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Review

Emerging Contaminants in Wastewater: Mitigation Approaches for Environmental Management and Future Sustainability

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Abstract

Emerging contaminants (ECs) are a diversely mounting group of chemicals and biological compounds found in air, water, and soil, which include pharmaceuticals, personal care products, per- and poly-fluoroalkyl substances (PFASs), microplastics, endocrine-disrupting chemicals, and various other industrial compounds. Unlike conventional pollutants, ECs are usually unregulated, found in very small amounts, and can persist and build up in living organisms, resulting in toxic risks for both ecosystems and human health. These contaminants originate from various anthropogenic activities and enter the environment through wastewater, stormwater, landfill leaching, and atmospheric deposition. This article documents a holistic literature review of ECs available from the last five years, covering classification, sources and pathways of contamination, and environmental behavior, while assessing their ecological, human health, and socioeconomic impacts. Advances in detection, including high-resolution mass spectrometry, non-target screening, real-time sensors, and AI-assisted monitoring, are addressed. Management strategies including advanced oxidation, membrane filtration, electrochemical treatments, and nature-based solutions are explored. It also analyses global and regional policy frameworks, highlighting regulatory gaps and the need for standardized monitoring. The study emphasizes integrated, multidisciplinary approaches combining scientific innovation, sustainable chemical design, predictive modeling, and public engagement. Synergizing technology, governance, and prevention could reduce the risks related to ECs and protect the environment. The novel contribution is an end-to-end, decision-oriented synthesis that links what monitoring can reliably infer to be feasible, integrated control strategies and sustainability outcomes, supporting risk-based prioritization, targeted pollution treatment, and prevention-focused management.

Keywords: microplastics; policy framework; nature-based solutions (NBS); wastewater treatment; pollutant mitigation; recalcitrant compounds

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1. Introduction

Emerging contaminants (ECs) are an increasingly diverse group of recalcitrant chemicals and biological agents that have gained attention due to their widespread presence

and potential risks to both the environment and human health [1]. These include pharmaceuticals, personal care products, microplastics, endocrine disruptors, flame retardants, industrial solvents, and nanomaterials which remain largely understudied [2]. ECs are concerning due to their persistence, bioaccumulation, and toxicity at very low concentrations, leading to their classification, while being ubiquitously found in air, water, and soil [3–5]. ECs are commonly classified by persistence, bioaccumulation, and toxicity [5]. PFASs, for example, persist for years, resisting breakdown and cycling through environmental media, while some pharmaceuticals, though less persistent, still pose chronic risks [6]. Risk assessment is hampered by limited toxicology and uncertain mixture interactions [7].

ECs enter the environment via multiple human-driven sources, majorly contributed by urban sources (treated and untreated wastewater, hospital discharges, stormwater runoff, landfill leachate), industry sources (solvents, dyes, metals, synthetic additives), and agriculture sources (pesticides, veterinary medicines, nutrient runoff) [8,9]. Wastewater treatment plants have the potential to be focal for ECs remediation, as conventional systems target organic matter and nutrients but often fail to remove complex compounds [10]. Addressing EC removal is urgent due to their wide-ranging effects, as at very low concentrations they can disrupt hormones, impair reproduction, foster antibiotic resistance, or alter immune responses in humans and wildlife [11,12]. PFAS exposure has been linked to cancer, metabolic disorders, immune dysfunction, and developmental issues [13]. On the other hand, microplastics cause physical harm and can transport toxic chemicals, potentially contributing to cardiovascular, neurological, and inflammatory disorders [14]. Ecologically, ECs disrupt food webs, reduce the population of sensitive species, and accumulate in top predators. Socioeconomic consequences include biodiversity loss, reduced fishery yields, higher healthcare costs, and increased demands on water treatment infrastructure [15].

EC detection and monitoring have advanced significantly; analytical techniques such as high-performance liquid chromatography (HPLC), gas chromatography, and mass spectrometry, along with non-target screening, enable identification at ultra-trace levels. Coupling these tools with Artificial Intelligence and machine learning (AI-ML) has the scope to enhance predictions of contaminant movement, transformation, and biological uptake [16]. For pollutants like PFASs, geospatial analysis and computational models improve the mapping of contamination and exposure risks. Emerging sensing technologies, such as microfluidic sensors, offer the potential for rapid in situ detection [3].

