ciprofloxacin and ampicillin removal efficiencies using zeolite and alum-based adsorbents (Rahardjo et al., 2011; El-Shafey et al., 2012). Their low cost and abundance in nature make them a desirable option for large-scale water treatment.

6.2.4 Hydrothermal carbonization (HTC) of biomass

Hydrothermal carbonisation (HTC) is a thermochemical conversion process without redrying, converting wet biomass into hydrochar, a solid material rich in carbon rich (Babeker & Chen, 2021). This process reduces the oxygen and hydrogen content of the biomass while doing so in an aqueous environment at 180–250 °C under autogenous pressure (Wang et al., 2018). Hydrochar gained attention because of its potential as a precursor for activated carbon, which is widely used in wastewater management, soil remediation, and as fuel. In addition to the commonly used lignocellulose biomass, HTC can be applied to an array of derived waste, such as solid municipal waste, algae, and sewage sludge (Kambo & Dutta, 2015). The degree of coalification and reaction severity of the raw biomass are controlled by hydrothermal parameters, notably temperature and residence time (Wiedner et al., 2013). According to Azzaz et al. (2020), the oxygen functional groups in hydrochar react with organic molecules and heavy metals. Ma et al. (2021) demonstrated hydrochar had an adsorption amount of 145 mg/g for tetracycline and 74.2 mg/g for ciprofloxacin. In order to remove tetracycline, copper, and Zinc, Deng et al. (2020) produced hydrochar which demonstrated adsorption amounts of 361.7, 214.7, and 227.3 mg/g, respectively. In a recent study, Qin et al. (2023) reported $PO4^{3}$-modified hydrochar had an adsorption capacity of 119.61 mg/g for lead and 98.38 mg/g for ciprofloxacin. Based on the feed stock, pyrolysis and carbonisation parameters, as well as activation/modification methods, hydrochar's phosphate adsorption capacities range from 14 to 386 mg g^{-1} (Shyam et al., 2022). A recent review (Jalilian et al., 2024) goes into further detail about the application hydrochar and modified hydrochar in treating wastewater, CO_2adsorption, removing pharmaceuticals, heavy metals, and organic dyes (both cationic and anionic). The biggest advantage of HTC is the conservation of energy that would have been spend in predrying, as well as the utilization of organic waste to produce hydrochar which is useful for bioremediation.

6.2.5 Coagulation-flocculation

Coagulation flocculation, one of the conventional ways used for treating wastewater, destabilizes the colloidal particles and then aggregates them to form clumps, making them easier to remove (Teh et al., 2016). Huerta-Fontela et al. (2011) reported using aluminium sulfate $[Al_2(SO_4)_3]$, a coagulant, along with sand filtration removed medicated compounds like warfarin, betaxolol, and hydrochlorothiazide by 80%. This method has also shown to be potent in eliminating some hydrophobic pharmaceuticals like doxazosin and chlordiazepoxide but its efficiency drops to less than 5% for compounds like estrone and estradiol (Bundy et al., 2007; Le-Minh et al., 2010). It also demonstrated to remove musky compounds, commonly found in skincare products and cosmetics. Suarez et al. (2009) reported this process could achieve removal rates of 78%, 79%, and 83% for tonalide, galaxolide, and celestolide, respectively, in hospital wastewater. Nyström et al. (2020) demonstrated the effectiveness of this process in treating stormwater, it was effective in lowering oil, polycyclic aromatic hydrocarbons (PAHs) and total metals (90% reduction). Coagulation-flocculation is an efficient technique for removing a variety of ECs from water and therefore is widely applied attributing to its simplicity and ease.

