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Emerging Aquatic Contaminants, Human Health and Environmental Sustainability: A PRISMA-Based Systematic Literature Review Towards Achieving SDGs

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Abstract
Emerging aquatic contaminants (ECs) have grown in popularity, persistence, toxicity and impact on water environment and human health making them a major concern for the global environment. Persistent contaminants including pharmaceuticals, antibiotics, endocrine disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics, heavy metals, pesticides, and flame retardants are commonly found in surface water, ground water, sediments and aquatic organisms. Many of these pollutants exist at trace levels, but their persistent emissions, bioaccumulation, biomagnification and potential mixture effects have a potential harmful impact on biodiversity, ecosystem services, food security and public health. This challenges progress in relation to various United Nations Sustainable Development Goals (SDGs): SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).
The objective of this systematic literature review is to compile and synthesise scientific information on the occurrence, ecological effects, public health risks, monitoring methods, remediation technologies and relevance to sustainability of emerging aquatic contaminants in recent literature. In addition, the review assesses the contribution of existing research to the achievement of SDGs and identifies knowledge gaps that need to be addressed in the future.
The review was done according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The emerging contaminants articles published from 2020 to 2025 were systematically retrieved from databases (ScienceDirect, Scopus, Web of Science) with the suitable keywords for emerging contaminants, water pollution, ecological risk, human health, aquatic ecosystems, and sustainable development. After the removal of duplicates, title and abstract screening, full-text eligibility assessment and quality appraisal, relevant studies were synthesised by seven major thematic areas: (i) occurrence of emerging contaminants, (ii) microplastic pollution, (iii) heavy metal contamination, (iv) endocrine-disrupting chemicals, (v) pharmaceuticals and antibiotics, (vi) monitoring technologies, and (vii) mitigation strategies.
The literature reviewed clearly showed the presence of pharmaceuticals, endocrine disruptors (EDCs), pesticides, antibiotics, heavy metals and microplastics in freshwater, estuarine, coastal and marine environments around the world. They have been transferred to sediments and aquatic organisms, resulting in higher ecological risks due to bioaccumulation, trophic transfer, loss of biodiversity, endocrine disruption, oxidative stress, impaired reproduction and habitat destruction. Exposure to humans is mainly via contaminated drinking water and through the consumption of seafood, and it is associated with concerns of carcinogenicity, antimicrobial resistance, neurological disorders, and endocrine-related diseases. In recent years, the use of artificial intelligence, machine learning, environmental DNA (eDNA), remote sensing, biosensors, and advanced analytical techniques has significantly enhanced contaminant detection, ecological risk assessment, and predictive monitoring capabilities. Other solutions for water quality improvement based on natural processes, new adsorption materials, phytoremediation, biofiltration and the implementation of circular economy practices have also demonstrated a good potential for water quality improvement and environmental sustainability.
In summary, it is evident that the integrated environmental monitoring, interdisciplinary research, enhanced regulatory measures, innovative treatment technologies and international cooperation are the keys to effective management of EACs. Improving these strategies will play a major role in supporting the protection of aquatic ecosystems, public health, water security and global efforts to achieve the SDGs.

Keywords: Chisel Plow, Hardpan Layer, Crop Growth

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Introduction
1.1 Water Pollution
Water plays a critical role in the ecological, economic, agricultural, industrial and human health. During the last ten decades, however, rapid industrialisation, urbanisation, intensive agriculture, population growth and climate change have led to a considerable increase in pollutant loads in aquatic environments, causing a considerable degradation of water quality in the world. The riverine, aquatic, wetland, estuarine, ground water and marine ecosystems are being polluted by a diverse range of chemicals,

biological and physical pollutants, which pose risks to aquatic biodiversity and human health. While traditional pollutants like nutrients, suspended solids, pathogens and heavy metals have long been a focus of concern, emerging contaminants (ECs) have emerged as one of the biggest environmental problems of our time, they are introduced into aquatic environments continuously, they are persistent, and they are not readily removed by conventional wastewater treatment processes.

Another issue is persistent pollutants, which will not degrade easily in the environment, and can persist in the aquatic system for some time. They bioaccumulate, long-range transport and biomagnify in food chains in sediments and water bodies. Aravind Kumar et al. (2022) noted that persistent organic pollutants (POPs) such as pesticides, industrial chemicals and industrial products' by-products are highly chemically stable and persistent and can affect the aquatic ecosystem in a long-term way. They also noted that, around the world, agricultural run-off, industrial effluents and waste disposal practices are still the biggest contributors to the world's persistent organic pollution.

The focus of scientific research has been on emerging contaminants in recent years, as many of these contaminants are present in the environment in large numbers, but at very low concentrations and are not routinely monitored. Pharmaceuticals, personal care products, endocrine-disrupting chemicals, antibiotics, flame retardants, plastic additives and microplastics, per- and polyfluoroalkyl substances (PFAS), steroid hormones and nanomaterials are all emerging contaminants. These pollutants are often found in the environment at very low concentrations (nanogram or microgram per litre) but can still cause chronic toxicity, in addition to endocrine disruption, oxidative stress, behavioural changes, and reproductive impairment in aquatic organisms.

Xu et al. (2023) examined the fugacity modelling and chemical indicators of steroid hormones and their metabolites in the watershed environment. In the water of their research, they found 13 steroid compounds, between 1.0 and 76 ng/L, and in sediments, 121 ng/g. The researchers calculated that the river transports about 89 kg of steroid compounds each year, thereby showing the river's continual transport of biologically active contaminants to water ecosystems. The results show that diffuse pollution sources and wastewater effluents are still significant sources of contamination of the environment.

Likewise, endocrin disrupting compounds (EDCs) are contaminants of global concern because they are known to disrupt hormonal regulation in wildlife as well as in humans. The levels of 17α-ethynylestradiol (EE2) in 32 countries were reviewed systematically by Tang et al. (2021) and found from 0 to 17,112 ng/L, where about one in three water bodies had moderate to high estrogenic risk suggesting widespread contamination and a need for better environmental management strategies.

Contamination of pollutants derived from plastic is another emerging environmental problem. In 2020, Wang et al. conducted a study that tested bottled drinking water samples for bottles made from polyethylene terephthalate (PET) and polycarbonate (PC) and found bisphenol analogues in both materials. Bisphenol A (BPA) levels were found in reusable plastic containers, with PET bottles ranging from 12.4 to 44.9 ng/L and polycarbonate bottles ranging from 111.8 to 6452.8 ng/L, suggesting higher estrogenic exposure risks for reusable plastic containers, specifically polycarbonate bottles.

Another category of emerging contaminants of high scientific interest are per- and polyfluoroalkyl substances (PFAS). Zango et al. (2023) comprehensive summarized the occurrence, toxicity, extraction and removal technologies of perfluoroalkyl carboxylic acids (PFCAs) in aquatic environment. The authors found the carbon–fluorine bonds in PFAS to be very strong and they noted that PFAS have the potential to be transported long distances and bioaccumulated in aquatic environments. In addition, PFAS have been linked to endocrine disruption, developmental toxicity, immune system impairment and carcinogenicity, demonstrating the group to be one of the most difficult to manage in the environment.

The problem of emerging contaminants and the degradation of water quality is not just an environmental problem but multi-dimensional sustainability problem as well. The effects of contaminated water are on ecosystem functioning, biodiversity, fisheries, agricultural productivity, drinking water safety, tourism and public health. Furthermore, the toxicity of combinations of more than one contaminant can be synergistic or additive, much more damaging than when the contaminants are present individually. Traditional wastewater treatment facilities were not meant to address pharmaceuticals, micro-plastics, endocrine disruptors, and PFAS and many of these pollutants are being released in receiving waters continuously.

Thus, the higher the amount of contamination of aquatic environments the less resilient the ecosystem will be and the less sustainable water resource management will be internationally. Recent literature accumulated in the last decade has shown that emerging contaminants are a worldwide problem that must be addressed through a holistic environmental monitoring, treatment systems, and risk assessments as well as evidence-based policy development. The issues are the basis of an understanding of the wider ecological, health and sustainability impacts which are explored in the remaining sections of this systematic literature review.

1.2 Emerging Contaminants

Emerging contaminants (ECs) are naturally occurring or synthetic compounds that have recently become objects of scientific and regulatory focus, due to their prevalence in the environment, persistence, bioaccumulation, and potential harmful effects to humans and the environment. While many of these compounds have been around for decades, technological developments in analytical chemistry have now made these compounds detectable at trace levels in water, sediments, and aquatic biota. Although the scientific evidence shows that emerging contaminants are routinely discharged to aquatic environments via municipal wastewater, industrial effluents, agricultural runoff, aquaculture, landfill leachate and precipitation, the majority are not routinely monitored under existing water quality regulations. As a result, the spread of ECs is a one of the biggest problems in water resource management in the world. These emerging contaminants are a wide group of chemicals such as pharmaceuticals and personal care products (PPCPs), antibiotics, endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics, pesticides, flame retardants, nanomaterials, steroid hormones, and industrial additives. These pollutants are continually released into the environment, and are not completely eliminated from wastewater by conventional treatment facilities, allowing them to remain in the aquatic system and providing more opportunity for chronic exposure, bioaccumulation, and trophic transfer. Additionally, many emerging contaminants are found in combination, and the mixture toxicity can have a greater ecological impact than the individual contaminants can independently.

1.2.1 Pharmaceuticals and Antibiotics

Pharmaceuticals are one of the most rapidly growing groups of emerging contaminants due to rising global usage of medicines, ageing demographics, vast growth in healthcare provision and intensive livestock farming. High percentages of pharmaceuticals are secreted in their unchanged form or as active metabolites and end up in wastewater treatment plants. However, conventional treatment technologies fail to remove these compounds from the water entirely and discharge continues to rivers, lakes, estuaries and coastal waters.

The concentrations of twenty pharmaceutical compounds in the five major river basins in China were evaluated by Dai et al. (2021), and some pharmaceuticals, such as estrogens and sulfapyridine, showed high risk quotients (RQs) of up to 17.2. The study also confirmed that aquatic food chains provided a significant additional source of human pharmaceutical exposure compared to drinking water, indicating the importance of fish as an additional pathway of exposure .

Similarly, Khan et al. (2021) studied the contamination of pharmaceuticals in the Yamuna River during different seasons and found that the concentration of ofloxacin was 1,726.5 ng/L during the post-monsoon season. The risk quotients of several pharmaceuticals such as diclofenac, diazepam, ofloxacin and simazine were always > 1 during the year, suggesting high year-round ecological risk. The results indicate that pharmaceutical contamination is not a one-time event, but rather is ongoing and needs to be monitored continually.

Aside from their direct toxicity, antibiotics are a major driver of one of the world's most urgent public health problems: the emergence and spread of antimicrobial resistance (AMR). Antibiotic residues in water systems create selection pressure in a microbial community, which allows the emergence of antibiotic resistance and the production of antibiotic resistance genes. Wang et al. (2024) identified 37 antibiotics in the surface water (78.4–225.6 ng/L) and sediment (19.5–229 ng/g) of mangrove aquaculture systems. Importantly, there was an ecological risk level of medium to high for antibiotic mixtures for 37.5% of the water samples and 66.7% of the sediment samples, highlighting that the effect of multiple contaminants should be considered, not individual compounds.

1.2.2 Endocrine-Disrupting Chemicals

Endocrine Disrupting Chemicals (EDCs) are chemicals that can disrupt the hormonal signaling pathways and have a negative impact on growth, metabolism, immune system, and reproduction in wildlife and humans. Pharmaceuticals, pesticides, personal care products, industrial chemicals and household wastewater are all examples of sources for EDCs.

One of the most thorough reviews of 17α-ethynylestradiol (EE2) contamination worldwide was performed by Tang et al., 2021. They analyzed studies from 32 countries, and found EE2 concentrations up to 17,112 ng/L, with about 65% of the surface waters analyzed, showing moderate to high estrogenic risk to aquatic organisms . These types of contamination have been linked to feminisation of fish stocks, abnormalities in reproduction, sex ratio imbalance and biodiversity loss.

The seasonality adds complexity to EDC management. Cunha et al. (2022) analyzed 37 endocrine-disrupting chemicals in estuaries of the Tagus and Douro Rivers, such as pesticides, bisphenols, synthetic musks and UV filters. HHCB was detected in over 96% of water samples, whereas pesticide and UV-filter levels were significantly higher in warmer seasons, due to increased recreational use and agriculture activities during that time. This shows the effect of seasonal and anthropogenic factors on the occurrence of contaminants.

Chandran et al. (2025) recently studied the endocrine-disrupting phenols of plasticisers in the Bay of Bengal and found that the concentrations in seawater, sediments and tissues of fish reached up to 3,949 ng/L, 2,195 ng/g and 2,609 ng/g, respectively. Nonylphenol had value of hazard quotient greater than one, suggesting both an ecological risk and a dietary risk via seafood. The results reaffirmed worries about the movement of contaminants from one environment to another.

1.2.3 Microplastics

Microplastics are one of the most widely researched emerging contaminants due to the rise in plastic production, lack of waste management and environmental persistence. Microplastics are defined as plastic debris less than 5 mm in size, either as primary plastic particles produced for industrial purposes or as secondary plastic particles that are fragments of larger plastic debris.

Microplastics have been found in rivers, lakes, oceans, sediments, drinking water, indoor air, seafood and even in human tissue. They are not only ingested but also serve as a vector for many other substances, such as heavy metals, pharmaceuticals, pesticides, and persistent organic pollutants, which are often absorbed onto their surfaces.

