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Research paper

A comprehensive review of emerging contaminants in water sources

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Abstract

The quality of water is crucial for the health of both the environment and humans, but new challenges from emerging contaminants threaten this vital resource. This paper reviews the origin and significance of water quality issues linked to emerging pollutants, including pharmaceuticals, personal care products, endocrine-disrupting chemicals, per- and polyfluoroalkyl substances, microplastics, pesticides, and industrial chemicals. These persistent chemicals exhibit complex behaviors and have the potential to impact ecological systems and human health significantly. The review comprehensively examines the pathways through which these pollutants enter water systems, such as agricultural runoff, industrial discharges, and urban stormwater runoff. It also covers the latest techniques for identifying these pollutants, emphasizing recent advancements in sampling methods and analytical techniques while highlighting the challenges of detecting contaminants at low concentrations. The discussion includes the environmental behavior of these contaminants, focusing on their properties, degradation mechanisms, and bioaccumulation potential. It further explores the impacts of these emerging contaminants on ecosystems and human health, examining both conventional and innovative treatment technologies. Additionally, the review identifies current research gaps and future trends in the analysis of new pollutants. It underscores the importance of public awareness, effective communication strategies, and innovative approaches to environmental protection.

Keywords: *Water Quality; Emerging Contaminants; Pharmaceuticals; Environmental Impact; Detection Methods.*

1. Introduction

Water quality is an integrally important factor to environmental health, affecting ecosystems, public health, and economic activities. Inevitably, clean and safe water should be available for drinking purposes, agriculture, industry, and recreation. However, the rising contamination of water resources from traditional and emerging pollutants presents an overwhelming challenge. Although a lot of studies have been conducted about the pathogens, nutrients, and heavy metals in water, the constant emergence of new contaminants has made the situation still worrying in recent years [1]. Emerging pollutants is a group of manufactured or naturally occurring substances that are not routinely monitored but they can enter water ecosystems and cause known or suspected adverse effects to the environment and human beings. These include pharmaceuticals and personal care products, endocrine-disrupting chemicals, polyfluoroalkyl substances, microplastics, and several industrial chemicals. Unlike conventional contaminants, many of the emerging contaminants occur at very low concentrations, typically making them quite difficult to detect and monitor. Their persistence in the environment, ability to bioaccumulate, and potential for long-term effects underline the need to have a more comprehensive understanding of their sources, environmental behavior, and impacts [2].

This review considers the new pollutants reviewing their categories, origins, identification techniques, environmental consequences, and effects on ecosystems and human health in water sources. Moreover, this review will be undertaken with an eye toward the assessment of current regulatory structures and remediation methods in place for the various compounds, with identification of knowledge gaps, and proposition of future research directions. This review synthesizes the most recent developments and current challenges in the light of providing constructive information to policymakers, researchers, and stakeholders on the importance of emerging contaminants and the requirement for their effective management strategies.

Emerging contaminants in water sources encompass a wide range of chemical substances that have recently gained attention due to their potential adverse effects on the environment and human health [3]. These contaminants are often not regulated or only partially regulated, and their presence in water sources can be attributed to various human activities. Several types of emerging contaminants were discussed in detail (fig. 1).

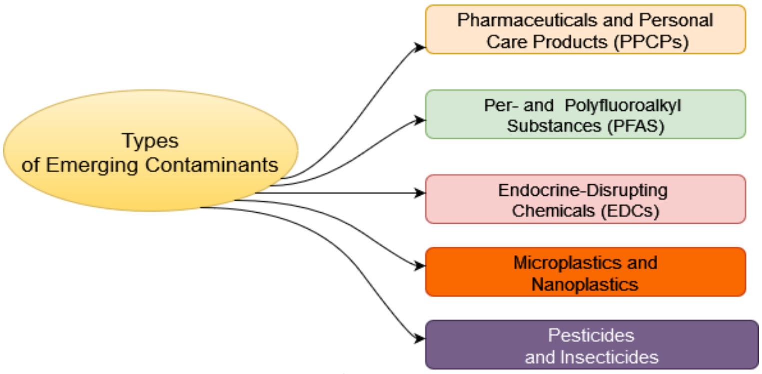

Fig. 1: Types of Emerging Contaminant.

2. Emerging contaminant

Emerging contaminants encompass a diverse group of man-made or naturally occurring substances that are not regularly monitored but have the potential to infiltrate water habitats and pose significant risks to environmental and human health. types include pharmaceuticals and personal care products (PPCPs), which enter water systems through improper disposal and human activity; endocrine-disrupting chemicals (EDCs), often originating from industrial discharges, agricultural runoff, and household products; per- and polyfluoroalkyl substances (PFAS), known for their persistence and resistance to degradation, used in firefighting foams, non-stick cookware, and water-repellent fabrics; and microplastics, tiny plastic particles from the breakdown of larger plastic debris or direct release from products like cosmetics and synthetic clothing. Additionally, various industrial chemicals, such as those used in manufacturing and processing, can contribute to water pollution through spills, improper disposal, and leaching from waste sites. The complexity and low concentrations of these contaminants make their detection and regulation challenging, necessitating advanced treatment technologies for effective management [4].

2.1. Pharmaceuticals and personal care products (PPCPs)

Recent studies have documented the presence of emerging chemical pollutants, known as "emerging micro-pollutants," at trace concentrations (ng/L – μg/L) across various environmental compartments [5]. These pollutants currently lack legislative regulations Since 2000, the European Union has identified 33 chemical compounds in surface waters (freshwater and marine) as priority pollutants, which must be addressed within two decades to protect aquatic ecosystems [6]. In 2007, several chemical compounds, including phthalates, iopamidol, diclofenac, carbamazepine, triclosan, clofibric acid, musks, and ibuprofen, were classified as priority pollutants. Many of these toxic substances are known endocrine disruptors or carcinogens [7]. These anthropogenic micropollutants primarily consist of industrial chemicals [8], pesticides [9], and pharmaceutical and personal care products (PPCPs) [10]. Among these, PPCPs represent the largest group of chemical pollutants, used in various daily applications.

PPCPs are a diverse group of chemicals used for health, hygiene, and beauty and include pharmaceuticals, cosmetics, and fragrances. These products have become emerging environmental pollutants because of their use worldwide and persistence in the environment. PPCPs get into the water through various routes, including human excretion, improper disposal of medications, agricultural runoff from farms using animal drugs, and leachate from landfills. Wastewater treatment plants are one of the major routes for PPCPs to enter the water system since conventional techniques of treatment often do not completely remove them. For example, Analyzed the presence of antibiotics such as sulfamethoxazole and ciprofloxacin in various water resources, showing their persistence in surface and groundwater and hence a risk of promoting the development of antibiotic-resistant bacteria [6] detected antibiotics, including erythromycin and trimethoprim, at the influent and effluent of the United States WWTPs, proving that these compounds usually go through the process without being removed. Another European study cited the omnipresent existence of the most widely used analgesics, ibuprofen and diclofenac, in rivers and lakes, underlining that a great task to effectively treat these chemicals from wastewater had been achieved [9]. Estrone and 17β-estradiol represent hormones from birth control pills that were identified to pass into rivers and disturb the hormone systems of aquatic organisms, which leads to reproductive and developmental disorders [11]. Triclosan represents an antimicrobial substance, which might form toxic by-products while entering a river and sediment, and this may put a risk to the environment since it is toxic in nature. In addition, UV filters in sunscreens, oxybenzone, and octocrylene, were also traced in coastal waters, while it has been evidenced that they can persist in the environment and pose a serious threat to marine organisms. Additionally, the artificial musks galaxolide and tonalide used in perfumes are persistent in the aquatic environment and could bioaccumulate in aquatic organisms, thus posing a long-term environmental concern. These examples illustrate ways in which PPCPs can disrupt ecological systems and underline the need for effective environmental management strategies. Several PPCPs are likely to remain intact in conventional treatment methods of wastewater, like activated sludge processes, due to their complex chemical characteristics.