6.2.6 Advanced oxidation processes

Advanced oxidation processes (AOP) facilitate the conversion of contaminants into into less toxic and more easily degradable substances by generating free radicals, specifically hydroxyl radicals (Ikehata et al., 2008).UV radiation is typically the first step in the production of hydroxyl radicals, which can be produced using a variety of techniques, including ozone (O3), hydrogen peroxide (H2O2), photolysis with ultraviolet light, homogeneous Fenton reagent, heterogeneous semiconductors, electrolysis with ultrasound (sonolysis), and microwave radiation (Gogoi et al., 2018; Pavithara and Jaikumar, 2019). Sichel et al. (2011), , using UV/chlorine advanced oxidation, degraded ECs such as 17α- ethinylestradiol, sulfamethoxazole, diclofenac, benzotriazole, carbamazepine, tolyltriazole, iopamidol, desethylatrazine and carbamazepine. AOPs based on ozone treatment have been shown to be effective in treating wastewater containing a variety of pharmaceuticals, including angiotensin II receptor antagonists, cocaine, its metabolite benzoylecgonine, anti-inflammatory medicines, cholesterol-lowering statins, and antibiotics (Ibannz et al. 2013). Research has demonstrated the efficacy of AOPs in degrading pharmaceutical compounds in water, either individually or in combination with other degradation methods—over 80% and up to 90%—when used with various processes namely coagulation, flocculation, nanofiltration, and electrocatalytic oxidation (Pavithra & Jaikumar, 2019; Rayaroth et al., 2016).

6.2 6.1 Photocatalysis

Photocatalysis, also called accelerated oxidation, is a chemical reaction in which pollutants are oxidized more quickly by light-activated catalysts (Macwan et al., 2011; Sornalingam et al., 2016). Semiconductor metal oxides, like titanium dioxide (TiO2), are commonly used as photocatalysts because of their affordability, stability, and capacity to produce reactive species when exposed to ultraviolet light. A study showed main wastewater effluent containing pharmaceutical compounds like sulfamethoxazole, metoprolol, acetaminophen, hydrochlorothiazide, caffeine, carbamazepine, diclofenac, antipyrine, and ketorolac, was treated using aerobic degradation combined with heterogeneous solar photocatalysis using TiO_2 (Gimeno et al., 2016). Prieto Rodríguez et al. (2013) and Shahid et al. (2021) have reported great removal efficiency (99-100%) of antibiotics like amoxicillin, ampicillin, and chloxacclin, as well as pesticides like aldrin, diazinon, and malathion, using photocatalysis in the presence of H2O2.

6.2 6.2 Fenton and Fenton Processes

Fenton oxidation is a chemical reaction where iron reacts with H2O2, producing hydroxyl(*OH) radicals (Shemer et al., 2006). Widely used in AOPs due to their ease of use and effectiveness in breaking down a variety of ECs. Lucas and Peres (2015) achieved deterioration of four kinds of parabens by Fenton reagent: methylparaben, ethylparaben, propylparaben, and butylparaben. Solar Photoelectro-Fenton (SPEF) process degraded beta blockers such cendol, propranolol hydrochloride, and metoprolol tartrate with an efficiency of 88–93% (Klamerth and others, 2013).

6.2.7 Ozonation

Ozone is a widely recognised and effective oxidant that can chemically react with many natural and non-toxic molecules (Coca et al., 2016). The reaction is caused by other oxidants such as hydroxyl radicals (HO*), which are formed when ozone has side reactions with effluent organic matter (EfOM) components such as phenols or amines (Rizzo et al., 2019). Numerous studies have demonstrated that ozonation is highly effective in removing personal care products and pharmaceuticals, with most of these contaminants being successfully eliminated. It is important to understand that ozone has a brief 1/2 life, and if its awareness exceeds about 23%, it will become risky (Shen et al., 2019). Ozone reveals selectivity, mainly targeting electron-wealthy rising contaminants ECs with deprotonating amine action such as sulfamethoxazole and trimethoprim, especially at low pH levels. In assessment, hydroxyl radicals (HO*) are non-selective and highly reactive, allowing them to attack a large spectrum of ECs, together with those proof against ozone, mainly at higher pH degrees (Rizzo et al., 2019; Gogoi et al., 2018; Barbosa et al., 2016; Sui et al.,2010) .