The severity of this problem is illustrated in studies from Malaysia. Increased urbanisation has been associated with a high abundance of microplastics, with Tuan Anuar et al. (2023) reporting mean values of 179.6 items/L in the Kelantan River Basin and 1,464.8 items/L in the Langat River Basin, which is a highly urbanised area. Likewise, Praveena et al. (2022) detected microplastics in all bottled water brands from Malaysia with a range of 8-22 particles/L, with estimated daily intake showing that children are more vulnerable than adults with regards to chronic exposure.

1.2.4 Per- and Polyfluoroalkyl Substances (PFAS)

The PFAS class of contaminants is also important due to the high resistance to degradation in the environment and the highly stable chemical properties. PFAS are known as "forever chemicals" and are extensively applied in fire extinguishing foams, clothing, food packaging, electronics and industrial processes. They have high carbon–fluorine bond strength, which leads to great persistence, allowing them to be transported long distances and spread around the globe.

The current knowledge on perfluoroalkylic carboxylic acids (PFCAs) was reviewed by Zango et al. (2023), who found these compounds to have high aquatic mobility, as well as high toxicity to humans, including endocrine disruption, developmental toxicity, immune dysfunction, and possible carcinogenicity. In addition, the review noted that solid phase extraction and adsorptive treatment technologies are the most promising means of removal, albeit on a small scale.

1.2.5 Flame Retardants and Plastic Additives

Certain chemicals used in the production of plastics or as flame retardants have become a growing concern as contaminants due to their persistence in the environment and widespread use in industry. Alternative halogenated flame-retardant chemicals such as polybrominated diphenyl ethers (PBDEs) and plasticisers are found in aquatic organisms and sediments, where they can cause developmental toxicity and endocrine disruption.

In the past, Sun et al. (2024) identified PBDEs and other alternative halogenated flame retardants in 16 species of wild fish from the South China Sea. The range of PBDEs was from 1.69 to 47.6 ng/g lipid weight; the concentration of DBDPE was 21 ng/g lipid weight. The present diet risks were thought to be moderate but the authors reiterated that ongoing monitoring is required due to the persistence and bioaccumulative nature of these compounds.

1.2.6 Knowledge Gaps

While there has been considerable progress in analytical technologies and environmental monitoring, there are still a number of important knowledge gaps. Current research focuses on specific groups of contaminants, while aquatics are impacted by complex mixtures of contaminants. Long-term monitoring data are still limited, especially in tropical developing countries where rapid industrialization and urbanization are occurring. In addition, variation in analytical approach, sampling technique, reporting units and ecological risk assessment approaches makes meaningful comparisons between studies difficult.

Overall, the evidence presented here shows that emerging contaminants are no longer just a single environmental problem, but a set of global sustainability challenges. The integrated monitoring, enhanced wastewater treatment, further robust controls, and multi-disciplinary research needs for sustainable management of water resources are highlighted by the combined impacts of pharmaceuticals, antibiotics, endocrine disruptors, PFAS, micro plastics and flame retardants on aquatic biodiversity, ecosystem functioning, food security and human health.

1.3 Ecological Effects of Emerging Contaminants

With continual discharge into aquatic environments, emerging contaminants (ECs) are currently a major ecological concern, as they have the potential to impact organisms at every biological level from molecular and physiological response to population dynamics and ecosystem function. Many ECs are able to remain in the environment for long periods of time and are chemically stable, persisting and bioaccumulating in sediments and aquatic organisms that would not necessarily degrade readily as would conventional pollutants. As a result, low level exposure to contaminants can cause chronic toxicity from exposure over time, through bioaccumulation, biomagnification, endocrine disruption, oxidative stress, immune suppression, and reproductive impairment. Such effects can not only harm aquatic biodiversity, but also decrease the recovery capacity of ecosystems and the provision of key ecosystem services like fish production, water purification and nutrient cycling.

1.3.1 Bioaccumulation and Biomagnification in Aquatic Organisms

Bioaccumulation is the gradual increase of concentrations of a contaminant in an organism over time, while biomagnification is the increase of concentrations of a contaminant from one trophic level to another in a food web. Persistent contaminants like heavy metals, endocrine disrupting chemicals, pesticides, pharmaceuticals and microplastics are especially significant due to their extended duration of biological availability.

Zhao et al. (2022) explored nutrient and potentially toxic element uptake by rehabilitated mangrove ecosystems in south China. The study showed that following ecological restoration, some of these fish species, through bioaccumulation factors (BCF) and target hazard quotient (THQ) analysis, had significant levels of toxic elements. Lead (Pb) and chromium (Cr) had some fish species with THQ values higher than the accepted safety limit of one, suggesting possible health risks for wildlife and humans that eat contaminated seafood and possible ecological stress. The results indicate that there is no universal remedy available for removing the accumulation of contaminants with ecological restoration if a contamination source exists.

Likewise, Liao et al. (2024) studied the detection, migration and transfer of endocrine-disrupting chemicals (EDC) into the Xiangjiang River system. In the course of their investigation they found sediments to be a significant source of contaminants, continually discharging EDCs into the water column where they were taken up by fish. An additional result of the Monte Carlo simulations was that children and pregnant women were determined as the most vulnerable groups of consumers due to their higher dietary exposure per body weight compared to other groups. The findings indicate that, despite decreases in direct pollutant inputs, the contamination of sediments continues to be an ongoing threat to ecological and human health.

Heavy metals are still one of the most significant bioaccumulative contaminants as they are not bio-degradable. To assess the effects of heavy metal toxicity in wild mud crabs (Scylla olivacea) sampled from polluted coastal ecosystems in Malaysia, Razali et al. (2024) used an integrated omics approach to analyze the effects of the pollutants. The presence of high levels of nickel (Ni), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr) and cadmium (Cd) changed the expression of proteins and metabolic pathways significantly. Of particular interest, stress proteins like Hsp70 were up-regulated by ca. 5.47-fold in contaminated crabs, which is a molecular indication of chronic environmental stress. These molecular "warning signs" of ecosystem degradation occur before biodiversity loss is apparent to the naked eye.

1.3.2 Sediments as Secondary Sources of Contamination

Sediments can be both sinks and secondary sources of contaminants, and thus have a dual ecological function. Once persistent pollutants enter the rivers and riverside water bodies they often adhere to suspended particles and are carried down to the bottom sediments where they can stay for years or decades. These contaminants can then be re-suspended into the water column by physical disturbances, flooding, dredging, bioturbation and changes in water chemistry, and, repeated exposure to these contaminants occurs throughout the life of aquatic organisms.

In a study by Xu et al. (2023), they found that not only river water, but also sediments contained steroid hormones, with concentrations up to 121 ng/g, which shows that sediments can make a significant contribution to long-term storage of contaminants and delayed release to the environment. Similarly, Chandran et al. found endocrine-disrupting phenolic plasticisers in marine sediments at concentrations of up to 2195 ng/g, which indicates that sediment compartments are also important reservoirs of persistent pollutants that can continue to provide exposure to ecosystems even long after a first exposure.

Sediment contamination also affects benthic organisms which are the basis of aquatic food chains. Benthic invertebrates also collect contaminants, which are then transferred to fish, birds, reptiles and mammals, and thus are passed on down the food chain through aquatic ecosystems. Sediment quality assessment is therefore an ever increasingly important tool in ecological risk management.

1.3.3 Food Chain Transfer and Trophic Magnification

One of the biggest challenges with emerging contaminants in aquatic food webs is the transfer of contaminants up the food chain. Plankton, benthic invertebrates and molluscs, which are small aquatic organisms, take up the contaminants directly from water and sediments. These organisms are then eaten by fish, birds, marine mammals and humans, and the level of contamination goes up progressively at each step.

Ramish et al., 2024 examined the carcinogenic metals in commercially relevant freshwater fish species, and found that, in most cases, the hazard indices of non-carcinogenic metals were not exceeding the limits, but in the case of lead, cadmium and chromium, the cancer risks were exceeding the same. They noted that repeated dietary exposure (from fish) could be a major long-term public health concern given relatively low environmental concentrations.

Likewise, Panda et al. (2023) did a thorough systematic review of heavy metal pollution in all aquatic species across the globe. Their analysis showed that the levels of lead (44.3 mg/kg), chromium (27 mg/kg), copper (35.54 mg/kg) and zinc (103.2 mg/kg) in contaminated fish species were recorded. Based on the results of the meta-analysis, it is again concluded water fish can be used as effective bioindicators of aquatic pollution as lead and chromium were found to be the most hazardous pollutants with respect to the risk of cancer and non-cancer among all the metals studied.

Although microplastics are small contaminants, their importance in the trophic transfer of contaminants by the presence of heavy metals, pharmaceuticals, pesticides, and organic pollutants on their surfaces is not overlooked. The ingestion of microplastics effects aquatic organisms in two ways: it brings in physical particles and related chemical contaminants, which adds to the toxicological complexity and ecological uncertainty.

1.3.4 Ecological Consequences for Wetlands and Aquatic Ecosystems

The functions of wetlands, mangroves, estuaries and coastal ecosystems are important such as nutrient cycling, flood regulation, carbon sequestration, conservation of biodiversity and nursery habitats of commercially important fish species. But these ecosystems are especially sensitive due to the "flushing" of contaminants brought in from upstream catchments.

Even with ecological success in restoring mangroves, the ecosystems continued to build up toxic elements, as found in a study by Zhao et al. (2022) that showed a need to integrate contaminant management with habitat rehabilitation in ecological restoration programmes. Similarly, Dalu et al. 2022 indicated that contaminant exposure was a key factor in macroinvertebrate community composition in Ramsar wetlands, highlighting the close link between contaminant exposure and ecosystem functioning.

These ecological effects could be exacerbated by climate change, which is likely to further change temperature, rainfall, river flows and the pathways of contaminants. Flooding may resuspend contaminated sediments, and extended droughts can enrich pollutants in shrinking water bodies, increasing the amount of contact between water organisms and contaminants. There is a need for integrated ecosystem management rather than treating contaminants separately as demonstrated in such interactions.

1.3.5 Ecotoxicological Responses at the Organism Level

Emerging contaminants impact aquatic organisms in many ways, both physiologically and at the molecular level. The effects of oxidative stress, endocrine disruption, impaired osmoregulation, developmental abnormalities, altered immune function, behavioural changes and reproductive failure have been documented in a broad spectrum of aquatic species in the laboratory and in the field.

Horng et al. (2023) showed that the impairment of osmoregulatory ability due to exposure to the metal silver severely affected the survival of medaka fish during salinity adaptation by affecting ion regulation, showing that exposure to the metal severely affected the osmoregulatory ability of euryhaline medaka. Similarly, Suleiman et al. (2024) found that the genes involved in 4137 pathways were altered in Asian seabass fingerlings exposed to dietary polyethylene microplastics, leading to high mortality, damage to the liver, oxidative stress, immune system dysfunction and metabolic disruption. Based on these molecular data, emerging contaminants' effects on biology are evident well before measurable ecological effects are observed.

1.3.6 Synthesis of Ecological Impacts

The literature reviewed here shows that emerging pollutants have complex ecological impacts that are found beyond just the impact on one pollutant or one species. Persistent contaminants bioaccumulate in aquatic organisms, biomagnify in food chains, and cause chronic toxicity, BDI, and oxidative stress and loss of ecosystem functioning. These ecological impacts affect fisheries, wetland protection, freshwater biodiversity, ecosystem resilience and also expose human populations to risks due to contaminated drinking water and seafood.

The evidence also shows that there was a need to move away from single contaminant assessments and adopt more holistic ecosystem-based approaches that would take into account contaminant mixtures, chronic exposure, and climate change interactions. Therefore, enhancing ecological monitoring, sediment management and biomonitoring programmes, as well as developing more sophisticated risk assessment approaches will be vital to securing protection for aquatic ecosystems and sustainable environmental management in line with SDGs 6, 14 and 15.

1.4 Human Health Implications of Emerging Aquatic Contaminants

Emerging contaminants (ECs) are becoming a public health problem after ever becoming a part of the environment. Acute and chronic health effects are likely to occur if people are exposed to contaminants in their drinking water, seafood, recreational water activities or indirect food-chain transfer. Many emerging contaminants are biologically active and can bioaccumulate over time in human tissues when present in low concentrations, unlike the conventional pollutants. Endocrine disorders, neurological impairments, reproductive dysfunction, developmental abnormalities, carcinogenicity, and immune system disruption have all been tied to pharmaceuticals, endocrine-disrupting chemicals (EDCs), heavy metals, pesticides, antibiotics, microplastics and industrial chemicals. Therefore, the understanding of exposure routes of humans and related health risk is critical to making effective environmental policies and to achieve sustainable public health outcomes.

1.4.1 Drinking Water as a Major Exposure Pathway

Humans are exposed to emerging pollutants via drinking water, one of the biggest sources. Surface water and groundwater are principal drinking water sources globally but many of the water treatment plants are engineered to remove suspended solids, nutrients and microbial pathogens, and not pharmaceuticals, endocrine disruptors, PFAS or microplastics. These contaminants can, therefore, be detected in low levels in treated drinking water.

Dai et al. (2021) performed a comprehensive evaluation of the pharmaceutical contamination in the five main river basins in China and showed that the concentration of pharmaceuticals varied from 0.09 ng/L to 304 ng/L, and that certain pharmaceuticals were highly persistent in the environment and posed serious health and environmental risks to humans. Risk quotient analysis revealed estrogens and sulfapyridine to be compounds of greatest concern and dietary exposure assessment showed that pharmaceutical residues in drinking water and aquatic food products are a source of cumulative human exposure. While concentrations of most individual pharmaceuticals were below the acute toxicity limits, the authors noted that chronic exposure and combined effects of contaminants have not yet been studied and should be taken into account as a future area of research, given that few drinking water standards consider contaminant mixtures.