To mitigate ECs, several engineered strategies such as advanced oxidation, membrane filtration, adsorption using activated carbon or novel materials, and electrochemical treatments are being developed. Additionally, nature-based approaches like constructed wetlands, phytoremediation, biochar application, and microbial degradation provide sustainable solutions towards low-level contamination [7]. Emerging nanotechnology, including light-activated materials for the breakdown of pharmaceutical compounds, offers promise but requires thorough environmental safety evaluation. In parallel with these approaches, regulatory frameworks are also evolving but remain inconsistent worldwide. Some countries have set strict limits for specific contaminants like PFASs in drinking water, supported by funding for compliance and treatment upgrades. Internationally, there is growing recognition for documenting harmonized standards, coordinated monitoring programs, and shared governance to manage pollutants that cross borders. The “One Health” approach, linking human, animal, and environmental health, is increasingly promoted as a comprehensive management framework; however, substantial challenges persist [12]. Regulations need to emerge targeting damage control, while majorly developing regions lack the expertise, funding, and infrastructure needed for effective EC monitoring and remediation [9]. Real-time detection systems are still limited, and scaling laboratory solutions to field applications faces technical and economic hurdles [17]. The sheer diversity

of ECs, the constant emergence of new chemicals and transformation products, and their poorly understood effects make prioritization and risk assessment difficult. Furthermore, detecting contaminants at extremely low concentrations demands highly sensitive and expensive methods [3].

Despite rapid growth in emerging contaminant research, the literature remains fragmented across detection and monitoring, mitigation technologies, and governance/implementation. This limits decision-making because monitoring outputs are not consistently translated into actionable treatment selection, residuals management, and prevention strategies under realistic constraints. This review addresses that gap by providing an integrated, management-oriented synthesis that links detection capability (including proxy vs. compound-specific approaches) to feasible mitigation pathways and policy needs. This review is intended to document the management of emerging contaminants (ECs), emphasizing their sources, impacts, detection methods, and mitigation strategies. It also evaluates the perspective of policy frameworks and highlights future priorities such as green chemistry, predictive modeling, and global policy coordination. Overall, it emphasizes the need for integrated, forward-thinking approaches that combine innovation, governance, and stakeholder collaboration to safeguard public health and environmental management in relation to sustainable developmental goals (SDGs).

This review followed a structured narrative synthesis approach to identify and critically evaluate recent evidence on emerging contaminants (ECs) in wastewater. The literature was searched in Scopus, Web of Science, and Google Scholar using combinations of terms related to EC classes, wastewater/WWTPs, detection (LC–MS/MS, HRMS, suspect/non-target screening, sensors), mitigation (AOPs/ozonation, activated carbon, membranes, electrochemical, nature-based solutions), and policy/risk. The primary screening focused on studies from the last five years. Peer-reviewed and authoritative sources relevant to wastewater occurrence, monitoring, treatment performance, and implementation were prioritized. Evidence was synthesized thematically with an emphasis on feasibility, residuals/by-products, and scalability.

2. Types of Emerging Contaminants

ECs comprise a broad range of synthetic and natural chemicals increasingly recognized for their persistence and risks to both human health and ecosystems. Major groups include pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), polyfluoroalkyl substances (PFASs), microplastics (MPs), nanomaterials, and industrial chemicals and by-products (ICBs) (Table 1). PPCPs, such as antibiotics, analgesics, and cosmetics, enter the environment via wastewater effluents, improper disposal, and agricultural runoff, disrupting aquatic and terrestrial systems [18]. EDCs including bisphenol A, phthalates, and pesticides interfere with hormonal signaling, impairing growth, reproduction, and metabolism in humans. PFASs, known as "forever chemicals," resist degradation due to strong carbon–fluorine bonds, and are bioaccumulated and linked to carcinogenic, metabolic, and reproductive harm [19]. MPs, generated by the fragmentation of plastics or microbeads, now occur across terrestrial, aquatic, and even airborne environments, causing oxidative stress, digestive blockages, and impaired nutrient uptake in plants [20]. MPs can also act as vectors by sorbing and transporting hydrophobic organic contaminants, potentially modifying their environmental fate and exposure pathways [21]. Nanomaterials, while valuable in technology, raise ecotoxicological concerns through size-dependent mutagenicity and phytotoxicity. ICBs, including heavy metals, solvents, and dioxins, contaminate soils and waters, contributing to chronic toxicity and ecosystem disruption. Collectively, these contaminants highlight the complex challenge of regulating and mitigating diverse, persistent pollutants.