6.2.8 Chlorination

Chlorination was carried out in one-litre amber glass bottles at room temperature (21 ± 2 °C). Free chlorine was added to each litre of simulated drinking water to achieve a Cl2 concentration of 9.0 mg/L. UV irradiation was conducted with a 254 nm wavelength light source from a 41 W low-pressure mercury lamp (Light Sources, Orange, CT, USA) (Huang et al., 2019). A quasi-collimated beam with a 254 nm wavelength, generated by 41 W low-pressure mercury lamps (Light Sources, Orange, CT, USA), was used for UV irradiation (Huang et al., 2019). The comparison of inactivation rates between antibiotic-resistant bacteria and general heterotrophic bacteria during chlorination highlights the relative resistance of antibiotic-resistant strains to chlorine. The bacterial response, survival, and inactivation patterns of both heterotrophic and antibiotic-resistant bacteria during chlorination were assessed. Data suggest that ampicillin- and penicillin-resistant bacteria in secondary wastewater are more susceptible to chlorine than other bacteria due to bacterial inactivation (Templeton et al., 2009).

6.2.9 UV irradiation

The average irradiance was measured at 0.8 mW/cm^2 using iodide/iodate chemical actinometry (Boltan et al.,2003). To speed up the reaction, all test solutions were agitated for 30 minutes at 350 rpm. 1440 mJ/cm^2 was the final UV dose. Standard procedures used in UV/chlorine advanced oxidation processes were used to determine the dosage of chlorine and length of UV irradiation. Wang et al.(2015) The majority of studies on the behaviour of micropollutants in UV or UV-based processes have been carried out in laboratory environments, usually with solutions prepared with lab water. Wastewater or natural river water samples are rarely used in research, resulting in limited data on the behaviour of micropollutants in wastewater during UV treatment (Cicek et al., 2007). By gathering samples at every stage of the treatment process, the elimination of estrogen in a full-scale wastewater treatment plant (WWTP) was investigated. Pathogens can be effectively inactivated by UV therapy, although their efficacy may be impacted by water quality parameters such as turbidity and the presence of organic matter (Linden et al., 2011).

6.2.10 Nanofiltration

A membrane filtering method called nanofiltration uses cylindrical pores the size of nanometers that are arranged perpendicularly through the membrane. These membranes are smaller than those used in microfiltration and have pore diameters ranging from 1 to 10 nanometers. Reverse osmosis (RO) membranes are slightly larger than those in ultrafiltration. Drugs can be eliminated using three different methods by nanofiltration (NF) membranes: adsorption, Sieving and electrostatic repulsion (Dolara et al., 2012). The nanofiltration (NF) capacity, a sophisticated membrane filtration method used to eliminate a range of pollutants, including organic compounds. It started to be used in wastewater treatment in 2003 due to the molecules, heavy metals and various ions it contains (Van der Bruggen & Vandecasteele., 2003). With pore sizes that typically range from 0.1 to 1 nanometre, NF membranes function at the molecular level, effectively rejecting larger particles while allowing smaller ions and water molecules to pass through (Yaroshchuk, 2000). Because of this, NF is especially useful for getting rid of drugs, substances that cause hormone disruption, and other new pollutants that are hard to remove using traditional treatment techniques (Hilal et al., 2004). It has low energy consumption and higher rejection of contaminants (Das et al., 2018). Because NF may achieve more than 90% clearance efficiency, it is a potential choice for pharmaceutical distribution (Bolong et al., 2009).

6.2.11 Nanomaterials

Nanomaterials (NMs) remain a highly discussed topic, with ongoing research focused on their environmental presence, behaviour, and toxicity, alongside the continuous development of new NMs. Nanosilver (nAg) is still the most widely used material, commonly found in bandages, body stockings, T-shirts, food containers, children's blankets, towels and toys. Nanomaterials such as graphene, fullerenes, single-walled carbon nanotubes, $nTiO_2$, nZnO and $nCeO_2$. There is a growing consensus that NM may also pose low environmental risk, although data are lacking in many areas (Lead et al., 2018). Nanomaterials have physical, chemical, and biological properties due to their nanoscale dimensions (usually 1 to 100 nm). The range of domains associated with the number usually affects their behaviour. Examples include carbon nanotubes, graphene, quantum dots, steel nanoparticles, and ceramic nanofibers. These materials' exceptional properties are used in various packaging applications in fields such as electronics, energy, and biomedicine. The flexibility and tunability of nanomaterials make them important in different industries, stimulating the development of technologies such as electricity and energy for medical and environmental technologies (Pomerantseva et al., 2019).