Likewise, Wang et al. (2020) examined bisphenol analogues in bottled drinking water and found that all the samples collected were contaminated with bisphenol analogues. In the polyethylene terephthalate (PET) bottles the BPA concentration was found to be 12.4–44.9 ng/L, and the concentration was significantly higher in the polycarbonate (PC) bottles 111.8–6452.8 ng/L. These results indicate that packaging material can directly lead to the migration of chemicals into drinking water and thus to greater human exposure to endocrine-disrupting chemicals . Even if the estimated exposure level is lower than the current regulation limits, the long-term health effects of BPA due to its persistence and endocrine activity continue to raise concerns, especially in infants, children and pregnant women.

Apart from pharmaceuticals and bisphenols, there is growing evidence that PFASs, pesticides, flame retardants and microplastics from industrial discharges, waste water effluents, agricultural run-off and plastic packaging materials are found in drinking water. Low-level exposure over time via drinking water may not result in acute clinical effects, but may lead to a cumulative body burden especially with dietary and occupational exposures.

1.4.2 Fish Consumption and Dietary Exposure

Another means of human exposure to emerging contaminants is through aquatic organisms. Fish, shellfish, crustaceans and other aquatic organisms readily absorb contaminants from surrounding water and sediment both directly and from their diet. Persistent contaminants are then bioaccumulated through aquatic food webs, causing the concentration of contaminants to increase in fish that are predators and food for humans.

In the central Brazilian Amazon, Meschede et al. (2024) found that mercury (Hg) is the highest source of concern for human health among the 8 fish species examined that were found to be contaminated. They found that children who ate carnivorous fish had the highest estimated health risk, as the high trophic level fish species contained higher amounts of contaminants and children ate more fish than their body weight. The authors also noted that processing, through cooking, reduced the levels of some of the metals, though it didn't significantly impact the mercury build-up, suggesting that preparation methods alone are not enough to remove dietary intake.

Tran-Lam et al. (2024) examined 114 marine fish samples from Vietnam and identified 44 endocrine-disrupting chemicals (EDCs) that had concentrations ranging from 105.5 to 208.3 ng/g of lipid weight. While the calculated hazard quotient values showed relatively low levels of non-carcinogenic risk, the authors highlighted that the high frequency of seafood consumption might further lead to higher cumulative exposure, mainly among coastal communities where the consumption of fish is a significant part of the diet. Their results also showed species-specific differences in the accumulation of contaminants, indicating that ecological properties affect contaminant accumulation and should be taken into account when assessing seafood safety in the future.

Heavy metal contamination is still very significant because these are non-biodegradable pollutants that can be accumulated in the edible parts of a fish. Shaaban et al. (2021) analysed 200 Nile tilapia samples and found the concentration of metals to be Fe > Zn > Cu ≥ Cr > Mn > Pb > Cd. Histopathological findings showed that liver tissues accumulated higher levels of contaminants than muscle tissues; however, the estimated daily intake (EDI) and target hazard quotient (THQ) and hazard index (HI) results suggested that fish consumption was at safe levels given the current consumption situations. However, the authors suggested to continue monitoring the environment as concentrations of contaminants may be raised with the growth of industrialization and agriculture.

1.4.3 Carcinogenic and Non-Carcinogenic Health Risks

Long-term exposure to many emerging contaminants is of concern because of their carcinogenic, mutagenic, teratogenic and endocrine-disruptive characteristics. A number of pesticides, pharmaceuticals and industrial chemicals share toxicological properties with the heavy metals, including cadmium, chromium, lead and arsenic, which are known or suspected to cause cancer. Cumulative dietary exposure was found to be also a significant source of pharmaceutical exposure compared with drinking water, as shown by Dai et al. (2021), suggesting that dietary intake should be included in future assessments of health risks. Similarly, Ramish et al. (2024) found that the carcinogenic risk of lead, cadmium and chromium was above the international acceptable limit although relatively low non-carcinogenic hazard indices were found, indicating the importance of the assessment of lifetime exposure and not only the short-term toxicity.

Another challenge is the double role of microplastics in transmitting persistent organic pollutants, heavy metals, and endocrine disrupting chemicals, which also makes them a more complex risk assessment for carcinogenic purposes. Hazardous chemicals adsorb to plastic surfaces and allow for multi-contaminant exposure, raising toxicological uncertainty and making traditional risk assessment methods difficult.

1.4.4 Endocrine Disruption and Reproductive Health

Endocrine disrupting chemicals (EDCs) have garnered much attention as one of the emerging contaminants because they disrupt the synthesis, transport, metabolism, receptor binding, and physiological regulation of hormones. Even very low exposure levels can disrupt endocrine signal during critical developmental periods, leading to permanent reproductive, neurological and developmental abnormalities.

A study by Tran-Lam et al. (2024) revealed several endocrine-disrupting chemicals in commercially important fish species, indicating that the consumption of seafood is a major source of chronic human exposure to these compounds. Likewise, Wang et al., 2020 measured significantly higher levels of BPA in polycarbonate bottles than in PET bottles, indicating that consumer behavior and packaging materials can affect exposure to EDCs.

Many epidemiological studies have linked long-term exposure to endocrine disruptors to decreased fertility, changes in the level of reproductive hormones, developmental disorders, metabolic diseases, thyroid disorders, obesity and diabetes, and hormone-dependent cancer. Concentrations in the environment are not high enough for acute toxicity but chronic exposures over the human lifetimes are not well understood.

1.4.5 Vulnerable Populations

Children and pregnant women, older adults and populations with high seafood consumption are consistently reported as being at high risk of emerging contaminants. Children are more vulnerable to the effects of contaminants on the endocrine system and neurodevelopment due to their rapid body growth and underdeveloped systems of detoxification. Contaminants can be transferred to the placenta during pregnancy, and breast-milk is another route for the transfer of some persistent contaminants to infants.

We have shown by probabilistic modelling that the children and pregnant women were most vulnerable to EDC exposure due to the bioaccumulation of contaminants in fish tissues (Liao et al., 2024). The study by Meschede et al. (2024) also underscored the vulnerability of children who eat carnivorous fish, and thus the need for specific dietary recommendations and environmental surveillance for these vulnerable groups.

1.4.6 Public Health Implications

The findings from this review show that there is no single source of exposure to humans of emerging contaminants, but multiple pathways which are interconnected. Cumulative contaminant exposures are the result of drinking water, seafood consumption, recreational activities, occupational exposure and atmospheric deposition. Exposure to complex mixtures of contaminants is not well understood and is often not included in current health risk assessments, but individual contaminants are often found at levels below regulatory limits.

Moreover, the current legislation focuses on one contaminant at a time, even though there is growing evidence that pharmaceuticals, endocrine disruptors, antibiotics, heavy metals, pesticides and micro plastics often occur together in aquatic systems. Future public health policies should therefore use integrated exposure assessment strategies that will account for environmental pollution and climate change interactions, chronic exposure to low doses of contamination and vulnerable populations.

In general, to ensure human health protection, efforts needed include greater investment in drinking water treatment technologies, scaling up environmental surveillance programmes, the development of contaminant-specific environmental regulations, and enhancing interdisciplinary cooperation between environmental scientists, toxicologists, public health and policy makers. These actions are essential for attaining SDG 3 (Good Health and Well-being) and help to achieve SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water).

1.5 Emerging Aquatic Contaminants and the Sustainable Development Goals (SDGs)

In 2015, the United Nations (UN) established the 2030 Agenda for Sustainable Development to address global environmental, economic and social problems by outlining 17 Sustainable Development Goals (SDGs). Of these, three SDGs are directly affected by the emergence and management of contaminants in the aquatic environment: SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). Increased exposure to pharmaceuticals, endocrine disrupting chemicals (EDCs), micro-plastics, antibiotics, pesticides, heavy metals and other contaminants endangers freshwater and marine ecosystems, threatens public health and poses challenges to the sustainable management of water resources. This is why tackling emerging contaminants is crucial to reach SDGs and sustainable environment in the long term.

1.5.1 SDG 3: Good Health and Well-being

SDG 3: Ensure healthy lives and promote well-being at all ages. The detection of emerging contaminants in drinking water, aquatic food products, and in recreational water bodies, however, has emerged as an important public health issue. Human exposures are mainly due to the ingestion of contaminated water and seafood, which can lead to endocrine disorders, neurological impairment, reproductive dysfunction, carcinogenicity and antimicrobial resistance.

This review highlights several studies that have shown measurable effects of pharmaceuticals, endocrine disrupting chemicals, heavy metals and micro plastics on human health. Dai et al. (2021) also reported that pharmaceutical residues were detected in five major river basins in China and that it was estimated that the consumption of fish was the primary pathway for the exposure of humans. Likewise, marine fish are found to be an important source of chronic human exposure to 44 EDCs by Tran-Lam et al. (2024). In addition, Meschede et al. (2024) found mercury as the main health concern for the consumers of carnivorous fish especially children, and Shaaban et al. (2021) showed that the continuous monitoring is still necessary even though the present hazard indices are safe.

As more and more contaminants appear to have endocrine-disrupting properties, there are added concerns; these compounds are biologically active at very low concentrations. Chronic exposure may be linked to developmental abnormalities, decreased fertility, thyroid problems, obesity, diabetes, immune system problems, and hormone-related cancers. This calls for increased monitoring of contaminants and better drinking water technologies and policies to be based on evidence, all of which are necessary for reaching SDG 3.

1.5.2 SDG 6: Clean Water and Sanitation

SDG 6 is water and sanitation for all and sustainable management. The availability of emerging contaminants presents a widespread direct threat to this goal, including by affecting the quality of water and the complexity of treatment, and by posing challenges for existing regulations.

Original intentions of conventional wastewater treatment plants (WWTPs) were to filter nutrients, solids and pathogens, not pharmaceuticals, PFAS, endocrine disruptors, antibiotics, or microplastics. Many contaminants, therefore, move through treatment systems to receiving rivers, lakes, estuaries and coastal waters.

Pak et al. (2021) showed that more extensive monitoring is needed to account for sensitivity of parameters and missing data when assessing Water Quality Index (WQI). Their results showed that to have water quality assessment with a 2% tolerance level, they needed about 130 monitoring samples to ensure good monitoring programmes. Similarly, Azha et al. (2023) created an artificial neural network to predict the health of the river with a validation accuracy of more than 97%, thereby minimizing reliance on laboratory analysis, thereby facilitating the real-time monitoring of the environment. In addition, Mohd Said et al. (2025) found that the ammonia nitrogen, total suspended solids, and biochemical oxygen demand were removed by 99%, 94%, and 80% respectively from the wastewater by the Wolffia arrhiza, respectively, showing the potential of nature-based treatment technologies to improve wastewater quality.

These technological innovations contribute to SDG 6 by providing better monitoring and more efficient treatment, and also to sustainable water resource management.

1.5.3 SDG 12: Responsible Consumption and Production

SDG 12 encourages more sustainable consumption patterns and the efficient use of resources and environmentally responsible chemical management. The majority of emerging contaminants come from unsustainable production and use practices such as over-prescribing of drugs, single-use plastics, use of industrial chemicals, pesticides, personal care products and improper disposal of waste.

The case of microplastic pollution is a good example of the impact of unsustainable production systems. Plastic particles do not just accumulate in the oceans and seas, but are continuously added, e.g. into the aquatic environment via plastic packing, synthetic textiles, fishing gear, tyre wear and industrial products, and remain there for decades. In the same way, Aravind Kumar et al. (2022) identified persistent organic pollutants, which are mainly produced in industry and agriculture, thus reinforcing the direct link between the inefficiency of chemicals management and long-term environmental pollution.

In addition, Chee et al. (2023) noted that pollutants loads to Malaysian coastal ecosystems are still on the rise caused by high rate of coastal reclamation and urban development, which are altering habitats, augmenting coastal runoff and enhancing industrial operations. The results highlight the importance of sustainable urban planning and responsible production systems to minimise the release of contaminants in the future and to implement the principles of circular economy.

The reduction of plastic waste generation, better chemical stewardship, promotion of environmentally friendly production processes, enhanced extended producer responsibility programmes, and promotion of sustainable consumer behaviour are all part of SDG 12.Hence, the reduction of plastic waste generation, chemical stewardship, promotion of environmentally friendly production processes, strengthening extended producer responsibility programmes, and promotion of sustainable consumer behaviour are all part of SDG 12.

1.5.4 SDG 13: Climate Action

Climate change affects the emergence of contaminants not only in terms of their occurrence but also their effects, through changes in hydrological cycles, transport of contaminants, water temperatures and ecosystem functioning. Rising temperatures will speed up chemical reactions, affect the breakdown of contaminants, and promote the growth of harmful algal blooms, and heavy rain and flooding will increase the amount of contaminants transported from urban and rural areas to rivers and estuaries.

Using satellite observations and machine learning algorithms, Al-Wardy et al. (2025) predicted large increases in the volume of cyanobacteria harmful algal blooms in future climate scenarios. They used their Long Short-Term Memory (LSTM) model to estimate significantly greater bloom occurrences under the SSP585 climate scenario, suggesting a potential increase in water quality degradation and ecological risk with climate change. Similarly, Virdis et al. (2024) projected that over 80 lakes in Southeast Asia are projected to experience warming more than 2.29°C by 2100 for high-emission scenarios, with lake surface warming continuing. These changes are likely to affect the distribution of contaminants, cycling of nutrients, dissolved oxygen levels and aquatic biodiversity.