Advanced treatment processes, such as membrane filtration, advanced oxidation processes, and adsorption methods, are potential solutions, but they generally are very expensive and operationally problematic.[10] evaluated several advanced treatment processes and reported that while ozonation and activated carbon adsorption have some effectiveness for PPCP removal, they are resource-intensive and infastically burdensome. One critical area of PPCP research is the development of more effective and economically feasible treatment solutions to cope with PPCP contamination of aquatic environments, mitigating associated health and ecological risks.

2.2. Endocrine-disrupting chemicals (EDCs)

Endocrine-disrupting chemicals (EDCs) are chemical agents that interfere with the body's hormonal processes, affecting the synthesis, secretion, transport, metabolism, and binding of natural hormones [12]. These disruptors can alter the control mechanisms and release of hormones [13]. EDCs originate from both natural and synthetic sources. Natural EDCs, which come from living organisms, include estrogens, androgens, progestogens, and phytoestrogens [14]. Synthetic EDCs fall into six categories: phthalates, pesticides, phenolic compounds, polyhalogenated compounds, drugs, and pharmaceutical and personal care products (PPCPs) [14]. Commonly studied EDCs include estrone (E1), 17β-estradiol (E2), ethinylestradiol (EE2), estriol (E3), bisphenol A (BPA), nonylphenol (NP), nonylphenol ethoxylates

(NPnEO), octylphenol, and triclosan [15]. The presence of EDCs is primarily driven by the manufacturing, usage, disposal, and discharge of chemicals and pharmaceuticals, significantly impacting the environment and living organisms [16].
The EDCs are a diverse group of substances that can interfere with the hormonal systems of organisms, leading to various adverse effects on development, reproduction, and health. EDCs include compounds such as bisphenol A (BPA), phthalates, pesticides, and industrial chemicals. This section explores the mechanisms by which EDCs disrupt endocrine function, their environmental and health impacts, and the challenges associated with their regulation and remediation.
Endocrine Disrupting Chemicals (EDCs) can disrupt the endocrine system by affecting hormone functions through various primary mechanisms. Mimicking natural hormones is a crucial mechanism. Endocrine disruptors can mimic the configuration of natural hormones, enabling them to attach to hormone receptors and trigger or block hormonal processes. For example, Bisphenol (BPA), a frequently utilized chemical in plastics, can imitate estrogen and interfere with reproductive health [10]. Study and uncovered the harmful effects of BPA at low doses, connecting it to reproductive issues and developmental abnormalities in animals. EDCs imitate natural hormones to deceive the body's endocrine system into reacting improperly, resulting in different health problems.
Another important way EDCs interfere with endocrine function is by blocking hormone receptors or changing hormone synthesis, transport, or metabolism. Certain endocrine-disrupting chemicals can attach to hormone receptors without triggering them, thereby obstructing the normal function of the natural hormone. [6] reported that Atrazine, a commonly used herbicide, demonstrates this by blocking the androgen receptor and impacting sexual growth in wildlife. Furthermore, EDCs can disrupt the production or breakdown of hormones, resulting in disruptions in hormone levels. Phthalates, often utilized as plastic softeners, have been shown to impact the functions of androgens, leading to consequences for reproductive health. [17] discovered that male infants with prenatal exposure to phthalates were linked to reproductive abnormalities. Not only this, there various researches that shows how various EDCs disrupt the body (Table 1). By disturbing the normal equilibrium and operation of hormones, EDCs create substantial dangers for the health of both humans and wildlife.

Table 1: EDCs and Their Mechanisms

EDC	Mechanism of Disruption	Study
Bisphenol A (BPA)	Mimics estrogen, causing reproductive and developmental issues	[8]
Phthalates	Interferes with androgen function, leading to reproductive issues	[17]
Atrazine	Induces aromatase, converting androgens to estrogens	[6]
DDT	Alters hormone levels, linked to breast cancer and reproductive issues	[7]
Polychlorinated Biphenyls (PCBs)	Alters thyroid hormones affects brain development	[16]
Polybrominated Diphenyl Ethers (PBDEs)	Affects thyroid hormone regulation and neurodevelopment	[9]

EDCs may also trigger drastic ecological impacts, including those leading to reproductive anomalies and even population declines of such animals. For instance, case studies on the effects of endocrine disrupters in aquatic fauna have found intersex fish in waters contaminated with EDCs [18]. The large ecological implications are underlined as EDCs may cause skewing sex ratios and populations to start decreasing in different species. EDCs have been associated in humans with a variety of health problems (Table 2), ranging from reproductive disorders and developmental abnormalities to certain cancers. BPA has been associated with risks of breast cancer, while phthalates have been linked to reduced sperm quality in men. EDCs, such as PCBs and PBDEs, have been linked with neurodevelopmental deficits and thyroid dysfunction.

Table 2: Health Impacts of EDCs

EDC	Health Impact	Study
Bisphenol A (BPA)	Reproductive disorders, breast cancer risks	[10]
Phthalates	Reduced anogenital distance, lower sperm quality	[17]
Atrazine	Feminization and hermaphroditism in frogs	[16]
DDT	Increased risk of breast cancer, reproductive issues	[12]
Polychlorinated Biphenyls (PCBs)	Neurodevelopmental deficits, thyroid hormone alteration	[11] [
Polybrominated Diphenyl Ethers (PBDEs)	Altered thyroid hormones, developmental neurotoxicity	[14]

2.2.1. Regulatory and remediation challenges

The growing need for metals in society forced an increase in mining activities due to the increased usage of natural resources. Thus, an increase in the number of industries results in increased resource and water consumption, which releases a significant amount of effluent that is heavy in metals. As a result, industrial wastewater management has gained international attention. Numerous studies have explored various treatment processes[19]. However, many of these methods face drawbacks, including low efficiency, high solvent and reagent demands, and the production of secondary pollutants like waste residues, sludge, toxic chemicals, and effluents Therefore, there is a pressing need for cost-effective and eco-friendly wastewater treatment methods with improved efficiency worldwide.
Controlling and fixing Endocrine Disrupting Chemicals (EDCs) present major difficulties because of their widespread use, long-lasting presence in nature, and intricate ways of functioning. Existing regulations are often inadequate, as they are commonly outdated and do not cover all EDCs or their effects at low doses. There is a pressing requirement for modern and thorough policies that integrate the most recent scientific knowledge to efficiently handle the dangers presented by EDCs [20].
Various advanced treatment technologies are being utilized to address EDC contamination (Table 3). The use of activated carbon is efficient in eliminating EDCs from water; however, it can be costly and requires appropriate disposal of the spent carbon[21]. Ion exchange is an alternative technique for eliminating EDCs, however, it also necessitates proper handling of used ion exchange resins [21].Advanced oxidation methods reduce the toxicity of EDCs, yet require significant resources. Biofiltration and phytoremediation, which are biological techniques for removing EDCs, offer potential but are still in the early stages of widespread use. These technologies demonstrate the challenges and resources required to adequately manage EDC pollution.

Table 3: Remediation Approaches

Approach	Description	Example Study
Activated Carbon Adsorption	Removes EDCs from water and air	[19]
Ion Exchange	Removes EDCs from water	[2O]
Advanced Oxidation Processes	Degrades EDCs into less harmful substances	[21]
Biofiltration and Phytoremediation	Uses biological systems to remove or degrade EDCs	[21]

2.3. Per- and polyfluoroalkyl substances (PFAS)

To better understand the fate of per- and polyfluoroalkyl substances (PFAS) in conventional and advanced wastewater treatment, 42 PFAS compounds (C3–C14 perfluorocarboxylic acids, C3–C10 perfluorosulfonic acids, per- and polyfluoroethers, and perfluoroalkyl acid precursors) were analyzed at two municipal wastewater treatment plants (WWTPs) using targeted analysis, the total oxidizable precursor (TOP) assay, and sludge partitioning estimates. Higher concentrations of short-chain (C3–C7) PFAAs were found in wastewater, while long-chain (≥C8) PFAAs predominated in sludge. The wastewater treatment processes significantly elevated PFAA concentrations, especially after biological treatment (increases of 191.3% and 185.1% at WWTP-A and B, respectively). After TOP oxidation, PFCAs, especially the short-chain ones, rose considerably (up to 311.4% and 409.3% increases at WWTP-A and B). The findings suggest that the transformation of precursors into shorter-chain PFAAs during biological treatment and the partitioning of longer-chain PFAS into sludge are crucial factors in determining PFAS outcomes in WWTPs. With the increasing influence of short-chain PFAS, future research should assess the fate and distribution of historical and emerging PFAS in these facilities [22].