7 Innovative and combined treatment technologies

Wastewater treatment plants (WWTPs) are transforming because of innovative and combined treatment technologies that improve sustainability, efficiency, and contaminant removal. Combining biological treatment techniques with advanced oxidation processes (AOPs) like photocatalysis and ozonation is a cutting-edge strategy. Reactive species produced by these AOPs, such as hydroxyl radicals, degrade emerging and persistent organic pollutants, which are frequently impervious to standard biological processes (Wang et al., 2012; Vilhunen & Sillanpää, 2010). Another novel combination that merges biological treatment and membrane filtration is the membrane bioreactor (MBR). MBRs are ideal for water reuse applications because they efficiently remove bacteria, suspended solids, and even some dissolved pollutants, resulting in superior effluent quality (Judd, 2011). Additionally, biogas production can be improved while sludge volume is reduced and energy recovery maximized by combining anaerobic digestion with membrane filtration (Appels et al., 2008; Bolzonella et al., 2018). Bioaugmentation involves introducing particular microorganisms into wastewater remedy structures to enhance the elimination of pollutants, which include microplastics. research has demonstrated that bioaugmentation in secondary remedy approaches—such as activated sludge, sequencing batch reactors, and membrane bioreactors—can gain high microplastic removal efficiency, reaching up to 100% with certain polymer-microbe combinations.

8 Challenges of the treatment technologies

The influence of wastewater treatment on biophysical ecosystems and living creatures poses considerable issues. Regulations controlling waste management are not the only elements influencing these difficulties; socioeconomic and regional considerations also play a role. It is challenging to find a universal technique that will remove every contaminant from wastewater. Many biological, physical and chemical treatments have been developed and published in the last three years (Barakat, 2011; Rathoure, 2015). Although wastewater treatment technologies are crucial for reducing pollution, they face several serious obstacles. The intricate and varied makeup of wastewater is a significant problem that can reduce the efficacy of treatment processes (Köhler et al., 2018). Emerging contaminants which include drugs, personal care items, and microplastics are difficult for conventional methods to remove and require sophisticated treatment methods that are frequently expensive and energy-intensive (Drewes et al., 2016). Managing the residuals and byproducts produced during treatment presents another difficulty. For example, advanced oxidation processes (AOPs) and membrane technologies can generate hazardous byproducts or concentrated waste streams that need additional handling or disposal, increasing operational complexity (Parsons & Jefferson, 2006). Membrane fouling is a recurring issue in membrane-based technologies, necessitating frequent maintenance and replacement, which raises operational costs (Li et al., 2017). Similarly, the high energy requirements of procedures like electrocoagulation and reverse osmosis raise concerns regarding the sustainability and carbon footprint of wastewater treatment (Shannon et al., 2008). Furthermore, there are budgetary and logistical difficulties in integrating new technologies into existing treatment facilities. Modernizing infrastructure to support novel treatments frequently necessitates a large financial outlay, and maintaining these cutting-edge systems calls for qualified staff (Chen et al., 2015). Further research and regulation are necessary to ensure the safe application of emerging treatment technologies, as their potential impacts on human health and the environment, such as the use of nanomaterials, are not yet fully understood (Qu, Alvarez, & Li, 2013).

9. Future Directions

Emerging contaminants (ECs) present a significant challenge for water treatment systems due to their presence in trace quantities. Although physical, chemical, biological, and hybrid treatment processes have proven effective for many ECs, complete removal remains elusive. Consequently, several promising research directions are suggested to address this issue, including:

- Development of Specialized Microbial Consortia: Future research should prioritize the creation of specialized microbial consortia designed to target contaminants of emerging concern, including drug-related and daily used products. Engineering microbial communities with tailored metabolic pathways and synergistic interactions can enhance the efficiency and specificity of bioremediation. By optimizing these consortia, researchers can improve the degradation rates and expand the range of pollutants addressed, leading to more effective and adaptable wastewater treatment solutions.
- Advancement in Detection and Monitoring Technologies: There is an urgent need for advancements in detection and monitoring technologies to manage the treatment of emerging contaminants effectively. Real-time analytical tools, including high-resolution mass spectrometry and advanced biosensors, can provide accurate and timely data on contaminant concentrations and degradation progress. These innovations will enable more precise control over the treatment processes, allowing for quicker adjustments and enhanced removal of pollutants from wastewater.
- Integration of Bioremediation with Advanced Oxidation Processes (AOPs): Integrating bioremediation techniques with advanced oxidation processes (AOPs) offers a promising avenue for improving the treatment of persistent emerging contaminants. By combining biological methods with chemical treatments such as photocatalysis and ozonation, hybrid systems can achieve more comprehensive degradation of pollutants. This approach leverages the strengths of both biotic and abiotic processes, potentially overcoming the limitations of each method and leading to more effective and robust wastewater treatment solutions.