These studies illustrate that there is no separation between management of contaminants and adaptation to climate change. Effective water management, therefore, will be increasingly a key component of climate-resilient development in the future to meet SDG 13.

1.5.5 SDG 14: Life Below Water

Marine and freshwater systems offer valuable ecosystem services such as fisheries, conservation of biodiversity, carbon sequestration, nutrient cycling and food security. New contaminants, however, pose hazards to aquatic life by being toxic, degrading habitat, impairing reproduction, disrupting hormones and bioaccumulating.

Zhao et al. (2022) have shown that even in restored mangrove habitat, accumulation of toxic elements occurred, suggesting that even in the absence of pollution sources, habitat restoration can't stop contaminant exposure. Likewise, the impact of exposure to heavy metals on significant changes in molecular and metabolic profiles has been reported in mud crabs from Malaysia by Razali et al. (2024) and in commercially important fish species by Ramish et al. (2024) who also observed that heavy metals can be transferred up the food chain to human consumers, leading to an increased risk for ecological and human health.

Aquatic biodiversity must be protected by merging all measures needed for the monitoring of contaminants, for maintaining aquatic habitats, for pollution prevention and for ecosystem-based management approach in line with SDG 14 goals.

1.5.6 SDG 15: Life on Land

Fresh water ecosystems, wetlands, rivers and riparian habitats are important interfaces between terrestrial ecosystems and water ecosystems, though they are not thematically addressed in SDG 15.While SDG 15 focuses on terrestrial ecosystems, fresh water ecosystems, wetlands, rivers and riparian ecosystems are also an important interface between terrestrial ecosystems and freshwater ecosystems. Agricultural, urban, mining, and industrial sources of pollution move from the land to the water, impacting biodiversity on both the land and the water.

The study by Babel et al. (2022) revealed that even though the overall water security in river basins in Thailand has improved, the watershed health dimension is still one of the lowest. Therefore, integrated catchment management is needed. Mohd Said et al. (2025) presented the advantages of circular economy approaches such as phytoremediation and biomass reuse while Chee et al. (2023) argued the importance of sustainable land use planning to prevent pollutants being transported to rivers and coastal zones. Therefore, the protection of wetlands and the restoration of degraded catchments with a reduction in diffuse pollution from land use and the integration of land use planning and water quality management are key points for achieving SDG 15.

The incorporation of Emerging Contaminant Management into the SDGs.

The literature examined supports the conclusion that emerging aquatic contaminants are a cross-cutting sustainability issue that impact environmental quality, ecosystem resilience, biodiversity conservation, public health, food security, climate adaptation, and economic development. To overcome these challenges, the research and development of environmental scientists, engineers, toxicologists, ecologists, public health scientists, policy makers and industry are needed.

The integrated environmental monitoring, the development of more sophisticated monitoring technology, the construction of predictive technology based on artificial intelligence, nature-based solutions, the principles of the circular economy and the harmonization of international regulations should be the focus of future strategies. This will support progress towards multiple SDGs, not environmental, health, and sustainability SDGs.

1.6 Research Questions

Based on the identified knowledge gaps and sustainability challenges, this systematic literature review addresses the following research questions:

RQ1: What are the major categories of emerging contaminants affecting aquatic ecosystems worldwide?

RQ2: What ecological impacts have been reported regarding the occurrence, bioaccumulation, and trophic transfer of emerging contaminants?

RQ3: How do emerging aquatic contaminants affect human health through drinking water, seafood consumption, and other exposure pathways?

RQ4: What monitoring technologies and mitigation strategies have been developed to detect, assess, and control emerging contaminants in aquatic environments?

RQ5: How does current scientific evidence contribute towards achieving the United Nations Sustainable Development Goals (SDGs), particularly SDGs 3, 6, 12, 13, 14, and 15?

Methodology

2.1 PRISMA 2020 Framework

This systematic literature review (SLR) was undertaken in compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 Statement, which outlines internationally recognised principles for transparent, reproducible and comprehensive systematic reviews. The PRISMA 2020 framework increases the quality of the reporting of the conducted search for relevant studies by standardizing the identification, screening, eligibility assessment, and inclusion of relevant studies and thus reduces selection bias and increases methodological transparency.

The PRISMA approach uses a structured evidence-based methodology, which ensures that studies are systematically identified, evaluated and synthesized based on predetermined eligibility criteria, in comparison with traditional narrative reviews. This method ensures the reliability of the results by keeping track of all review procedures, from database searching to the final selection of studies. As a result, PRISMA is currently one of the most commonly used reporting standards in environmental sciences, public health, ecology and medical research.

The present review adopted the four major PRISMA phases:
Identification – Relevant articles were identified through comprehensive database searches.
Screening – Duplicate publications and clearly irrelevant studies were removed after reviewing titles and abstracts.
Eligibility – Full-text articles were assessed according to predefined inclusion and exclusion criteria.
Inclusion – Studies satisfying all eligibility requirements were included for qualitative synthesis.
To avoid selection bias and to be consistent in the review process, the methodology was developed prior to the literature search. The selection process for the studies is summarized in the PRISMA flow diagram (Figure 1).

2.2 Literature Search Strategy

The literature search was extensive and included journal articles that were peer-reviewed and published in English dealing with emerging aquatic contaminants, ecological effects, human health impacts, monitoring technologies, remediation technologies, and Sustainable Development Goals (SDGs). Three internationally recognised scientific databases were chosen as they span the breadth of environmental, ecological, engineering and health sciences:

- ScienceDirect
- Scopus
- Web of Science

Only those articles published during the years 2020-2025 were included in the review, to capture the latest scientific advances and current environmental issues related to emerging contaminants.

Boolean operators (AND, OR) and truncation symbols were used in the search strategy to ensure maximum retrieval with relevance. Keywords were developed from the research objectives and refined by doing some preliminary searches.

The principal search string was as follows:
("emerging contaminant*" OR pharmaceutical* OR antibiotic*
OR endocrine disruptor* OR PFAS
OR microplastic* OR heavy metal*
OR pesticide* OR flame retardant*)
AND
("water quality" OR freshwater
OR river OR marine OR estuary
OR groundwater OR aquatic ecosystem*)
AND
("human health" OR ecological risk
OR bioaccumulation
OR biomagnification)
AND
("sustainable development goals"
OR SDG*)
Further search using combinations of the categories of contaminants (e.g. pharmaceutical, endocrine disrupting, microplastics, antibiotics, PFAS, pesticides, heavy metals) was also undertaken to fully cover the literature.
The reference lists of the relevant review articles were also manually scanned to find any studies that might not have been retrieved from the databases.

2.3 Eligibility Criteria

In order to make it consistent and relevant, inclusion and exclusion criteria were pre-defined before the inclusion of studies began.

2.3.1 Inclusion Criteria

Studies were included if they satisfied all of the following criteria:

- Published in peer-reviewed scientific journals.
- Published between 2020 and 2025.
- Written in English.
- Investigated emerging contaminants in aquatic environments.
- Examined ecological impacts and/or human health risks.
- Reported original research findings or comprehensive systematic reviews.
- Included quantitative, qualitative, experimental, field-based, modelling, or review methodologies.

- Demonstrated relevance to one or more Sustainable Development Goals.

2.3.2 Exclusion Criteria

Studies were excluded if they:

- Were conference proceedings.
- Were book chapters.
- Were editorials, commentaries, letters, or short communications.
- Were published in languages other than English.
- Lacked full-text availability.
- Focused exclusively on terrestrial pollution without aquatic relevance.
- Investigated conventional pollutants without reference to emerging contaminants.
- Were duplicate publications.

Adopting these criteria allowed only high quality, scientific rigor studies that were directly relevant to the objectives of the review to be included.

2.4 Study Selection Process

The study selection process was done following the PRISMA 2020. The records found in the databases selected were downloaded to reference management software and duplicate articles were identified and eliminated.

All other studies were given a two-stage screening. In the first phase, titles and abstracts were screened for their relevance with respect to emerging contaminants, aquatic ecosystems, ecological effects, human health, monitoring technologies, and sustainable development. Such studies that did not meet the inclusion criteria were excluded.

The second step was the full-text evaluation of the remaining articles. All studies were assessed individually to the set criteria. Studies that met all of the research goals and presented adequate methodological and scientific details have been included for qualitative synthesis.

All doubts about article eligibility were answered by the repeated evaluation of the full text, in order to be consistent and to reduce the reviewer's bias.

2.5 Data Extraction

Relevant information for each included article was systematically extracted after the selection of studies on a standardised data extraction form, to enable comparisons between studies.

These data were gathered:

- Author(s)
- Year of publication
- Country or study location
- Type of aquatic ecosystem
- Emerging contaminant category
- Study objectives
- Theoretical or analytical framework
- Research methodology
- Sample size
- Monitoring techniques
- Ecological findings
- Human health implications
- Monitoring technologies
- Mitigation strategies
- Sustainable Development Goals addressed

The extracted information was organised into a comprehensive evidence matrix to support thematic synthesis and comparative analysis.

An example of the data extraction framework is presented in Table 1.

Author	Contaminant	Ecosystem	Methodology	Main Findings	Related SDG
Xu et al. (2023)	Steroid hormones	River	Field sampling & modelling	Steroid contamination reached 76 ng/L	SDG 6
Dai et al. (2021)	Pharmaceuticals	River basin	Risk assessment	Pharmaceutical RQ reached 17.2	SDG 3
Tuan Anuar et al. (2023)	Microplastics	River	Field monitoring	Langat River recorded 1,464.8 items/L	SDG 14

2.6 Quality Assessment

All eligible studies were subjected to methodological quality assessment to assure the scientific reliability. The following criteria were taken into account for the appraisal:

- Clearly stated research objectives.
- Appropriate study design.
- Adequate sample size.
- Valid analytical methods.
- Transparent statistical analyses.
- Appropriate ecological or health risk assessment.
- Clearly reported findings.
- Logical conclusions supported by evidence.

Studies that met high-quality criteria in terms of both study design and reporting were included in the synthesis. During the eligibility stage, articles lacking in methodological information or sufficient scientific evidence were excluded.

2.7 Data Synthesis

Because of this variety of contaminants, analytical methods, ecological indicators, and outcome measures, a qualitative thematic synthesis was chosen over a meta-analysis.

The included studies were classified into seven thematic categories:

1. Occurrence of Emerging Contaminants
2. Microplastic Pollution
3. Heavy Metal Contamination
4. Endocrine-Disrupting Chemicals
5. Pharmaceuticals and Antibiotics
6. Monitoring Technologies
7. Mitigation Strategies

For every theme, the similarities and differences, research trends and methodological developments, as well as the ecological impacts and human health implications were critically compared and synthesised, while the contributions to the SDGs were also considered.

2.8 PRISMA Flow Diagram

Records were identified during literature search from the three selected databases. Following duplicate removal and screening of the titles/abstracts of potentially relevant articles for further evaluation, full text was assessed before final inclusion.

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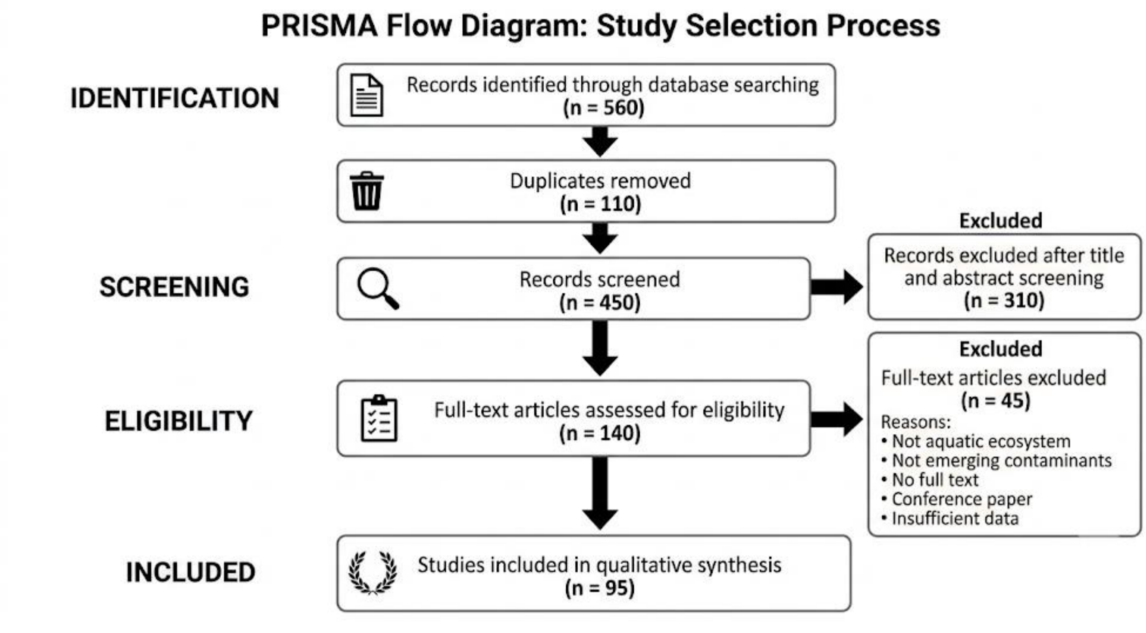

2.9 Summary of Methodological Framework

Adoption of the PRISMA 2020 framework led to the transparent, reproducible and systematic review process. Using strict search protocols, inclusion criteria, quality assessment and thematic synthesis, this review is comprehensive and evidence-based for the evaluation of emerging aquatic contaminants, their ecological and human health impacts, and their implications for achieving the Sustainable Development Goals.