PFAS is a wide group of synthetic chemicals, well-known for the strength of the carbon-fluorine bonds, which give their strength in the environment like persistent organic contaminants. PFASs are generally divided into two main classes, based on their chemical structures: long-chain and short-chain PFASs. The subcategory of PFAS, exemplified by PFOA and PFOS, has the abbreviation LC-PFAS, with the L meaning long in carbon. PFOA is associated with cancer of the kidneys and testicles, and PFOS, a common environmental contaminant in the past, has been proven to accumulate in aquatic animals and impede their development and reproductive stages of the water organisms. The short-chain PFAS that are substituting long-chain ones are the perfluorobutanesulfonic acid and perfluorobutanoic acid. However, such chemicals still pose significant ecological and health risks because of their mobility and persistence in the environment [23]. Due to the high environmental persistence of PFAS, it accumulates within the food web and poses chronic ecological effects. However, increased concentrations of PFOS were found in surface water and sediments, the promise of chronic persistence in the environment notwithstanding [24]. Shorter-chain PFAS compounds, such as PFBS and PFBA, are, however, still a concern because such chemicals can still readily flow through water systems to cause environmental pollution, while they might be less persistent than PFAS-c6 and PFAS-c8 compounds. Surprisingly, new research shows that fluorinated surfactants may degrade into hazardous products, which are nonbiodegradable offer limited opportunities for destruction, and warrant better management strategies to avoid pollution. PFASs can bioaccumulate in the human body, and even though the environmental levels are low, they can affect people's health in the long term [25].

Long-term exposure to PFAS was found to pose numerous adverse effects on the health of individuals, such as liver damage, developmental and reproductive problems, and impacts on the immune system. Based on several studies, PFOA exposure has been reported to cause elevated cholesterol levels and abnormal liver enzymes. The cleanup and regulation of PFAS contamination face a set of complex challenges. Whereas long-chain PFAS have been subject to elimination, short-chain alternatives still exist in the market, amid concerns over their safety, according to the EPA of 2020. Only advanced treatment methods, including adsorption with activated carbon, ion exchange, and advanced oxidation techniques, have been effective against PFAS pollution. However, these have been considered resource-intensive again in 2020 by the EPA.

2.4. Microplastics and nanoplastics

Microplastics and nanoplastics have become a highly prevalent source of environmental pollution causing quite an immense ecological and health concern. Generally, microplastics have been defined as plastic fragments of a diameter of less than 5 millimeters. While nanoplastics are smaller, measuring less than 1 nanometer to 1 micrometer in diameter. Two primary sources of these particles are primary microplastics, purposely made for certain uses, such as microbeads or industrial abrasives, and secondary microplastics, formed when larger plastic items break down into smaller pieces caused by environmental actions [26]. Nanoplastics are highly mobile and can spread easily through air, water, and soil; they can also be produced deliberately, lending their use in coatings and other products. Micro- and nanoplastics accumulate in marine ecosystems and influence different environmental compartments such as the sea surface, water column, and seabed [27]. Microplastics, when ingested, can cause physical damage and exposure to chemicals not just in marine, but also in terrestrial fauna. For example, fish and invertebrates could consume the microplastics, and through bioaccumulation within the food chain, they could reach humans, causing potential health risks from the accumulative toxicity. These particles may also leach harmful substances such as POPs and heavy metals into the environment or bioaccumulate organisms, thus posing additional risks. Due to their minute size, nanoplastics can breach cellular membranes and potentially cause oxidative stress, inflammation, and other forms of cellular damage [28]. Studies have shown that microplastics and nanoplastics can disrupt aquatic environments and affect organisms at different levels in the food web [29].

In recent years, small plastic particles known as microplastics (MPs) have gained significant attention [27]. MPs are defined as plastics smaller than 5 mm, while those smaller than 1 μm are termed nanoplastics (NPs) [26]. They have been found in various environments, including seawater [25], freshwater [24], sediments [23], and soil [27]. Studies indicate that MPs can have adverse effects on aquatic organisms' ecosystems, and human health. Numerous anthropogenic sources of MPs exist, with municipal wastewater treatment plants (WWTPs) identified as significant urban contributors. Microbeads from personal care products can enter WWTPs via sewer systems and may evade removal during treatment due to their small size. Despite the effective removal of some MPs during particulate matter processing, a substantial number can still enter aquatic environments due to high wastewater flow [28]

At the same time, more emphasis is laid on the regulations and implementation by the government and other international bodies for restricting the use of microplastics in products and dealing with plastic wastes, including bans on microbeads in personal care products. Innovative ways are being explored for removing these pollutants from the environment as part of the remediation efforts. Advanced filtration systems, chemical treatments, and biological methods offer some effective solutions for the management of pollution. Techniques to reduce the effects of these emerging persistent pollutants include magnetic separation, chemical oxidation, and bioremediation efforts [29]. In addition, given growing long-term health threats by micro and nanoplastics, in a bid towards developing an inclusive approach towards the presence of these elements in the landscape profiles, there is gradually more focus on their impacts on human health and developing approaches to mitigate the effects of any future pollution incident [28].

2.5. Pesticides and insecticides

In this process, pesticides play a key role in agriculture, controlling pests with considerable risks to both the environment and human health. Pesticides are chemical substances created to aim at particular pests; they can be categorized in terms of their function or chemical characteristics. Insecticides such as chlorpyrifos, an organophosphate, act by inhibiting some essential enzymes in the body of insects, while permethrin, a pyrethroid, acts by inhibiting nerve function [30]. Herbicides are classified into two major categories as selective and nonselective, which are applied to control unwanted plants. 2,4-D lies in the herbicides put to control the growth of broadleaf weeds, which do not affect cereal crops. On the other side, glyphosate is a non-selective herbicide in that it kills plants both through contact and systemically. Fungicides are not used against fungal pathogens, and rodenticides, such as brodifacoum, do the same thing against rodents—anticoagulation. Even though these chemicals are effective at pest management, they can result in large amounts of environmental damage. For example, pesticides can harm nontarget species, such as bees, and contaminate water through runoff procedures [31].

Pesticides and herbicides have deep and diverse influences on the environment by causing big damage to the ecosystem and the quality of soils. Runoff of pesticides in the water may lead to contamination of water; this harms underwater life and upsets the ecosystems. Herbicides like glyphosate contribute to the development of herbicide-resistant weed species, introducing an escalating cycle of herbicide applications and resistance [31]. In addition, herbicides can affect the health of the soil by changing its critical microbial communities for fertility. Other important environmental issues include reduced populations of bees due to pesticides; these are important to agriculture and natural ecosystems because they pollinate many crops and other plants. These will have to be better understood for the formation of effective plans for pest management with reduced impacts on the environment.

The short-term contact can result in effects such as sickness, migraines, and breathing issues, which mainly affect people in direct contact with the substances. Long-term exposure can result in serious health problems, including cancers and neurological disorders. Glyphosate has been categorized as a probable human carcinogen, and chronic pesticide exposure has been linked to many types of cancers, such as leukemia. The International Agency for Research on Cancer indicated that herbicides are known endocrine disruptors and can cause endocrine disruption, leading to reproductive and developmental problems. These hazards are overseen partly by the regulatory structures and IPM strategies. While organizations like EPA and EFSA control pesticide safety through strict testing, IPM approaches are biological, physical, and chemical approaches to minimize risks posed to the environment and health by the chemicals. Also, organic farming methods are used as the alternative sustainable means of reducing the environmental and health risks associated with chemical pest control methods [32].