10.Conclusion

In conclusion, managing Emerging Contaminants (ECs) is a complex and evolving challenge that requires a comprehensive, multi-faceted approach. The following key points summarize the critical considerations for addressing ECs effectively:

- Diverse and complex Nature of ECs: ECs, such as prescribed drugs, endocrine disruptors, nanomaterials, and microplastics, are numerous and complicated, complicating their detection, monitoring, and management.
- Limitations of Current Technologies: Existing treatment technologies face significant limitations in effectively removing ECs, highlighting the need for innovative and integrated systems that can bridge the gaps in individual methods.
- Regulatory Shortcomings: While there are regulations in place to control ECs, they are not yet sufficient to fully address the scale and complexity of the issue, necessitating more comprehensive and precautionary measures.
- Emerging Health and Ecological Impacts: The potential effects of ECs on human health, wildlife, and ecosystems are still emerging, underscoring the urgency of improving detection technologies and treatment methods.
- Need for Interdisciplinary Collaboration: Addressing the challenges posed by ECs requires sustained research, innovation, and collaboration across scientific, industrial, and regulatory sectors.
- Ongoing Innovation and Policy Development: To ensure the preservation of the environment and public health, it is imperative that ongoing efforts be made to improve current strategies, create fresh approaches, and put into place sensible laws that can lessen the risks connected to ECs.

Declaration of interests

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

Credit Author Statement

Vidiksha Sangla, Investigation, Writing original draft, Writing review & editing. Shanvi Rana, Investigation, Writing original draft, Writing review & editing. Anubhuti Jain, Writing original draft, Writing review & editing. Himanshu Srivastava, Writing review and editing. Geetansh Sharma, Visualization, Supervision. Himani Chandel, Conceptualization, Supervision, writing review & editing.

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Table 1: List of emerging contaminants from various sources and categories

S .No.	Source Type	Category
1.	WWTP, Landfill leachate, Surface water	Personal Care Products
2.	Domestic and industrial wastewater	Industrial chemicals
3.	Agricultural runoffs, Sewage treatment plants, Sediments, Soil, Surface water	Herbicides/ Pesticides
4.	Hospital and Industrial wastewater, Surface water, WWTP	Pharmaceuticals
5.	Landfills, WWTPs, Sewage, Urban runoff	Persistent organic pollutants (PO
6.	Drinking and surface water, Sediments, Soil, Secondary sludge	Endocrine disrupting chemicals (E
7.	Mining and minerals processing industrial waste water	Surfactants
8.	Recycling plants, Hospital waste water, Petroleum refineries	Rare earth elements (REEs)
9.	Nuclear power plants, Pacific ocean	Radionuclides/ Nuclear waste
10.	Accidental spillages, rainwater runoff	Nanoparticles
11	Agriculture, Livestock, Farming and Hospitals waste water	Antibiotic- resistant micro- organi
12.	Wetlands, Lakes, Reservoirs, Streams, Rivers	Algal toxins
13	Contaminates/ effected/ endemic areas	Bioterrorism
14.	Research lab effluents	Other biological contaminants

Table 2: Overview of Treatment Techniques for Emerging Contaminants

S.No.	Treatment Technique	Target Emerging Contaminant	Removal Efficiency
1.	Aerobic a)Granular sludge b)MBR	Roxithromycin 17a-ethinylestradiol	95.2% 93%