The subsequent major section is 3. This is done, beginning with Theme 1: Occurrence of Emerging Contaminants, with the studies in the theme being critically synthesized by contaminant type, environmental distribution, concentration ranges and patterns of occurrence globally, instead of being described individually. This is normally the longest part of a journal quality SLR.

Results

The selected studies, after going through the PRISMA 2020 screening process, were then synthesized in a themed approach in order to determine the main research trends on emerging aquatic contaminants, their ecological impacts, impacts on human health, monitoring technologies, and mitigation strategies. Given the variety of contaminants, environmental compartments, analytical methods, and geographical locations, it was decided that it would be more appropriate to conduct a qualitative thematic synthesis than a quantitative meta-analysis.

The literature reviewed shows that the studies published since 2020 are increasingly dominated by six groups of contaminants: pharmaceuticals and antibiotics, endocrine-disrupting chemicals (EDCs), microplastics, heavy metals, pesticides and flame retardants. The vast majority of studies focused on the presence of contaminants in freshwater rivers, estuaries, lakes, wetlands, mangroves, coastal waters, aquaculture and marine environments. Focus has also shifted to contaminant transport, bioaccumulation, trophic transfer, ecological risk assessment, human exposure and sustainable remediation technologies.

The results are organised into seven major themes.

3.1 Theme 1: Occurrence of Emerging Contaminants in Aquatic Ecosystems

The literature reviewed clearly shows that emerging contaminants have spread across all freshwater, estuarine, coastal and marine ecosystems worldwide, including those in the developing and developed world and irrespective of geographical region. The main sources of these pollutants are municipal wastewater discharge, industrial effluents, agricultural runoff, pharmaceutical production, aquaculture, mining, leachate from landfills and urban stormwater runoff. As a result of their persistent release they have left behind a legacy of water body contamination in spite of the advancement of conventional wastewater treatment technologies. Steroids, pharmaceuticals, antibiotics, endocrine-disrupting chemicals (EDCs), pesticides, and other contaminants have been found in surface water, groundwater, sediments, and aquatic organisms, and are widespread in the environment and persistent over time. Xu et al. (2023) reported that steroid hormones concentrations in river water ranged from 1.0 to 76 ng/L and up to 121 ng/g in sediments, indicating the persistent movement of contaminants in watersheds. Likewise, Tang et al. (2021) reported the occurrence of 17α-ethynylestradiol (EE2) in 32 countries, with concentrations up to 17,112 ng/L and about 65% of the water bodies tested being in moderate to high estrogenic risk categories. Pharmaceutical contamination was also prevalent, with Dai et al. (2021) finding concentrations of 0.09 to 304 ng/L for the pharmaceuticals observed in the main river basins of China, and Khan et al. (2021) noting ofloxacin concentrations up to 1,726.5 ng/L in the Yamuna River, with several pharmaceuticals exceeding ecological risk thresholds. Wang et al. (2024) also showed medium to high ecological risk of the treatment with antibiotic mixtures in mangrove aquaculture systems in both water and sediments. Chandran et al. (2025) reported high levels of EDPs in seawater, sediments and fish whereas Cunha et al. (2022) revealed the occurrence of EDPs in estuarine environment is influenced by seasonality. Agricultural contaminants are also still a major concern, as Olisah et al. (2022) found organophosphate pesticides at levels that could pose a threat to fish and aquatic invertebrates. As the sum of these studies shows, these emerging contaminants are more likely to be found as mixtures in sediments, where they can be long-lived in aquatic ecosystems and represent a long-term threat to human and ecological health. These results highlight the need for comprehensive monitoring programmes, innovative wastewater treatment systems, and robust environmental regulations, to reduce the entry of pollutants and help attain the SDG 6, 14, and 15 water quality, ecosystem protection, and public health goals.

3.2 Theme 2: Microplastic Pollution in Aquatic Ecosystems

Microplastic pollution is one of the fastest growing environmental issues that have arisen because of the resistance of plastic particles to natural degradation, their ubiquity, and persistence. The literature reviewed shows that microplastics have infiltrated aquatic environments to varying degrees, and are found in virtually all rivers, lakes, estuaries, coastal waters, sediments, drinking water, aquatic animals and aquaculture systems. They are more related to human activities such as urbanization, industrialization, discharge of municipal wastewater, agricultural runoff, tourism, fisheries operations, and poor management of solid wastes. In contrast with conventional pollutants, microplastics can be physically, chemically and biologically weathered into smaller and smaller pieces, such as nanoplastics, which may stay in aquatic environments for long periods of time and also may adsorb harmful chemicals like pesticides, pharmaceuticals, heavy metals and EDCs. Tuan Anuar and his colleagues (2023) found that the amount of contamination varies significantly from river basin to river basin in Malaysia, with the Kelantan River Basin being found to have an average of 179.6 items/L, while the Langat River Basin, a more urbanized area, had an average of 1464.8 items/L, with the dominant polymers being polyethylene, polypropylene and polyethylene terephthalate with the primary source being mainly from domestic plastic waste. Likewise, the concentration of microplastics was also found to be significantly higher in freshwater ecosystems with higher human disturbances, which indicates that higher human disturbances, including urbanisation and recreational activities, were associated with higher microplastic concentrations (Yin et al., 2021). Several other pathways for human exposure are now becoming apparent: Praveena et al. (2022) concluded that the packaging materials are a direct source of contamination of bottled drinking water, with the presence of microplastics in all of the samples analysed they found ranging from 8 to 22 particles/L, which means that children are likely to be exposed to a higher level of microplastic contamination than adults, due to their body weights relative to their total water consumption. Bioaccumulation studies also show that micro-plastics get easily into the aquatic food chain. The presence of microplastics in the gastrointestinal tract (86%) and fish gills (92%) in Malaysian waters was found by Jaafar et al. (2021), and higher microplastic contamination in dried fish compared to fresh fish was reported by Hasan et al. (2023), suggesting that processing and handling may further lead to the human exposure with microplastics. Likewise, Shamim et al. (2025) reported that the aquaculture systems were largely polluted and the number of particles found in the cultured fish was 1.19 particles/g. Microplastics can also disrupt feeding, assimilation, growth and reproduction as well as serve as a means of transport for toxic substances within aquatic food chains. Nevertheless, methodological inconsistencies in the sampling and analytical processes are also noted in the reviewed studies. Sui et al. (2025) found that the higher the mesh size, the more significant the underestimation of fibre abundance, highlighting the need for standardisation of monitoring procedures to enable better comparisons between studies. Overall, the evidence indicates that the problem of microplastic pollution is a global phenomenon that needs an integrated waste management strategy, better wastewater treatment, standardised monitoring methods, and better enforcement of regulations for the preservation of aquatic biodiversity, food security, human health and the implementation of Sustainable Development Goals associated with the clean water, responsible consumption and life below water sectors.

3.3 Theme 3: Heavy Metal Contamination in Aquatic Ecosystems

Heavy metal pollution is one of the most persistent and dangerous types of water pollution as metals are not biodegradable, tend to be environmentally persistent, and may persist within sediments and the biota for long periods of time. The reviewed literature clearly shows that global levels of heavy metals in fresh, estuarine, coastal and marine water bodies remain high due to industrialisation, mining, agriculture, urbanisation, fossil fuel combustion and industrial wastewater discharge. Some metals, including iron, zinc and copper, are micronutrients, but they are toxic to aquatic organisms at high levels because they cause oxidative stress, enzyme inhibition, reproductive problems, neurological issues, immune dysfunction and mortality. Although the overall HPI was low, Razak et al. (2021) reported moderate ecological risk for aluminium and zinc in the Linggi River, in Malaysia, suggesting the possible future increase of contamination due to industrial and agricultural development. Mining activities are also a major source of pollution, with activities as far as 15 km downstream from the abandoned mining sites being found to contain high concentrations of Ni, Cu and Fe, and the contaminated sediments are seen to be persistent pollutant source even after the water quality has improved (Lin et al. 2022). Bioaccumulation continues to be one of the defining aspects of heavy metal contamination due to the direct uptake of water and food from the water column followed by concentration in the higher trophic level. In the study by Razali et al. (2024), the authors found that concentrations of Ni, Cu, Zn, Cr, Cd and Pb were significantly higher in the wild mud crabs collected from the polluted coastal water, and that the expression of Heat Shock Protein 70 was up-regulated in the polluted group with significant metabolic disturbances, suggesting high physiological stress. Likewise, Shaaban et al. (2021) reported higher tissue concentrations in the liver than in muscle tissue in Nile tilapia due to the role of liver tissue in detoxification processes. However, as the accumulation of pollutants is a progressive process and is dependent upon long-term environmental exposure, continuous monitoring was recommended, despite the fact that estimated dietary exposure did not exceed international safety limits. Additionally, Panda et al. (2023) verified in their worldwide systematic review that freshwater fish can be used as reliable bioindicator for contamination as lead and chromium pose the maximum carcinogenic and non-carcinogenic threat to humans. Similarly, Ramish et al. (2024) showed that non-carcinogenic hazard indices were acceptable, while the carcinogenic risks of chronic exposure to lead, cadmium and chromium were higher than recommended. All these results indicate that the contamination of aquatic habitats with heavy metals remains a problem for aquatic biodiversity, ecosystem functioning, seafood safety, and public health. Therefore, it is essential to continuously monitor the environment, remediate sediments, establish more stringent industrial pollution discharge standards, implement sustainable mining practices, and implement integrated pollution management to reduce the input of pollutants, protect the water resources, and achieve sustainable development goals.

3.4 Theme 4: Endocrine-Disrupting Chemicals (EDCs)

An emerging group of contaminants that have become one of the most critical concerns in the environment are the endocrine disrupting chemicals (EDCs), which can disrupt endocrine function at very low environmental levels. All the studies cited here clearly illustrate that these compounds are ubiquitous in aquatic resources such as rivers, estuaries, coastal waters, sediments, and aquatic life and that they are of great concern with regard to ecological effects and human health. Sources of EDCs include municipal wastewater, industrial discharges, agricultural runoffs, pharmaceutical residues, personal care products, plastic manufacturing and household chemicals. EDCs are different than traditional pollutants in that they disrupt the synthesis, transport, metabolism and binding of hormones in aquatic organisms, leading to reproductive disorders, developmental abnormalities, endocrine imbalance, decreased fertility and population level effects. Tang et al. (2021) pointed out that 17α-ethynylestradiol (EE2) is found in 32 countries worldwide, ranging from below detection limits to 17,112 ng/L, and that almost 65% of the surface waters analyzed in the countries in their study had moderate to high estrogenic exposure. Likewise, Cunha et al. (2022) found that Portuguese estuaries were frequently contaminated with endocrine-disrupting chemicals such as bisphenols, pesticides, musks and ultraviolet filters, where HHCB presence in water samples was reported in more than 96% of the collected samples, and seasonal fluctuations were related to agricultural activities, recreational activities, and hydrological conditions. Another important pathway of chronic human exposure is through food-chain transfer; food-chain transfer is the reason Tran-Lam et al. (2024) found 44 endocrine-disrupting chemicals in marine fish, with total levels ranging from 105.5 to 208.3 ng/g lipid weight. Similarly, Chandran et al. (2025) reported the presence of phenolic plasticisers in seawater up to 3,949 ng/L, sediments up to 2,195 ng/g and fish tissues up to 2,609 ng/g, with nonylphenol showing high hazard quotient values and thus high ecological and dietary risks. Liao et al. also showed contaminated sediments to be long-term reservoirs, leading to the accumulation of contaminants in fish, and probabilistic risk assessments were performed to identify children and pregnant women as vulnerable groups due to higher exposures due to seafood consumption. In addition to environmental occurrence, Wee et al. (2024) showed that people's knowledge about EDCs is still limited, and pesticides and plastics are more widely recognized than pharmaceuticals and cosmetics, highlighting the importance of environmental education and other regulatory measures. Together, these studies suggest EDCs remain in several environmental compartments, bioaccumulate in aquatic food chains, and cause long-term ecological and public health impacts. In order to mitigate these risks, it is necessary to implement advanced wastewater treatment technologies, regular monitoring of the environment, assessment of sediments, surveillance of the safety of seafood, strict regulation of endocrine-active compounds and spreading awareness of the public to minimise the release of these compounds and contribute to sustainable management of aquatic ecosystems.