Table 4: Summary of Emerging Contaminants

Contaminant Type	Description	Sources	Environmental Impacts	Health Risks	Treatment Challenges	Examples & References
Pharmaceuticals and Personal Care Products (PPCPs)	Substances for health, hygiene, and beauty purposes.	Human excretion, improper disposal, agricultural runoff, and leaching from landfills.	Persistent in water, disrupts aquatic ecosystems, potential for antibiotic resistance.	Endocrine disruption, reproductive issues, and development of antibiotic-resistant bacteria.	Conventional methods are ineffective; advanced methods are expensive and complex.	[30]
Endocrine-Disrupting Chemicals (EDCs)	Chemicals that interfere with hormonal systems.	Industrial chemicals, pesticides, plasticizers.	Reproductive abnormalities, skewed sex ratios, population declines in wildlife.	Reproductive disorders, cancers, developmental issues.	Outdated regulations, and high costs for advanced treatment technologies.	[31]
Per- and Polyfluoroalkyl Substances (PFAS)	Synthetic chemicals are known for persistence and bioaccumulation.	Industrial processes, firefighting foams, consumer products.	Long-term environmental persistence, bioaccumulation, and potential to form harmful degradation products.	Liver damage, developmental issues, cancer risks.	Expensive and resource-intensive treatments; ongoing use of short-chain PFAS.	[32]
Microplastics and Nanoplastics	Small plastic particles from the breakdown of larger items or intentional use.	Product degradation, industrial abrasives, personal care products.	Physical harm to organisms, chemical pollution, and widespread environmental dispersion.	Potential for health risks through the food chain, cellular damage.	Innovative and costly remediation techniques; limited long-term health data.	[32]
Pesticides	Chemicals for pest control in agriculture.	Agricultural use for pests and diseases.	Water contamination, harm to non-target species, resistance development.	Acute and chronic health issues, including cancer and neurological disorders.	Management of runoff, development of resistant species, and regulatory updates.	[31]

3. Sources and pathways of emerging contaminants

Emerging contaminants in water sources originate from a variety of anthropogenic activities (Figure 2). Understanding these sources and the pathways through which contaminants reach water bodies is essential for developing effective mitigation strategies.

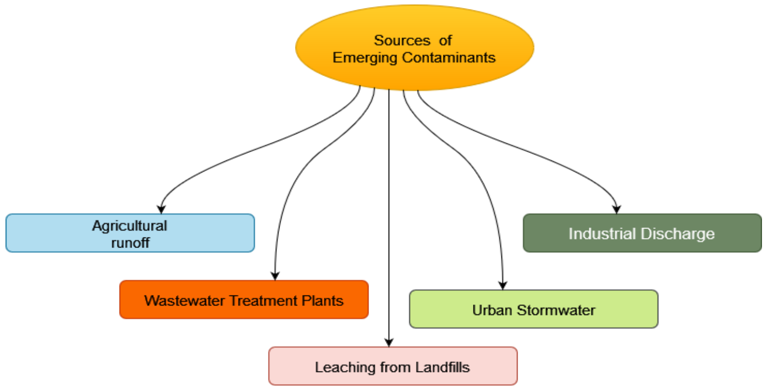

Fig. 2: Sources of Emerging Contaminants.

3.1. Agricultural runoff

Modern agriculture relies on fertilizers and pesticides to achieve high crop yields, leading to diffuse pollution. Agricultural runoff, which consists of these agrochemicals entering surface waters, is a primary source of non-point source (NPS) pollution. This runoff adversely affects wildlife, aquatic ecosystems, and human health through drinking water contamination, contributing to the degradation of surface and groundwater with significant environmental and economic repercussions. Constructed wetlands (CWs) are a cost-effective and low-energy solution for treating agricultural runoff pollution and have gained popularity over recent decades for managing both agricultural runoff and agro-industrial wastewater. CWs represent a well-established green option for water management and wastewater treatment, with numerous successful applications worldwide and multiple environmental and economic benefits. Additionally, plants play a crucial role in enhancing nutrient efficiency and creating ideal conditions for microbial biodegradation, aiding in the mitigation of agricultural runoff. This chapter reviews the current understanding of CWs' capacity to mitigate various agricultural runoff pollutants, examines the role of plants in contaminant removal, and evaluates their overall effectiveness [33].

Furthermore, agricultural runoff is one of the major ways through which new entry of pollutants into the environment is primarily occurring; farmland practices have contributed to many internationally threatening levels of the very individuals and global ecosystems. Nutrient fertilizers, pesticides, and herbicides are the compulsively practiced regimes under which the whole process of farming is practiced for increasing crop yield and managing pests in the agricultural environment. However, potential consequences of pollution-causing materials arising from these chemical applications result when residues are carried by rainwater or irrigation runoff into the adjacent water sources. The antibiotics and the hormones in livestock waste may enter the soil and, through runoff, enter streams, rivers, and lakes, which may not degrade them further [34]. Modern formulations of pesticides, such as neonicotinoids, are designed to degrade pests but, in turn, persist in the environment and may be leached into water bodies through runoff. This runoff can result in issues such as an algae over-population blamed on strong nutrients from fertilizers and hormonal imbalance in aquatic animals because of factors such as pharmaceuticals and pesticides. Besides, it may facilitate the spread of resistant bacteria, an ever-growing challenge to public health, through agricultural runoff [35].

Farmers can practice contour plowing, design vegetative buffer zones, and precision agriculture practices to maximize chemical usage and reduce waste, therefore reducing chemical runoff. Studies on the development of eco-friendly pesticides and fertilizers will advance sustainable farming to keep check on the best methods. Monitoring programs are essential in keeping track of new sources of pollutants in water bodies and environmental impacts, thus informing policy decisions. Public education campaigns will also serve to inform farmers and the public on how best to use and discard agricultural chemicals, thus very significantly preventing the entry of contaminants into the ecosystem [36]. In Summary, agricultural practices are fundamental to food production, and management of the emerging contaminants so produced is essential in ensuring protection for the environment and public health.

3.2. Industrial discharge as a source of emerging contaminants

The industrial wastes contribute much to the emergence of pollutants in the environment from the release of many substances including chemicals, heavy metals, and synthetic compounds from production activities. The pharmaceuticals, personal care products, PFAS, and microplastics in these industrial waste streams are generated from factories and plants. Because of their complex chemical makeup and persistence, most of these pollutants pass through conventional means of wastewater treatment to be released into recipient water bodies, inclusive of rivers, lakes, and oceans, PFAS are very persistent chemicals used in various products, from firefighting foams to non-stick coatings; therefore, they can build up over time in the environment. Because most of the emerging contaminants are not or are poorly monitored, despite regulations, they eventually end up and are prevalent in water environments, thus with adverse effects on the ecosystem and human health [37].

POPs and trace metals like mercury and cadmium bioaccumulate through the aquatic food chains and take a long time to decay, thereby posing a threat to wildlife and, in turn, causing an imbalance in the ecosystem [38]. Pharmaceuticals and personal care products, even in trace concentrations, could potentially disrupt the endocrine systems of aquatic animals, leading to adverse impacts on their reproduction and development. Water polluted by these means poses a risk to human health through chronic diseases and cancer; it even allows the transfer of antibiotic-resistant bacteria originating from industrial waste. To fully bring these challenges under control, a holistic approach has to be taken, which can only be achieved by strict regulations, advanced treatments, and embracing green chemistry. Equally important would be public awareness and community engagement in effective environmental protection measures and sustainable industrial practices [39].