S.No.	Treatment Technique	Target Emerging Contaminant	Removal Efficiency
2.	Anaerobic a)Sludge b)AnMBR	Ciprofloxacin Erythromycin	85% 86%
3.	Activated Carbon adsorption a)Powdered b)Granulated	17-Alphaethylestradiol Metoprolol	83.3% 95%
4.	Biochar Assisted Adsorption (from tea waste)	Sulfamethazine	33.81mg/g
5.	Clay Minerals Assisted Adsorption (modified zeolites)	fluoroquinolones	99%
6.	Hydrothermal Carbonization	Pb(II), ciprofloxacin	119.61 98.38 mg/g
7.	Coagulation – Flocculation	Acetaminophen, Diclofenac	$< 20\%$
8.	Advanced Oxidation Processes	Sulfamethoxazole	$> 90\%$
9.	Ozonation a)single b)catalytic	Ibuprofen (IBU)	26% 90%
10.	Chlorination	17α-estradiol, Estriol	$> 90\%$
11.	UV Irradiation	Tetracyclines, Fluoroquinolones	80–95%
12.	Nanofilteration	Amoxicillin	99%

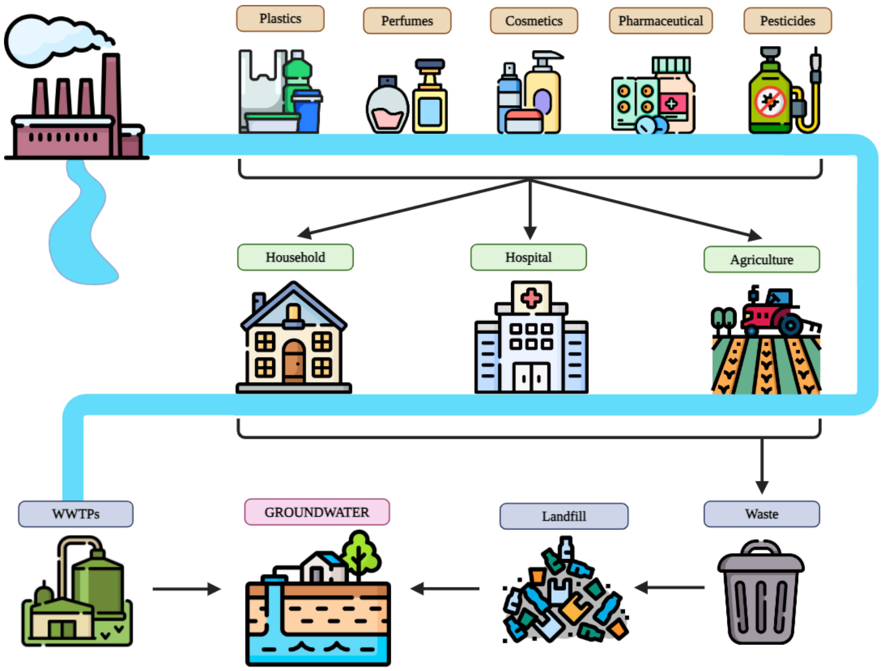

Fig.1: Overview of the Source and Types of Emerging Contaminants

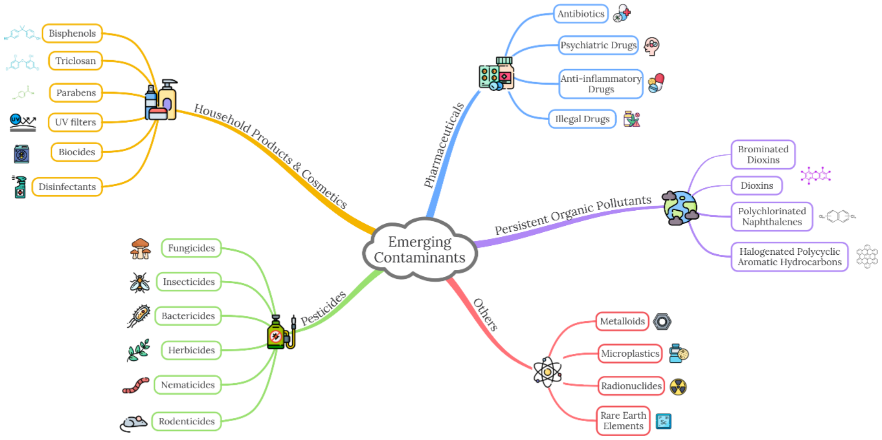

Fig.2: Pathways and Distribution of Emerging Contaminants