3.5 Theme 5: Pharmaceuticals and Antibiotics

All of the reviewed literature pointed to pharmaceuticals and antibiotics as contaminants of emerging concern, with a marked increase in the use of these products in medicine and health care worldwide, the discharge of large volumes of antibiotics and medications from hospitals, waste from domestic sewage, livestock production, aquaculture, and the misuse of unused medicines. In conventional waste water treatment plants these biologically active compounds are in general not completely eliminated and are discharged continuously into rivers, lakes, estuaries and coastal environments where they can continue to persist and accumulate, and cause chronic toxicological effects to aquatic organisms. Antibiotics also disrupt aquatic ecosystems and spread and foster antimicrobial resistance, a growing public health threat around the world. Khan et al. (2021) showed that even the Yamuna river was contaminated with pharmaceuticals with the concentrations of up to 1726.5 ng/L of ofloxacin during the post monsoon season, whereas the risk quotient for all the pharmaceuticals including diclofenac, diazepam, ofloxacin and simazine remained more than 1 even during the season. In China, Dai et al. (2021) reported levels of pharmaceuticals ranging from 0.09 to 304 ng/L in the major river basins, with risk quotients up to 17.2. They also found that fish consumption was a greater source of exposure to human pharmaceuticals than drinking water, highlighting the need for accounting for contaminant transfer via aquatic food webs. Aquaculture systems are especially problematic with regards to antibiotic contamination. Wang et al. (2024) identified 37 of the antibiotics in surface water and sediments around the mangrove aquaculture areas ranging from 78.4 to 225.6 ng/L for surface water and 19.5 to 229 ng/g for sediments. Ecological risk assessments (ERAs) showed that more than a third of the water samples and two-thirds of the sediment samples were medium to high ecological risk, and that the combined presence of sulfamethoxazole and multiple fluoroquinolones were among the priority contaminants due to their persistence and toxicity. The examined literature further indicates that PHCs interact with other emerging contaminants, like microplastics and sediments, which function as secondary reservoirs that can also adsorb the contaminants and increase the environmental exposure. Xu et al. (2023) additionally supported this concern by showing that biologically active compounds of the steroids are still present in water and sediments, and that compounds like pharmaceuticals can be long-lasting in aquatic systems. Considering all the evidence highlighted above, the availability of pharmaceuticals and antibiotics are a major environmental problem due to their persistent presence and incomplete elimination in the wastewater treatment plant, their toxicity to the environment, their ability to cause antimicrobial resistance and their potential to enter human bodies through contaminated seafood. Improvement of pharmaceutical stewardship, advancement of wastewater treatment technologies, revised hospital and industrial effluent regulations, responsible antibiotic application in agricultural and aquaculture products, and complete public education programs for decreasing environmental contamination and safeguarding the health of aquatic ecosystems are important measures to take for effective mitigation.

3.6 Theme 6: Monitoring Technologies for Emerging Aquatic Contaminants

The variety and complexity of emerging contaminants have made a conventional water quality monitoring that mostly relies on physicochemical parameters like pH, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, nutrients, and suspended solids ineffective. While these indicators are still important for tracking overall water quality, they will not provide detection for trace amounts of pharmaceuticals, antibiotics, chemicals that disrupt the endocrine system (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics and other emerging contaminants. As a result, the reviewed studies showed a notable shift toward the implementation of integrated monitoring strategies that integrate advanced analytical chemistry, artificial intelligence (AI) and machine learning (ML), environmental modelling, biosensors, nanotechnology, remote sensing and environmental DNA (eDNA) for enhancing contaminant detection, ecological risk assessment and environmental management. Xu et al. (2023) showed that field sampling and fugacity modelling, coupled with advanced chemical analyses, can be valuable tools for quantifying the distribution and environmental fate of steroid hormones in water, sediments, and watershed transport pathways, offering a comprehensive understanding of contaminant sources. Similarly, Wang et al. (2024) used liquid chromatography–tandem mass spectrometry (LC-MS/MS) to quantify 37 antibiotics in both sediment and water, demonstrating the ability of high-tech analytical instrumentation to identify a wide array of contaminants and target them at very low concentrations. Nanotechnology has also seen significant advances in recent years, which has further enhanced the ability to monitor the environment. Hojjati-Najafadi et al. (2022) noted that magnetic nanosensors could be used to quickly and sensitively detect heavy metals, pesticides, pharmaceuticals, endocrine disruptors, and persistent organic pollutants, and that this approach would outperform traditional laboratory analysis methods due to its faster analysis time and increased sensitivity. Water quality prediction is another area in which AI has gained more and more significance. Hridoy et al. (2025) reported that the Light Gradient Boosting Machine (LightGBM) model successfully estimated Water Quality Index (WQI) with an R^2 of 0.9685 with about 99.65% prediction accuracy while Azha et al. (2023) stated that Artificial Neural Networks can predict river health with high accuracy of over 97% and can detect the deterioration of environmental conditions quickly. Additionally, Pak et al. (2021) argued the importance of sufficient sample size and uncertainty analysis for better environmental decision making in reliable prediction of WQI. In addition to laboratory analyses, remote sensing, Geographic Information Systems (GIS), Internet of Things (IoT) sensors, and environmental DNA offer opportunities to achieve continuous large-scale monitoring by bringing together biological, ecological and environmental information. However, there is consistent methodological variability in all of the above aspects of sampling protocol, analytical procedures, reporting unit, and quality assurance as noted in the reviewed literature and restricting comparisons between studies. Hence, there is a need to incorporate chemical analysis, biological indicators, ecological assessment, AI-based prediction, remote sensing, biosensors and environmental modelling in the monitoring framework in a harmonised way with the capacity to provide real-time environmental surveillance. This holistic approach will further enhance the evidence-based environmental management and the early warning systems, and bolster the protection of aquatic ecosystems, reflecting on the realization of the Sustainable Development Goals in the areas of clean water, technological innovation, climate change resilience, and aquatic biodiversity conservation.

3.7 Theme 7: Mitigation Strategies for Emerging Aquatic Contaminants

Conventional WWTPs are generally ineffective at removing persistent contaminants such as pharmaceuticals and antibiotics, endocrine-disrupting chemicals, PFAS, microplastics, etc. Mitigating emerging contaminants will require integrated and sustainable approaches that are consistently shown in the literature. More recent research recommends a multi-barrier approach, which involves advanced wastewater treatment, NBS, pollution prevention, circular economy principles, regulatory interventions and integrated watershed management, as an approach to reduce the inputs of pollutants to the environment and minimise long-term ecological impacts. The advanced treatment technologies, including advanced oxidation processes, membrane filtration, activated carbon adsorption, photocatalysis, electrochemical treatment, nanofiltration and reverse osmosis, have been proven to have higher removal efficiencies than the conventional treatment technologies. Zango et al. (2023) have found that the technologies that are currently available for removing PFCAs are activated carbon adsorption and ion exchange resins, while membrane filtration also performs well, but at a higher operating cost and with the challenge of disposing of the concentrate. Likewise, Aravind Kumar et al. (2022) reported that the removal of persistent organic pollutants (POPs) by advanced oxidation, photocatalysis, and adsorption using nanomaterials can be significantly enhanced, however, the efficiency of the removal of these POPs is dependent on the physicochemical properties of the group of the pollutant. NBS can also offer environmentally sustainable solutions for the removal of contaminants. Mohd Said et al. (2025) showed that the removal of ammonia nitrogen, TSS, BOD, and TP were 99%, 94%, 80%, and 72% respectively, with the production of animal feed and biofertiliser biomass as a by-product to promote the principle of circular economy by resources recovery. Similarly, Amani et al. (2025) reported on the potential for wastewater reuse, nutrient recovery, groundwater recharge, and energy production to turn wastewater into a valuable resource. The reviewed studies also highlight the sustainability of pollution prevention over remediation. Measures such as safe disposal of drugs, treatment of hospital wastewater, limit antibiotic use, limit plastic waste, use bio-degradable alternatives and sustainable agricultural practices help to reduce the amount of contaminants released at the source. Technological innovation has to be backed by effective governance, however. Zango et al. (2023) and Aravind Kumar et al. (2022) emphasized the importance of coordinated environmental regulations, regular monitoring of key contaminants, more stringent industrial discharge limits, pharmaceutical stewardship programs, waste policies for plastics, and a holistic approach to watershed management within the framework of government, industry, research, and local communities. Overall, the evidence suggests that there is no single mitigation strategy available to effectively resolve the complexity of emerging contaminants. However, the best way to achieve Sustainable Development Goals related to clean water, responsible consumption, biodiversity conservation, and sustainable environmental management, while protecting aquatic ecosystems and public health, is to integrate advanced treatment technologies, ecological restoration, pollution prevention, resource recovery, and evidence-based environmental policies.

Discussion

The results of this SLR reveal that the emerging aquatic contaminant (EAC) issue has become one of the most critical environmental problems of the twenty first century. Emerging pollutants, such as pharmaceuticals, antibiotics, endocrine-disrupting chemicals, microplastics, heavy metals, PFAS, pesticides, and flame retardants, are found around the world in many rivers, lakes, estuaries, coastal waters, sediments, wetlands, groundwater and aquatic organisms, and are not typically covered in environmental regulations. The literature reviewed also suggests that these contaminants are seldom found alone but are instead exposed to aquatic ecosystems as complex contaminant mixtures from several anthropogenic sources. Therefore, knowledge of contaminant occurrence is not enough. For good environmental management, contaminant transport, ecological interactions, human exposure, monitoring technologies, and sustainable mitigation strategies must all be considered in the context of the other.

This review also illustrates the shift in the field of environmental research from the conventional pollution assessment to interdisciplinary research, in which environmental chemistry, ecology, toxicology, artificial intelligence, remote sensing, public health, and sustainability science are integrated. If the contaminants are to be influenced by the climate change, land use, wastewater infrastructure, ecological processes, and socioeconomic development, such integration is essential.

4.1 Global Pollution Trends

The reviewed studies provide some of the best evidence of the worldwide presence of emerging contaminants in a wide range of aquatic environments. Pharmaceuticals, endocrine-disrupting chemicals, antibiotics, heavy metals, micro plastics, PFAS, and pesticides were found in all freshwater, estuarine, and marine habitats monitored, irrespective of economic status or geographic location. The widespread finding indicates that emerging contaminants are a problem for all environments, not just a problem for a selected local area.

Xu et al. (2023) showed that steroid hormones could be transported continuously across the entire watershed and estimated that the annual flux to the receiving waters was around 89 kg per year. Likewise, Tang et al. (2021) found that around 65% of the water bodies studied globally had moderate to high levels of estrogenic risks caused by synthetic hormones and Zango et al. (2023) noted that the chemical stability of carbon–fluorine bonds gives PFAS remarkable environmental persistence. Taken together, all of these studies suggest that, in addition to local pollution sources, the occurrence of contaminants is also influenced by rising drug usage, urbanisation and industrialisation, agricultural intensification, wastewater discharge and global economic development.

A second trend that is important is related to mixtures of contaminants. The majority of the studies that were reviewed found several classes of contaminants, such as pharmaceuticals, antibiotics, endocrine disruptors, heavy metals, pesticides, and microplastics.

Traditional environmental regulations usually consider contaminants one at a time, but there is growing evidence that toxicity of a mixture may be greater than the sum of the parts. The limitation implies that future monitoring programmes need to move away from assessment of single contaminants and towards integrated monitoring of multi-contaminants risk assessment.

Climate change also exacerbates contaminant distribution by altering rainfall, water discharge in rivers, sediment transport, and evaporation and water temperature. Floods increase the ability of contaminants to be transported from the urban and agricultural landscape, while drought periods increase the concentration of contaminants in reduced water bodies. Proactive strategies for climate change adaptation should therefore be increasingly considered in the context of contaminant management.

4.2 Ecological Risks

The literature reviewed has found that emerging contaminants impact aquatic ecosystems in numerous biological ways such as biomagnification, bioaccumulation, immune suppression, oxidative stress, endocrine disruption, behavioural alteration and reproductive impairment. Such effects can be transmitted beyond the bounds of individual organisms and affect the composition of communities, biodiversity, ecosystem functioning and the stability of food-webs.

Heavy metals are still one of the most persistent ecological problems as they are not biodegradable. Razali et al. (2024) showed extensive molecular response in mud crabs under heavy metal polluted environments, showing that expression of Heat Shock Protein 70 was significantly increased, while many metabolic pathways were disrupted. These findings suggest molecular biomarkers are useful early warning signs of ecological stress prior to population declines.

Likewise, Zhao et al. (2022) reported toxic element accumulation in fish in restored mangrove habitats, showing that if pollution sources are still present, they can never be removed by habitat restoration alone. The discovery indicates that ecological restoration efforts must include remediation works to decontaminate the soil as well as works to restore habitat conditions in order to restore the ecosystem permanently.

Another important problem with EDCs is that they disrupt hormones which regulate growth, reproduction and development in the environment. Tang et al. (2021) and Liao et al. (2024) both showed that EACs were bioaccumulated by sediments and aquatic life and caused reproductive abnormalities and ecological vulnerability of fish populations. These multifaceted biological effects can also lead to long-term decreases in species diversity and ecosystem resilience.

Another aspect of ecological risk concerns microplastics that act as physical contaminants and as vectors of chemical pollutants. They have the capacity to adsorb pharmaceuticals, heavy metals, pesticides and persistent organic pollutants, allowing them to transport several contaminants within aquatic food webs. Thus, ecological risk assessments that consider only one contaminant at a time may underestimate the impacts to the ecosystem.

The studies reviewed indicate that the health of an ecosystem should be measured by a combination of the biological, chemical and ecological indicators, and not be measured based on the concentration of contaminants alone.

4.3 Human Health Risks

Exposure to emerging contaminants to humans is mainly via drinking water, seafood consumption, via recreation and indirect transfer through the food chain. While many contaminants are found in trace amounts, chronic exposure is of great concern as numerous contaminants have endocrine-disrupting, carcinogenic, neurotoxic, immunotoxic, or reproductive effects.

Dai et al. (2021) highlighted pharmaceuticals in aquatic food chains as a significant route of exposure, as ingestion of fish was found to be a more important route for pharmaceutical exposure than drinking water. Likewise, accumulation of mercury inside carnivorous fish was the major source of health risks due to food consumption by children (Meschede et al., 2024), and various endocrine-disrupting compounds were found in the commercially traded marine fish species (Tran-Lam et al., 2024).

Metal pollution is also a major health problem for the population. Although the non-carcinogenic hazard indices were low, carcinogenic risk indices were reported by Ramish et al. (2024) to be great for lead, cadmium and chromium exceeding internationally accepted limits. The results show that life time exposure to these substances might have more health concern than conventional short-term toxicity tests.