3.3. Wastewater treatment plants as a source of emerging contaminants

Large-scale wastewater treatment plants (WWTPs) in developed regions process substantial volumes of wastewater daily, yet lack effective methods to eliminate emerging contaminants (ECs). Therefore, studying the occurrence of ECs in WWTP effluents is, examined the concentration levels and pollution characteristics of typical ECs for source identification and risk assessment. Of the 39 ECs analyzed, 13 were detected, with oxolinic acid showing the highest concentration at 706 µg/L. Sulfaphenazole had a detection frequency of 100%, while Liede WWTP in Tianhe District recorded the highest concentration among sampling sites at 899 µg/L. Parallel factor analysis identified the dissolved organic matter (DOMs) from excitation-emission matrix spectroscopy (EEMS), enabling the establishment of links between DOMs and pollution sources based on previous data. Principal component analysis (PCA) and Pearson's correlation analysis assessed correlations between ECs and DOMs. Ecological and health risk quotients were calculated for EC risk assessment. The results indicated that oxolinic acid, sulfaphenazole, sulfaquinoxaline, sulfadimethoxypyrimidine, penicillin V, and flumequine likely originated from human activities and the livestock, poultry, and aquaculture industries; sulfadoxine and nafcillin were attributed to agricultural practices, food production, and the catering industry; sulfapyridine and erythromycin stemmed from hospital wastewater; while lincomycin, sulfameter, and sulfamerazine were linked to the petrochemical and chemical production sectors. Except for sulfadoxine, all detected ECs posed a high or medium risk to aquatic ecosystems, threatening aquatic organisms. Although only oxolinic acid, sulfaquinoxaline, and sulfadimethoxypyrimidine presented potential health risks to humans, the cumulative effects of ECs on human health warrant attention. The study highlights the threats posed by ECs from large-scale WWTPs in China's developed regions for the first time, potentially raising awareness of emerging pollution from WWTP effluents, advancing relevant policy development, and guiding future mitigation efforts [40].

WWTPs are committed to treating both urban and industrial wastewater. The issue is that they have a problem dealing with new pollutants. These plants are designed to process large amounts of sewage and industrial waste to meet the required environmental standards by releasing treated water into the natural water bodies. Even though very important, conventional treatment processes often are unable to correctly address a wide range of newly identified pollutants, including pharmaceuticals, personal care products, and industrial chemicals. Many of the compounds, such as antibiotics, antidepressants, and hormones, are not readily degraded by conventional treatment processes involving primary sedimentation and biological treatment. Hence, triclosan, bisphenol A, and several pharmaceuticals may remain in the treated wastewater and eventually enter the aquatic environment, therefore causing endocrine disruptions in aquatic organisms, besides contributing to the growth of antibiotic-resistant bacteria [41]. Further treatments like membrane filtration, adsorption by activated carbon, and advanced oxidation processes manifested significant improvement in the removal of these contaminants. New technologies could be retrofitted in existing WWTPs, which in principle could improve the efficiency of treating wastewater. Besides that, much more stringent regulatory frameworks and monitoring systems are required for a far more extended list of contaminants to be traced, with the output set to inform policy decisions. The contamination of wastewater systems can also be reduced by creating awareness among people regarding the right ways for disposal of pharmaceuticals and personal care products; such steps are linked with the preservation of environmental and human health also.

3.4. Urban stormwater as a source of emerging contaminants

Urban stormwater runoff is a significant way for new contaminants to reach aquatic environments, made worse by the abundance of impervious surfaces in urban regions. Rainwater in urban areas travels over paved surfaces, gathering pollutants like heavy metals, hydrocarbons, and pharmaceuticals, before entering stormwater systems and eventually being released into natural water sources. Everyday impurities consist of small amounts of medications from incorrect disposal, personal hygiene items like sunscreens and shampoos, and toxins from cars such as PAHs and heavy metals [42]. Traditional methods of managing stormwater, like retention ponds and street sweeping, frequently do not completely capture these pollutants, causing considerable harm to the environment [43]. These contaminants may build up in sediments, impact aquatic animals, and interfere with the food chain, whereas pharmaceuticals and personal care items can lead to endocrine disruption and other harmful impacts on wildlife [38]. Conventional techniques are not enough to properly handle new pollutants, so it is crucial to investigate new methods like green infrastructure solutions. Green roofs, permeable pavements, and bioretention systems aim to decrease runoff and filter pollutants, offering better ways to handle stormwater and enhance water quality [26]. These methods aid in reducing runoff, capturing pollutants, and reducing the risk of harmful algal blooms and increased pathogen levels in water bodies that may impact drinking water and public health.

3.5. Leaching from landfills as a source of emerging contaminants

Contamination from landfills has the potential to cause severe impacts on the environment because they release toxic materials into the neighboring soil and water systems. Solid waste disposal landfills can generate leachate; this is a liquid byproduct resulting from organic waste breakdown and percolating water from waste. This liquid waste could contain a variety of new pollutants, including drugs, beauty products, chemicals, and metals, These include sources of PFAS from industrial wastes and pharmaceutical residues from domestic wastes that could persist in the landfill ecosystem and, in turn, leach into the groundwater system, .feedback. A major concern is the circumstance under which such a leachate would impact groundwater through soil pollution, which would, in turn, contaminate various drinking water sources, thus affecting human health and agriculture. A sound management practice includes such things as leachate recirculation, engineered liners, and treatment processes that utilize reverse osmosis and activated carbon adsorption to name a few. The processes work in the way that the risk of leachate pollution is reduced and new contamination is prevented from moving into the environment. In addition to this, detailed monitoring programs are also used in the detection of pollutants and evaluation of the processing efficiency. These strategies would be beneficial in reducing the environmental impacts of landfill leachate on soil and water quality [44].

3.6. Atmospheric deposition as a source of emerging contaminants

Atmospheric deposition is among the key processes wherein contaminants from the atmosphere settle on land and water surfaces, consequently impacting both the terrestrial and aquatic environments. Atmospheric deposition transports pollutants such as POPs and nitrogen compounds by both wet deposition—in the form of acid rain—and dry deposition—in the form of dust—and can transport them over long distances before deposition. During transport, PCBs and PCDD/Fs come from industrial and vehicle emissions, while farming is the source of nitrogen compounds which can cause eutrophication in aquatic environments. Atmospheric deposition can introduce pollutants into soils and water bodies that influence environmental health through changes in plant growth, reduction in soil quality, and damage to water quality. Accumulation of heavy metals like mercury in aquatic organisms is harmful to environmental and human health. The problem with air deposition can be compensated by the combination of regulatory and technological measures adopted by both. Global treaties, such as the Stockholm Convention, aim at reducing the amount of POPs emitted into the atmosphere; local and national regulations target industrial emissions and air quality improvement initiatives to reduce the amounts deposited into the atmosphere by these pollutants. Successful management of atmospheric deposition will involve monitoring pollutant levels, enforcing emission controls, and advocating for policies that help protect the environment. Through the integration of these efforts, it becomes possible to reduce the spread of pollutants via atmospheric deposition and handle the larger problem of environmental pollution [45].

Table 5: Summary of the Sources and Pathways of Emerging Contaminants in Water Sources, Presented in A Tabular Form

Source	Description	Key Contaminants	Impacts	Management Strategies	References
Agricultural Runoff	Runoff from agricultural activities carrying residues from fertilizers, pesticides, and livestock waste into water bodies.	Antibiotics, hormones, neonicotinoids, excess nutrients	Algal blooms, endocrine disruption, spread of antibiotic-resistant bacteria	Contour plowing, vegetative buffer zones, precision agriculture, alternative pesticides, monitoring programs, public awareness campaigns	[43]
Industrial Discharge	Waste from industrial processes that can contain a variety of synthetic chemicals and heavy metals is released into water bodies through effluents.	PFAS, pharmaceuticals, heavy metals, microplastics	Bioaccumulation in food chains, endocrine disruption, chronic diseases, antibiotic resistance	Stricter regulations, advanced treatment technologies, green chemistry, public awareness and community engagement	[44]
Wastewater Treatment Plants	Facilities treating urban and industrial wastewater, often insufficiently removing emerging	Triclosan, BPA, pharmaceuticals, antidepressants	Endocrine disruption in aquatic organisms,	Advanced treatment methods (membrane filtration, activated carbon adsorption, advanced	[44]

	contaminants due to limitations of conventional treatment methods.		antibiotic-resistant bacteria	oxidation), regulatory guidelines, public education on disposal practices	
Urban Stormwater	Runoff from urban surfaces collecting pollutants and transporting them to water bodies.	Pharmaceuticals, personal care products, heavy metals, PAHs	Endocrine disruption, sediment accumulation, pollution of water bodies	Green infrastructure (green roofs, permeable pavements, bioretention systems), innovative stormwater management practices	[43]
Leaching from Landfills	Leachate from decomposing waste in landfills containing various contaminants that can infiltrate soil and groundwater.	PFAS, pharmaceuticals, heavy metals	Groundwater contamination, soil pollution, risks to drinking water supplies and agriculture	Leachate management (recirculation, engineered liners, advanced treatment), monitoring programs	[41]
Atmospheric Deposition	Contaminants settling from the atmosphere onto land and water surfaces through processes like acid rain and dust.	PCBs, PCDD/Fs, nitrogen compounds, heavy metals	Soil and water contamination, bioaccumulation, ecological and health risks	Regulatory measures (Stockholm Convention), emission controls, air quality improvements, pollutant monitoring	[45]

The table above (Table 5) provides a summary of each of the sources of the emerging contaminant, their key contaminants, impacts, management strategies as well as references for further reading.

4. Detection and analytical methods for emerging contaminants

Emerging contaminants (ECs) pose significant risks to human health and ecosystems. This review assesses the efficacy of sophisticated analytical techniques, in particular mass spectrometry, for the identification of ECs as well as their toxicity, metabolic routes, and environmental dissemination. Our results highlight the validity of existing methods and the promise of future approaches. Toxicological evaluations in vitro and in vivo are required due to the detrimental effects of ECs on marine life. Physical, chemical, and biological alterations of ECs are revealed by analyzing their dispersion and degradation. Waters contaminated with EC can be effectively treated using remediation techniques such as membrane bioreactors, adsorption, and advanced oxidation; combinations of these methods have the maximum efficacy. To mitigate the effects of ECs, proactive measures such as monitoring, regulation, and public education are essential. Future research should focus on enhancing detection methods and developing robust policies for EC management [46].

A good sampling technique is aimed at identifying and analyzing new pollutants in environmental research. Effective sampling ensures that the collected samples are highly representative of the levels being studied of the contaminants in an environment or matrix, respectively. There are various methods to sample water, depending on a study's objectives: grab and composite sampling. Grab sampling provides a snapshot in time, whereas composite sampling is more indicative of temporal or spatial changes in the contaminant levels. In soil sampling, samples are taken from different depths to analyze contaminants from various levels; core samples study the depths of the soil, while surface samples study recent contaminants. While passive sampling captures the contaminants over some time, active sampling captures the contaminants in real-time through the action of pumps. In fact, each sampling method should be chosen according to the contaminant, environmental medium, and objectives of the study to ensure that accurate data collection is representative.

After the collection of samples, appropriate analytical techniques should be selected for identifying and measuring new pollutants. Advanced techniques in HRMS and HPLC have evolved into sophisticated tools for detecting low-level contaminants and differentiating between intricate mixtures. HRMS techniques include Orbitrap and FT-ICR mass spectrometers that give very accurate mass measurements with high resolution. Combined systems like LC-MS/MS and GC-MS/MS enable the simultaneous detection of a large number of contaminants. Newer developments in the field of biosensors, ELISAs, and SPR sensors do present sensitive and accurate detection properties for real-time monitoring. Despite the advances, several challenges, though, exist here, especially with low-concentration contaminant detection in the presence of background noise, matrix effects, and high costs and sophistications for analysis using sophisticated technologies. It thus becomes necessary that new technologies keep on developing and the existing ones get improved for continued environmental monitoring and assessment of emerging contaminants [47].

The techniques of analysis are then required after collecting the environmental samples, to quantify and characterize the emerging contaminants. The major tools in the identification of the contaminants from trace levels are mass spectrometry and chromatography. Mass spectrometry defines the sample composition through the ionization of chemical compounds into charged molecules and then by their mass-to-charge ratio. Sophisticated MS techniques, such as QTOF and MS/MS, enable accurate identification and quantification of pollutants, even in complex environmental samples. Chromatography works along with MS to separate and analyze compounds in terms of physical and chemical characteristics. GC is applied to volatile pollutants and is usually combined with MS for increased sensitivity, while LC is applied to non-volatile and polar pollutants, also commonly combined with MS for complete analysis [44]

Methods of preparing samples, like liquid-liquid extraction and solid-phase extraction, are vital in separating contaminants from intricate matrices prior to analysis. These techniques aid in focusing pollutants and enhancing the precision of the following analytical methods [48]. Sophisticated chromatography methods such as high-performance liquid chromatography (HPLC) and ultra-high-performance liquid chromatography (UHPLC) provide improved detection of low-concentration contaminants due to their enhanced resolution and sensitivity. Advanced versions of traditional techniques, when paired with sophisticated analytical methods, play a crucial role in environmental monitoring and researching new contaminants. They are necessary for addressing issues like detecting trace levels and analyzing complex sample matrices.

4.1. Advances in detection technologies

Detection technologies have doubtlessly undergone great improvements, increasing the potential for the detection and measurement of new contaminants with better sensitivity and precision. Improvements in high-resolution mass spectrometry and high-resolution liquid chromatography have ultimately set up new improvements in the area of environmental analysis. High-mass accuracy and -resolution instruments, Orbitrap and Fourier-transform ion cyclotron resonance mass spectrometers, provide picogram contaminants detection with the potential for new substances discovery [49]. Tate-of-the-art analytical systems—methods include LC-MS/MS and GC-MS/MS—extend capabilities for the analysis of a broad range of pollutants simultaneously, yielding very detailed data of identity and levels, as noted by [50].

Other improvements worthy of mentioning in detection technologies involve biosensors and sophisticated analysis technologies for data. Biosensor devices, mainly ELISAs, and SPR sensors, can give correct and ultra-sensitive real-time detection and monitoring of contaminant presence in water. Machine learning and artificial intelligence strengthen data analysis by allowing the examination of big data and the discovery of patterns of contaminant presence and behavior, as one of the most important challenges is the achievement of enough sensitivity to be able to detect contaminant trace levels; this usually requires ultra-advanced techniques such as HRMS and UHPLC. Despite these progresses, serious issues remain, including signal-to-noise ratio problems and matrix effects interference, all frustrating any attempt at a more precise contaminant identification [51]. It is also in complex sample matrices that contaminant signals can be hindered by background noise and matrix effects, but solid-phase extraction and matrix-matched calibration are among the methods counteracting such difficulties. Among other reasons, including their expensive cost and specialized operational requirements, high-resolution analytical instruments and advanced technologies for environmental monitoring, remain restricted from routine use [52]

Another problem is that no standardized methodologies are available for the future identification of new pollutants, making following regulations and comparing results from multiple research studies impossible to some degree. Continued research and development will thus be required to improve detection technologies, innovate new methodologies, and develop comprehensive regulatory frameworks to improve the environmental management of emerging contaminants.

4.2. Environmental fate and transport of emerging contaminants

Emerging contaminants (ECs) such as pharmaceuticals, personal care products (PPCPs), perfluoroalkyl and polyfluoroalkyl substances (PFASs), and endocrine-disrupting chemicals (EDCs) pose significant threats to water resources due to their potential risks to ecosystems and human health, even at trace levels. Mathematical modeling serves as a valuable tool for studying the fate and transport of these contaminants in natural waters. However, modeling studies of ECs have received considerably less attention compared to field and laboratory studies. This review assesses the current status of EC modeling, focusing on selected representative contaminants, their sources, fate, mechanisms, and interactions within aquatic ecosystems. We critically evaluate the principles, mathematical derivations, ongoing developments, and applications of various EC models across different regions. Recommendations for enhancing data quality, monitoring strategies, and model development are provided. This review aims to establish a framework for a comprehensive EC modeling approach to assist researchers and policymakers in managing water resources affected by increasing levels of ECs [53].