Another challenge is to the vulnerable population. Physiological sensitivity and dietary habits of children, pregnant women, older adults and communities with high seafood intake consistently were associated with higher levels of seafood exposure to contaminants. The risks to these vulnerable groups may be underestimated by the existing environmental standards which assume average exposures of adults.

The review also emphasizes the lack of knowledge of mixture toxicity. Pharmaceuticals, endocrine disruptors, microplastics, antibiotics, heavy metals and pesticides are all present in the environment during concurrent exposure to humans and are not assessed in most regulatory assessments. Epidemiological and toxicological studies in the future should thus use cumulative exposure approaches that more closely mimic actual environmental exposures.

4.4 Research Gaps

While a significant scientific achievement has occurred, there are still some important gaps in scientific understanding.

Firstly, long-term environmental monitoring programmes are limited. The majority of the reviewed studies were cross sectional and could not assess temporal changes in the occurrence of contaminants, seasonal variability or long-term ecological recovery. There is a need for regular monitoring programs to detect trends in pollution and assess management effectiveness.

Secondly, tropical aquatic systems are relatively unstudied. Despite the high rate of urbanisation and industrialisation in Southeast Asia, Africa and South America, there is a lack of research in these areas when compared to Europe, North America and China. Continued studies in the tropical ecosystem are thus needed to expand knowledge of contaminant behavior throughout the world.
Third, methodological inconsistencies hinder comparisons among studies. Sampling design, analytical methods, extraction procedures, reporting units, ecological indicators and risk assessment models differ, which diminishes comparability and makes evidence synthesis difficult. Hojjati-Najafabadi et al. (2022) and Pak et al. (2021) both emphasised the importance of methodological standardisation to improve environmental monitoring reliability.

Fourth, interactions between contaminants are not well known. Given the fact that there is growing evidence that pharmaceuticals, microplastics, endocrine disruptors, antibiotics, heavy metals, and PFAS are often found together in aquatic ecosystems, most studies focused on individual contaminant groups. Future research should be directed towards the toxicity of mixtures, cumulative exposure assessment and ecosystem level interactions.

Last but not least, policy integration is still a challenge. Scientific knowledge has progressed much faster than environmental legislation, leading to major regulatory gaps for many contaminants of emerging concern. Therefore, it is crucial that the research, regulatory and industry and policy makers work together to ensure that the scientific results are translated into effective environmental governance.

4.5 Implications for Achieving the Sustainable Development Goals (SDGs)

The results of this systematic literature review reveal that EaCs are not just environmental pollutants but are multidimensional sustainability problems that affect the realization of several United Nations Sustainable Development Goals (SDGs). The studies reviewed are consistent in demonstrating impacts of pharmaceuticals, antibiotics, endocrine-disrupting chemicals (EDCs), microplastics, heavy metals, PFAS, pesticides, and other emerging contaminants on ecosystem health, food security, drinking water quality, biodiversity conservation, and human well-being. Effective management of emerging contaminants thus has the potential to support more than one SDG at the same time.

The SDG framework calls for comprehensive environmental governance, as opposed to traditional pollution management, which emphasizes the removal of pollutants and only addresses a single environmental issue at a time. The literature reviewed thus offers important evidence of the interdisciplinary approaches required to achieve sustainable development.

SDG 3: Good Health and Well-being

SDG 3 aims to achieve good health and well-being for all at all ages. The present review shows that emerging contaminants directly pose a threat to this goal via several routes of human exposure to these substances, such as through drinking water, seafood, recreational waters, and indirect transfer in the food chain.

Chronic health risks were always linked to pharmaceuticals, antibiotics, endocrine disruptors and heavy metals. Dai et al. (2021) showed that people get more exposed to pharmaceuticals from fish than from their drinking water, suggesting that aquatic food chains have become a significant route of human exposure to pharmaceuticals. Likewise, mercury pollution in carnivorous fish was reported by Meschede et al. (2024) as a serious health issue especially for children, and Tran-Lam et al. (2024) found a number of EDCs in edible marine fish.

Studies reviewed also suggest that chronic exposure to EDCs can lead to reproductive diseases, hormonal disruption, developmental defects, metabolic problems, immune system disorders, thyroid problems, and hormone-related cancers. The association of neurological impairment, kidney damage, cardiovascular disease and carcinogenic risks with heavy metals (cadmium, chromium, lead, mercury) continues.

- Protecting human health therefore requires:
- improved drinking water treatment;
- routine seafood safety monitoring;
- stricter regulation of hazardous chemicals;
- pharmaceutical stewardship programmes;
- public awareness regarding contaminant exposure.

Such interventions contribute directly to improving environmental health and achieving SDG 3.

SDG 6: Clean Water and Sanitation

Emerging contaminants in the aquatic environment have the greatest effect on SDG 6 of the Sustainable Development Goals. Conventional wastewater treatment systems are consistently shown to be ineffective at removing pharmaceuticals, antibiotics, endocrine disruptors, PFAS, and microplastics from wastewater. This means that even when wastewater treatment facilities are present, pollutants are constantly entering rivers, lakes, estuarine, and coastal ecosystems.

There are several studies that give encouraging technological solutions.

Pak et al. (2021) found that the accuracy of Water Quality Index modelling can be improved to make the monitoring of the environmental condition more reliable, and Azha et al. (2023) achieved an accuracy of more than 97% in predicting river health using artificial neural networks.

Likewise, Hridoy et al. (2025) noted that the machine learning models were able to predict the water quality index value with a 99.65% accuracy, which shows the ability of AI in real-time environmental monitoring.

However, there was also a high degree of potential in the field of nature-based treatment technologies. Mohd Said et al. (2025) reported that the Wolffia arrhiza showed an approximate growth of:

- 99% ammonia removal
- 94% TSS removal
- 80% BOD removal
- while simultaneously producing reusable biomass.
- Collectively, these findings indicate that achieving SDG 6 requires integrating:
- advanced wastewater treatment,
- AI-assisted monitoring,
- nature-based solutions,
- watershed management,
- continuous environmental surveillance.

SDG 12: Responsible Consumption and Production

The sources of emerging contaminants are mostly unsustainable production and consumption patterns, which involve SDG 12.The unsustainable production and consumption patterns are the main sources of emerging contaminants and are closely related to SDG 12.

As consumption continues to rise, the amount of plastic wastes, pharmaceuticals, industrial chemicals, pesticides, personal care products and flame retardants are all rising. When disposed of improperly, when managed inefficiently with chemicals or when too many resources are used, contaminants are directly released to water bodies.

Aravind Kumar et al. (2022) highlighted that when industrial production of PPCPs is not sustainable and waste management is not effective, PPCPs continue to be present in the environment.

In the same vein, Chee et al. (2023) showed that the environmental load of contaminants into aquatic systems is significantly increased by the rapid urbanization and development along the coast.

The reviewed studies collectively recommend:

- reducing single-use plastics;
- improving pharmaceutical disposal;
- promoting biodegradable materials;

- strengthening industrial waste management;
- implementing extended producer responsibility;
- encouraging circular economy practices.

Amani et al. (2025) also stated that the reuse of wastewater should be considered as a valuable resource instead of wastewater waste, which is beneficial for resource recovery and sustainable production systems.
Therefore, emerging contaminants management is a direct enabler for SDG 12 (responsible consumption, reduce waste, use of resources efficiently).

SDG 13: Climate Action
There are multiple environmental processes where climate change and emerging contaminants interact.
Higher temperatures can speed up chemical reactions, affect breakdown of contaminants, change dissolved oxygen levels, and increase the likelihood of HABs. Similarly, urban and agricultural areas contribute pollutants to aquatic environments during a flood, and during a drought, the pollutants are concentrated due to a decrease in dilution.

Using satellite observations and machine learning, Al-Wardy et al. (2025) projected rising cyanobacterial harmful algal blooms in the future under climate scenarios, and Virdis et al. (2024) estimated significant warming of Southeast Asian lakes in the twenty-first century.

These changes in the environment will probably:
- modify contaminant transport,
- increase ecological exposure,
- reduce water quality,
- threaten aquatic biodiversity.

Therefore, contaminant management should become an integral component of climate adaptation planning.
Future climate-resilient water management should integrate:
- predictive modelling;
- remote sensing;
- AI-based forecasting;
- ecosystem restoration;
- adaptive watershed management.
- Such approaches simultaneously strengthen climate resilience and water security.

SDG 14: Life Below Water
The evidence reviewed in this document highlights that emerging contaminants are a serious threat to marine and freshwater biodiversity.

The consistent association with: Microplastics, Endocrine disruptors, Pharmaceuticals, Antibiotics, Pesticides, and Heavy metals were all consistently associated with:
- bioaccumulation,
- biomagnification,
- reproductive impairment,
- oxidative stress,
- behavioural alteration,
- reduced biodiversity.

Zhao et al. (2022) showed that even after the restoration of the mangrove habitat, the toxic elements continued to be accumulated which highlights that even successful habitat restoration can not remove the toxic element exposure.
Likewise, Razali et al. (2024) observed molecular evidence of heavy metal stress in mud crabs and Ramish et al. (2024) found carcinogenic heavy metals in commercially important fish species.
Another risk to marine ecosystems caused by microplastics is the ability of these plastics to carry pharmaceuticals, pesticides, heavy metals and persistent organic pollutants.
Protecting aquatic biodiversity therefore requires:
- reducing contaminant discharge;
- restoring aquatic habitats;

- improving sediment management;
- strengthening fisheries monitoring;
- implementing ecosystem-based management.

All these measures contribute directly to SDG 14, which is about conserving aquatic ecosystems, and protecting marine resources.

SDG 15: Life on Land

Though SDG15 mainly deals with terrestrial ecosystems, the reviewed studies are clearly establishing the strong linkages between the terrestrial activities and aquatic pollution.

Contaminants from agriculture, mining, urbanisation, industrial processes and land-use change can be transported to rivers, wetlands, estuaries and coastal ecosystems.

Although there were improvements in other water security sectors, Babel et al. (2022) found that the health of watersheds remained as one of the less resilient areas of water security in Thailand.

Likewise, Chee et al. (2023) highlighted that sustainable land-use planning is crucial for minimizing pollutant movement to aquatic systems.

NbS like wetlands, riparian vegetation and phytoremediation also provide benefits to the terrestrial ecosystems and water quality in the aquatic environment.

Accordingly, achieving SDG 15 requires:

- protecting wetlands;
- restoring degraded catchments;
- reducing agricultural runoff;
- improving mining management;
- conserving riparian vegetation;

integrating land-use planning with watershed management.

This integrated landscape management enhances the conservation of biodiversity both in land and in water.

Integrating Emerging Contaminant Management Across the SDGs

One of the most important findings of this review is that emerging contaminant management should not be considered solely within the context of environmental pollution. Rather, it is an interdisciplinary sustainability problem that calls for collaborative efforts among environmental science, engineering, public health, ecology, economics and policy.

The reviewed studies show that technological innovation is not enough for sustainable contaminant management. To be successful in the long term, combine:

- advanced monitoring technologies;
- artificial intelligence;
- machine learning;
- nature-based treatment systems;
- circular economy principles;
- evidence-based policymaking;
- stakeholder engagement;
- international collaboration.

These holistic solutions help to achieve several Sustainable Development Goals, enhance environmental resilience, boost public health, and advance sustainable economic growth and development, all at once.

In conclusion, the evidence shows that good governance of emerging aquatic contaminants is essential to realizing the 2030 Sustainable Development Agenda. The future environmental policies should thus focus on integrated contaminant monitoring, adaptive governance, interdisciplinary research and sustainable technological innovation to ensure long term protection of aquatic ecosystems and human health and wellbeing.

Future Research

Results of this systematic review of literature show significant advances in knowledge concerning occurrence, environmental distribution, ecological effects, human health effects, monitoring technology and mitigation strategies of emerging aquatic contaminants (ECs). Despite this, however, the variety of contaminant sources, technology advances, climate changes, and sustainability issues, all point to the fact that there are still many areas of uncertainty. Future studies should therefore go beyond the traditional monitoring of contaminants to consider integrated and interdisciplinary, technology-driven approaches which can help deal with complex interactions between contaminants, ecosystems, climate change and human activities. Overall, the reviewed studies indicate a need for continued research and development in the field of environmental monitoring, particularly through the use of advanced technologies such as artificial intelligence (AI), machine learning (ML), remote sensing, environmental DNA (eDNA), early warning systems, nature-based solutions (NbS), climate-resilient water management, and circular economy principles, to enhance Environmental Monitoring and guide decision-making. Azha et al. (2023) reported that the Artificial Neural Networks was able to classify the health of the river with prediction accuracy above 97%, and Hridoy et al. (2025) showed that the Light Gradient Boosting Machine (LightGBM) model achieved an R^2 of 0.9685 and a prediction accuracy of approximately 99.65%. The results show the great promise of AI-based models to predict the presence of emerging pollutants, detect pollution hotspots, incorporate hydrological and climate data, automate ecological risk assessments, and enable intelligent environmental decision-making to cut down on monitoring expenses and enhance predictive capabilities.

The advancement of the fields of remote sensing, unmanned aerial vehicles (UAVs), Geographic Information Systems (GIS), and the Internet of Things (IoT) technologies should also be embraced by future research to create holistic monitoring systems for the environment. These technologies allow for continuous monitoring of water surface temperature, chlorophyll a, suspended sediments, harmful algal blooms and land use change over a large geographic area, as opposed to current field sampling. Combining satellite data with AI offers the potential for "smart" water resource management and real-time monitoring of environmental conditions. Future research should thus focus on the development of contaminant prediction models from satellites, the monitoring of rivers and wetlands with drones, building of IoT sensor networks for continuous water quality monitoring and the development of cloud-based environmental databases that can incorporate information from various monitoring platforms. This technological integration would significantly enhance environmental surveillance, enable quick detection of pollution events and would contribute to the effective long-term management of ecosystems in the context of a rapidly changing environment.