Comprehending the environmental destiny and movement of newly identified pollutants is crucial for evaluating their influence on ecosystems and human health. The physical and chemical properties of contaminants, such as solubility, volatility, partitioning behavior, and persistence, play a major role in their movement within the environment. The ability of contaminants to dissolve in water and move through aquatic environments is controlled by solubility. Highly soluble substances, such as pharmaceuticals, can disperse into natural water bodies from wastewater treatment plants, while less soluble contaminants may stay in sediments or bind to soil particles. The transfer of contaminants between the atmosphere and other environmental media is influenced by volatility; industrial process emissions or gasoline spills containing volatile organic compounds can evaporate into the air and travel far before being redeposited. Partitioning behavior refers to how pollutants spread among various environmental phases; a high octanol-water partition coefficient signifies a preference for accumulating in fatty tissues, while a high soil-water partition coefficient indicates an attraction to soil particles [54].

Furthermore, the processes of adsorption and desorption play a crucial role in comprehending the movement of contaminants in soil and sediment. These processes involve contaminants sticking to or coming off soil particles, a phenomenon impacted by factors like soil texture and pH. Persistence indicates the duration of contaminants in the environment, with persistent substances such as PCBs and PFAS building up in the food chain and presenting long-term ecological threats. The combined physical and chemical properties of emerging contaminants influence their environmental behavior, emphasizing the complexity of their fate and transport, necessitating comprehensive management strategies [55].

Understanding degradation and transformation is crucial in assessing how contaminants degrade or undergo changes in the environment, impacting their durability, harmfulness, and movement. These methods consist of photodegradation, where UV sunlight breaks down pollutants; hydrolysis, where contaminants react with water to form less harmful substances; biodegradation, where microorganisms break down contaminants; redox reactions, involving electron transfer to change contaminant chemicals; phytoremediation, where plants remove contaminants; and chemical oxidation/reduction with ozone or zero-valent iron to eliminate pollutants. Predicting the duration and effects of contaminants in the environment requires a thorough grasp of these mechanisms [54].

Table 6: Summary Table

Aspect	Description	Factors and Processes	Contaminants	References
Physical and Chemical Properties	Characteristics that influence contaminant movement and distribution.	Solubility, Volatility, Partitioning Behavior, Adsorption, Persistence	Pharmaceuticals, Pesticides, VOCs	[54]
Degradation and Transformation	Processes that alter the chemical nature of contaminants in the environment.	Photodegradation, Hydrolysis, Biodegradation, Redox Reactions, Phytoremediation	Pesticides, Pharmaceuticals, Heavy Metals	[55]

This detailed overview provides a comprehensive understanding of the factors affecting the environmental fate and transport of emerging contaminants and highlights the processes that influence their degradation and transformation.

4.3. Remediation and treatment technologies

Industrial emissions of dyes and heavy metals have led to significant global environmental pollution. Developing efficient, eco-friendly, and cost-effective wastewater treatment methods for these contaminants is essential. Biologically based techniques for treating effluents offer distinct advantages over conventional methods. This review examines recent advancements in biological approaches for the removal of dyes and heavy metals from wastewater, detailing the roles of various microorganisms, including algae, bacteria, fungi, and enzymes. It also highlights ongoing advancements, scientific challenges, and future prospects in this field. This review aims to provide an integrated understanding of biological wastewater treatment and to foster further research on its applications in water purification [56].

Traditional techniques for water treatment are the recognized methods utilized for eliminating impurities from water sources. These strategies are created to tackle a wide variety of contaminants and are essential to managing water quality. Traditional water treatment methods are a prime necessity in producing safe drinking water and treating wastewater. Generally, these methods involve several major steps. These include coagulation and flocculation, settling, filtering, and disinfecting. In coagulation and flocculation, chemicals are added, usually alum or ferric chloride, into the water to reduce the charges on the particles and cause them to form larger flocs that would settle easier [56]. The water then proceeds into a sedimentation tank, where gravity assists in causing the flocs to settle down at the bottom, thereby large solid impurities are entirely separated from the water [55]. It is passed over long filters of sand, gravel, or even activated carbon to rid the water of the rest of the suspended particles and other impurities [25]. Finally, residual pathogens are either killed or inactivated by disinfection techniques, which may involve chlorination, ozonation, or UV radiation, so that the water is now potable. While these methods were effective for many traditional contaminants, they may be inadequate to remove sufficient levels of emerging pollutants—pharmaceuticals and personal care products. Advanced treatment technologies have actually been specially developed to improve the shortcomings in the ability of conventional approaches to handle complex mixtures of pollutants. Membrane treatment encompasses microfiltration, ultrafiltration, nanofiltration, and reverse osmosis; it aims to remove a suite of impurities from the water. The reverse osmosis process is notably effective at extracting dissolved salts and organic compounds, particularly when dealing with the concentrations described in this study. Advanced Oxidation Processes (AOPs) such as O_3/$H2O_2$, UV/O_3, and Fenton's reagent exhilarate organic water pollution to degrade into less toxic forms through powerful radicals. The best technique for removing trace amounts of contaminants, like pharmaceuticals, was found to be adsorption with active carbon, including granular and powdered [57]. More developed biological treatment and treatment with constructed wetlands or biological aerated filters improve these natural mechanisms of water purification, offering simultaneously effective and sustainable solutions for pollutants' removal [19]. Advanced technologies are now implemented in the treatment processes for the management of contaminants where the traditional methods are ineffective and unsuitable, thus ensuring the public health safety and water quality.

4.4. Bioremediation and phytoremediation approaches

The extensive use of pesticides in agriculture leads to harmful contaminants in soil and water, adversely affecting terrestrial and aquatic ecosystems. These chemicals accumulate in living organisms, causing sublethal and lethal effects in humans and animals due to bioaccumulation and biomagnification. Bioremediation and phytoremediation are emerging as cost-effective and eco-friendly methods to remove pesticide contamination from water. Microorganisms and plants degrade pesticides through various biochemical and physiological processes, involving different enzymes that convert these substances into less toxic or non-toxic compounds. Notable pesticide-degrading microorganisms include bacterial species like Pseudomonas, Bacillus, Azotobacter, and Flavobacterium, fungi such as Aspergillus and Mycobacterium, and algae like Chlorella. The degradation effectiveness varies by species and target compound. To detoxify soil and water pollutants, bioremediation using plants and bacteria can be employed. Phytoremediation techniques include phytodegradation, phytoextraction, phytostabilization, phytovolatilization, rhizofiltration, and rhizodegradation for pollutant uptake. Various aquatic plants like Lemna, Eichhornia, Azolla, Hydrilla, Pistia, Spirodela, and Wolfia are particularly effective in reducing pesticide and other contaminant levels in aquatic environments. This chapter provides an overview of the remediation of pesticides from contaminated water using microorganisms and plants [58].

Bioremediation and phytoremediation represent a greener, practical approach in handling problems related to pollution. They recycle natural processes and natural organisms to destroy or nullify the pollutants. They therefore constitute another method considered a green technology that will manage pollution. All consist in a few biological processes that would address what are called environmental problems brought by the pollutants.

Bioremediation is one of the most used methods of biological contamination management where living microorganisms are used to either reduce the depleted or decrease the hazardous materials. It can be implemented on- or off-site of the impacted location. At the site of contamination, off-site can be known as bioventing. It is mostly employed treatment of bioremediation that increases the growth of existing bacteria by adding oxygen to the contaminated soil. Biopiles are made of piling up a contaminated soil and, in other words, maximizing aeration and moisture to encourage microbial degradation. The other one includes bioreactors. These refer to a vessel or a building that is constructed using microorganisms to purify the polluted water or soil in a more controlled environment [59], some bacteria can be applied to the biological principle of degrading the petroleum hydrocarbons during the oil spill, thus allowing the soils to limit the adverse effects of the calamities on the environment.

The application of plants in the phytoremediation of pollution in many different ways includes phytodegradation, a significant process in which plants take up the pollutants and, through metabolic pathways, transform them into relatively less toxic compounds. For phytoextraction, plants take up impurities in the soil and concentrate them in their plant tissues, which are subsequently harvested to pool the impurities and remove them from the site. For example, sunflowers can remove heavy metals such as lead and cadmium in contaminated soils, indicating the potential of plants to restore polluted environments. Phytoremediation is an aesthetic and cost-effective strategy to manage environmental pollutants and improve the quality and composition of soils.

Mycoremediation is one of the emerging fields in the processes of environmental clean-ups where fungi are put to use in decomposing challenging organic pollutants. Fungi have some specialized enzymes that enable them to decompose different kinds of pollutants, among them harmful industrial substances and oil-based products. This approach is very promising in the treatment of polluted soils and water because various fungi have been determined to break complex organic substances down [35]. Mycoremediation is a relatively new area within bioremediation, providing creative answers to tricky pollution situations. Bioremediation and phytoremediation are well-regarded for their small environmental footprint and cost benefits compared to many other conventional technologies. Due to their contained ecological processes, these approaches are less damaging environmentally. However, their potential may be influenced by other factors acting independently or interactively, such as the type of pollutant, the environmental setting in which the technology is implemented, and the biological technology being used.

4.5. Advances in detection technologies

The necessity for highly efficient wastewater treatment has become clear amid worsening water crises. With advancements in green technology, eco-friendly wastewater treatment methods are essential. Biotechnology offers a promising approach for addressing these challenges, encompassing both treatment and monitoring processes. Key differences in biotreatment methods are influenced by environmental conditions, biological processes, and the types of microorganisms involved. Identifying suitable biotreatment strategies for specific contexts is crucial. This review provides a comprehensive overview of optimized biotreatment processes under varied conditions, discussing the advantages and disadvantages of these biotechnologies and their application potential. Additionally, they explore recent advancements in biosensors (including optical, electrochemical, and others) for monitoring purposes [60].

Electrochemical processes are among the most flexible and effective treatment technologies, using electrical currents to trigger reactions that will deal with environmental contaminants. Electrochemical oxidation makes use of an electrical current to generate reactive species at the electrode surface, which in turn oxidize contaminants to innocuous forms. Therefore, this technique is very effective in degrading refractory organic pollutants that are resistant to conventional treatments. Another prominent technique is electrocoagulation, whereby

electricity is passed to activate coagulants on electrodes and form flocs that pick up pollutants, which can be separated from water. This technique is versatile and can be applied to a variety of pollutant types, from metals to organics, ensuring an effective and efficient solution for problems related to water treatment.
Nanotechnology is changing the face of environmental remediation due to the potential for control of materials only at a nanoscale level. Nanoremediation techniques make use of nanoparticles like zero-valent iron and titanium dioxide to undertake state-of-the-art chemical processes on pollutants. ZVI nanoparticles are utilized for dechlorinating dangerous organic pollutants, hence effectively converting the chlorinated compounds into less hazardous substances. Nanoparticles of TiO_2 have a role in photocatalysis, reacting with UV light and producing oxygen species that are reactive to the breakdown of organic pollutants. The high reactivity and specificity make these nanomaterials very suitable for solving some difficult contamination problems. One of the most prominent developments in the field of environmental remediation creates treatment systems. These new innovative designs and structures include techniques such as constructed wetlands and floating treatment wetlands, which improve the conventional treatment processes. The constructed wetlands try to mimic the functions of a natural wetland by utilizing plant life and microorganisms for purification and breaking down harmful elements. A further evolution is represented by the floating treatment wetland, which applies floating platforms combined with vegetation, able to integrate biological, chemical, and physical methods for effective water treatment [61]. These systems offer an improved solution in sustainability and aesthetic handling. Current improvements in sensor and monitoring technologies are increasing the ability for real-time identification and measurement of pollutants. Next-generation state-of-the-art technologies developed in the recent past—such as optical sensing, biosensing, and lab-on-a-chip devices—are attempts to analyze the quality of water and detect the presence of pollutants more accurately [62]. These new and innovative treatment strategies show the advances made in dealing with environmental pollution, offering new ways to approach the complexities of modern pollution problems. These techniques will evolve and develop as research unfolds, expanding our ability to protect and enhance the environment [63].

5. Summary

Emerging contaminants pose significant risks to water quality, impacting both the environment and human health. These pollutants include pharmaceuticals, personal care products, endocrine-disrupting chemicals, per- and polyfluoroalkyl substances, microplastics, pesticides, and industrial chemicals. They enter water systems through excretion, incorrect disposal, agricultural runoff, industrial discharges, urban stormwater runoff, leaching from landfills, and atmospheric deposition.Identifying these contaminants requires sophisticated sampling methods and analytical techniques, such as mass spectrometry and chromatography, due to the challenge of detecting low-le vel pollutants. Traditional water treatment methods often fall short, necessitating advanced technologies like membrane filtration, advanced oxidation processes, activated carbon adsorption, bioremediation, phytoremediation, electrochemical processes, nanotechnology, and constructed treatment systems. Future research should focus on understanding the behavior of these pollutants, developing innovative technologies, and enhancing public awareness and policy support to effectively address water quality issues. Public education is crucial, involving targeted campaigns, school curricula integration, and community workshops to inform about risks, contamination pathways, and reduction measures. Effective communication through media and digital tools can help navigate scientific complexities and combat misinformation, fostering advocacy for stronger regulations and encouraging safer practices. These efforts aim to improve water quality management and environmental protection.

6. Conclusions

In conclusion, emerging contaminant management requires a multilateral strategy involving technical and social dimensions of environmental protection. As noted in the review, conventional water treatment processes certainly provide a platform for contaminant management, but they are often inadequate to deal with new pollutants. Effective contamination control by contemporary technologies and innovative solutions needs to be backed by solid research, effective policies, and public engagement. In environmental management plans, awareness among the general public should be raised. If the public is informed about the risks of new pollutants, there could be more support for environmental regulations and community involvement in the prevention of pollution. Community involvement in monitoring and cleaning the environment may, as part of active participation, enhance the success of strategies in environmental management through well-informed individuals who become more prepared to support and argue for more stringent policy formulation on the environment. In the long term, research should be directed toward filling knowledge gaps by investigating new technologies and urging collaborations across different disciplines. Overcoming these challenges will lead to better practices in controlling new pollutants and safeguarding the water quality for future generations. High innovation and public engagement will be needed to continue countering these pollutants' challenges for lasting environmental sustainability.

7. Recommendations for future research

There would certainly be a focus in the near future on some critical areas that would go a long way to enhance the management of emerging contaminants. Better research will go a long way not only in the discovery of new pollutants but also in establishing better detection techniques and understanding their long-term adverse effects on environmental and human health. A need for interdisciplinary research collaboration is the need that can help us move forward. Further, new technologies for treating contaminants are urgently called for. Support the development and upgrading of state-of-the-art technologies, including innovative medicine treatments, to compensate for the weaknesses associated with technologies currently available and faster elimination of wastes. Improved public education through targeted outreach and education programs will gain community support for contamination management and foster improved environmental behavior. Finally, policymakers should allow the stimulation of policy innovation by exploring different possible regulatory frameworks and funding methods that will support and increase progress in research to implement efficient technologies for handling the contaminants that are emerging. The recommendations are guidelines for future initiatives to improve the management of environmental and public health in the light of inevitability in contamination challenges.

8. Declaration of interest

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

9. Authors' contributions

Ma'aruf Abdulmumin Muhammad: Conceptualization, formal analysis, writing – original draft, and supervision. Abubakar Muhd Shafi'i: Investigation, and writing – review & editing. Abubakar Musa Shuaibu: Validation and writing – review & editing. Usman Usman Alhaji: Writing – review & editing. Sabiu Rabilu Abdullahi: Writing – review & editing. Muhammad Ibrahim Abdurrashid : Writing – review & editing.

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