A potential research area is the use of environmental DNA (eDNA) to incorporate it into contaminant monitoring programs. While eDNA have been used for biodiversity assessment and species identification, the literature sampled indicated that using genetic monitoring in conjunction with chemical analysis could yield a more complete ecosystem health assessment. The use of eDNA alongside traditional chemical monitoring, biological indicators, and machine learning algorithms can offer a comprehensive evaluation of contaminant impacts on biodiversity, species sensitivity to contaminants, invasive species expansion, ecological recovery after remediation, and ecosystem resilience, which could be valuable for future investigations. These multidisciplinary approaches would enhance our understanding of the ecological response to contamination exposure and allow for earlier detection of ecosystem degradation than would traditional physicochemical monitoring.

The reviewed studies also show that existing environmental monitoring programmes are largely reactive and contamination is often only detected after ecological degradation has taken place. Future research should therefore focus on the development of integrated early warning systems which are able to detect pollution events prior to the occurrence of irreversible environmental damage. These should incorporate artificial intelligence (AI) prediction models, Internet of Things (IoT) water quality sensors, satellite data, hydrological forecasting, meteorological data, and contaminant transport modelling to deliver real-time environmental monitoring. Early warning systems would help environmental agencies to quickly detect pollution hotspots, better prepare for an emergency, reduce contaminant dispersal, and reduce losses to the environment and economy. With a changing climate, they are anticipated to become more important in a future climate scenario due to the increased number of floods, extreme events of rain, and longer dry periods which will likely exacerbate contaminant transport and change water quality dynamics.

Nature-based solutions (NbS) also warrant further research as they involve natural ecological processes to better water quality, while also supporting biodiversity and ecosystem services. Mohd Said et al. (2025) showed that Wolffia arrhiza could remove the ammonia with an efficiency of about 99%, total suspended solids (TSS) with about 94%, and biochemical oxygen demand (BOD) with about 80% and the resulting biomass can be reused for resource recovery. Based on this, future studies should be conducted to investigate the long-term performance of constructed wetlands, floating treatment wetlands, phytoremediation systems, phytoremediation using algae, mangrove restoration and riparian vegetation management under various climatic and hydrological conditions. These studies should also investigate treatment efficiency, economic feasibility, carbon sequestration capacity, ecosystem restoration benefits and long-term operational sustainability to assess their feasibility for widespread, large scale implementation in various environmental contexts.

The shift from pollution control to resource recovery also offers great potential for future research based on the principles of the circular economy. Amani et al. (2025) stated that wastewater should not just be thought of as a waste product to be disposed of, but as a resource that can provide reclaimed water, nutrients, bioenergy and reusable biomass. The nutrient recovery technologies, wastewater reuse strategies, biomass valorisation, energy recovery from sewage sludge, sustainable aquaculture systems and integrated water-energy-food nexus approaches that optimize resource utilization and reduce environmental pollution should be examined in future investigations. These circular economy approaches can significantly decrease the amount of contaminants released and can also enhance the economic sustainability of a business by converting waste flows into useful products that can support sustainable production and consumption.

Climate change is another key research priority as rising temperatures, changing precipitation patterns, droughts, flooding, and hydrological changes are expected to impact contaminant transport, water quality, ecosystems and biodiversity. Going forward, it would be valuable to study the effects of climate change on contaminant mobility, HABs, groundwater contamination, watershed resilience, and ecosystem adaptation. The incorporation of predictive climate models into contaminant monitoring programs would help to further define environmentally sensitive areas and assist in developing adaptation plans for environmental management to respond to environmental change in the future. Special focus needs to be placed on tropical regions where the combination of rapid urbanisation and climate change is a significant threat for aquatic ecosystems.

Another key issue that emerged in the literature reviewed is that there are insufficient methodologic consistency among monitoring studies. The comparability of results between geographical areas and contaminant groups is reduced by the differences in sampling strategies, extraction methods, analytical methods, reporting units, ecological indicators and risk assessment models. It is therefore opportune that future international cooperation focuses on harmonising the monitoring guidelines for pharmaceuticals, PFAS, endocrine-disrupting chemicals, antibiotics, microplastics and nanoplastics, to ensure data quality and enable environmental assessment on the global scale. Standardised methodologies would improve consistency of environmental monitoring and contribute to the creation of scientific evidence needed for policy making and international cooperation.

In conclusion, further research is needed to enhance the links between scientific knowledge and environmental policy and governance; otherwise, advancements in technology will not provide adequate solutions to emerging contamination pollution without proper regulations and stakeholders' engagement. An integrated approach, involving environmental scientists, ecologists, engineers, toxicologists, medical scientists, economists, policy makers and the public, is vital for creating holistic management strategies for contaminant pollution that address both environmental and socioeconomic aspects. Future research is thus needed to explore environmental governance, the effectiveness of the regulations, socioeconomic impacts, stakeholder involvement, public risk perception, and cost-benefit analyses of remediation technologies to enhance evidence-based policy-making and the implementation of sustainable environmental management strategies. In general, the examined evidence points to further studies on integrated smart environmental monitoring, the use of more sophisticated sustainable treatment technologies, climate-resilient water resources management, resource recovery and circular economy, and harmonised environmental governance. Together, these research priorities will improve the capacity of the world to monitor, predict and mitigate new contaminants in water and will drive progress towards SDGs 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production), 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land).

Conclusion

Emerging aquatic contaminants (ECs) are one of the most important environmental issues facing 21st century water resource management. This systematic literature review, performed according to PRISMA 2020 guidelines, aimed to compile the latest findings (2020-2025) on the presence, environmental effects, human health effects, monitoring technologies, mitigation methods, and the importance of emerging contaminants in aquatic ecosystems for sustainability. The review shows that contaminants like pharmaceuticals, antibiotics, endocrine-disrupting chemicals (EDCs), micro-plastics, heavy metals, per- and poly-fluorinated chemicals (PFAS), pesticides, and flame retardants are increasingly found in fresh water, estuarine, coastal, and marine environments globally. They are continuously discharged from wastewater treatment plants, industry, agriculture, urban areas, mining operations and aquaculture, causing long-term contamination of water, sediments and aquatic organisms, which poses a complex environmental challenge beyond normal pollution control.

Despite ongoing advances in wastewater treatment technologies, pharmaceuticals, endocrine disruptors, antibiotics and PFAS are now being detected at environmentally relevant levels in the reviewed literature. These contaminants are seen to be persistent due to the fact that many of the conventional treatment systems were not originally designed to remove biologically active trace compounds. Microplastics are one of the most prevalent and ubiquitous pollutant groups consistently found in river and lake water, in bottled drinking water, sediment, in fish, shellfish, and aquaculture systems. Heavy metals still present a serious ecological and human health threat due to their resistance to biological degradation, bioaccumulation and longevity. Together, these results suggest more complex mixtures of contaminants are increasingly being found in aquatic ecosystems, rather than individual contaminants, and call for more comprehensive monitoring and risk assessment protocols.

The review further highlights that emerging contaminants have significant ecological effects through bioaccumulation, biomagnification, endocrine disruption, oxidative stress, reproductive impairment, behavioural changes, immune disruption and loss of biodiversity. Sediments are reservoirs for long-term release, continually discharging a variety of contaminants to aquatic ecosystems and can be the source of trophic transfer through aquatic food-webs. Aquatic organisms, such as fish, crustaceans, molluscs and humans, ingest pollutants from the water that then bioaccumulate up the food chain. As a result, emerging contaminants pose a risk to ecosystem resilience, fisheries sustainability and the ecological services of aquatic ecosystems. The results confirmed the critical need for implementing ecosystem-based management strategies, which take into account interactions between water, sediment, aquatic organisms and adjacent terrestrial ecosystems.

Another significant concern highlighted in this review is the health effects that humans may experience. The major pathways of human exposure to contaminants are through drinking water, seafood consumption, recreational water exposure, and indirect transfer via food chains. Pharmaceuticals, endocrine-disrupting chemicals, heavy metals, and microplastics have all been linked to long-term health effects such as endocrine problems, neurological damage, reproductive dysfunction, immune system suppression, developmental abnormalities and metabolic disease, as well as risk of cancer. The groups most at risk, in terms of the risk of exposure to contaminants per unit of body weight were consistently identified as children, pregnant women, older adults and populations with high intakes of seafood, due to their high physiological susceptibility. Importantly, the reviewed studies show that existing regulations based on single contaminants could underestimate the actual health threats posed by contaminants in the water because chemicals in the water are usually a mixture of various classes of contaminants.

Important progress has also been made in the monitoring of contaminants and environmental assessment. The review illustrates that artificial intelligence, machine learning, environmental DNA (eDNA), remote sensing, biosensors, nanotechnology and advanced analytical chemistry have made significant contributions to the detection of contaminants, ecological risk assessment, and predictive environmental modelling. Light Gradient Boosting Machine (LightGBM) and Artificial Neural Networks (ANNs) are machine learning algorithms that have shown outstanding results in predicting water quality and forecasting the environment. Likewise, nanosensors and high resolution analytical methods are capable of detecting traces of contamination with greater sensitivity. These technological innovations offer great potential to create intelligent systems for environmental monitoring, which can contribute to real-time management of water quality and early warning programmes.

As for mitigation: The studies reviewed show that no single technology is able to completely remove emerging contaminants from aquatic systems. Rather, holistic solutions such as advanced wastewater treatment, adsorption technologies, membrane filtration, advanced oxidation processes, phytoremediation, constructed wetlands, circular economy principles, pollution prevention and NbS are needed to effectively manage wastewater. The concept of sustainable water management also needs to shift from pollution control to integrated environmental resource management, as is demonstrated by the implementation of resource recovery techniques that recuperate wastewater resources such as water, biomass, nutrients and energy. These measures not only help to enhance water quality, but also contribute to environmental sustainability, economic efficiency and climate resilience.

A major aspect of this review is the incorporation of new contaminant research into the United Nations Sustainable Development Goals (SDGs). The evidence clearly shows that management of emerging aquatic contaminants has direct impacts on SDG 3 (Good Health and Well-being) with the reduction of human exposure to hazardous chemicals, SDG 6 (Clean Water and Sanitation) through enhanced water quality monitoring and wastewater treatment, SDG 12 (Responsible Consumption and Production) through pollution prevention and circular economy practices, SDG 13 (Climate Action) through climate-resilient water resource management, SDG 14 (Life Below Water) through protection of aquatic biodiversity and fisheries, and SDG 15 (Life on Land) through integrated watershed conservation and ecosystem restoration. Therefore, the emerging contaminated management should be viewed as a priority for interdisciplinary sustainability rather than just a problem of pollution in the environment.

This review highlighted a number of key areas of research that have yet to be adequately addressed despite the advances in science. Long-term monitoring programmes are still scarce, especially in tropical developing countries where the pressure of contaminants is still high due to the rapid urbanisation and industrialisation. The lack of consistency between studies hinders comparability, and the toxicity of mixtures of contaminants and the cumulative human exposure is not well understood. The following will be recommended for future research: standardized monitoring protocols, interdisciplinary research, environmental prediction based on artificial intelligence, environmental DNA applications, remote sensing, environmental risk assessment, and watershed management that is climate resistant. There is a need to build partnerships between environmental scientists, engineers, toxicologists, public health professionals, economists and policy makers if the science is to be turned into effective environmental governance.

Finally, emerging aquatic contaminants are a serious problem for the environment that needs international cooperation.

Technological solutions are not the only element to sustainable management; it requires the utilization of scientific innovation, environmental policy, stakeholder engagement, public awareness and ecosystem-based management. Sustainable remediation, enhanced monitoring technologies, the circular economy and evidence-based policies can play a vital role in minimizing contaminant discharge, safeguarding aquatic life, ensuring long-term water security and maintaining public health. In the end, reaching these goals will help to speed progress towards the Sustainable Development Goals and help to create a more resilient, sustainable and environmentally friendly future of aquatic ecosystems and human societies.

Recommendations

Based on the results of this systematic literature review, the following recommendations are made:

1. Strengthen monitoring programmes by incorporating pharmaceuticals, PFAS, endocrine-disrupting chemicals, antibiotics, microplastics, and other emerging contaminants into routine national water quality monitoring.
2. Adopt advanced treatment technologies, including membrane filtration, advanced oxidation processes, adsorption systems, and nature-based solutions, to improve contaminant removal from wastewater.
3. Integrate Artificial Intelligence and Machine Learning into environmental monitoring programmes to enable real-time contaminant prediction and early warning systems.
4. Promote circular economy practices through wastewater reuse, nutrient recovery, biomass utilisation, and sustainable resource management.
5. Standardise international monitoring protocols to improve data comparability and support global environmental assessments.
6. Strengthen environmental legislation by establishing regulatory standards for priority emerging contaminants and enforcing stricter industrial and municipal wastewater discharge requirements.
7. Increase interdisciplinary collaboration among environmental scientists, engineers, ecologists, toxicologists, healthcare professionals, and policymakers to develop integrated contaminant management strategies.
8. Expand research in tropical and developing regions, where data remain limited despite increasing pollution pressures and rapid socioeconomic development.

The recommendations in this report will lead to better protection of aquatic ecosystems, better public health, greater environmental resilience and support the United Nations Sustainable Development Goals (SDGs).

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