The human health impacts of ECs span multiple systems and are increasingly well documented (Table 2). Neurological effects result from pesticides and industrial chemicals that disrupt neurotransmission, generate oxidative stress, and damage neurons, contributing to neurodevelopmental disorders and increasing risks of Alzheimer's and Parkinson's disease [22]. Carcinogenic risks are strongly associated with PFASs, which can disrupt estrogen signaling and promote tumor development, particularly in breast cancer [23]. Immune system effects include weakened host defenses, increased allergy susceptibility, and autoimmune disorders, often mediated by heavy metals and solvents that impair immune regulation and alter gut microbiota [24,25]. Cardiovascular and metabolic disruptions are particularly concerning: PFAS exposure is linked to hypertension, hyperlipidemia, diabetes, obesity, and fatty liver disease, conditions that elevate the risks of heart disease. Respiratory effects, largely associated with chronic particulate exposure, worsen asthma and COPD, increase hospitalization rates, and exacerbate childhood respiratory illness. These outcomes emphasize the urgent need for adaptive regulatory standards and mechanistic research [26]. Emerging chemicals circulate across interconnected air, water, soil, and human systems, leading to cumulative environmental and health impacts. Their cross-media transport, leading to bioaccumulation, disrupts ecosystem functions and microbial processes, while increasing risks to human respiratory, neurological, immune, and endocrine health (Figure 1).

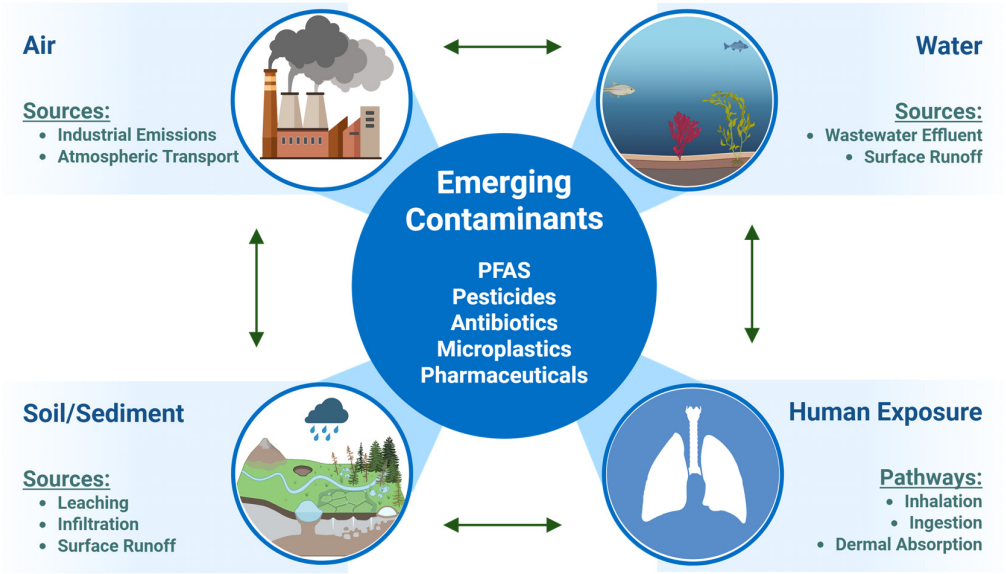


Figure 1. Environmental and health impacts of emerging chemicals across inter-systems.

Beyond direct human health, ECs exert a wide range of ecological effects. Nutrient-rich agricultural runoff coupled with pollutants accelerates eutrophication, drives algal blooms, and depletes oxygen in aquatic systems. MPs alter soil nutrient cycling, degrade habitats, and increase ingestion risks for organisms [27,28]. Wildlife is especially vulnerable: pharmaceuticals disrupt fish and amphibian reproduction, while EDCs and PFASs interfere with hormonal regulation; heavy metals and industrial toxins increase mortality and destabilize populations [29]. Persistent pollutants such as diclofenac, DDT, PFAS, and mercury have been detected even in remote arctic ecosystems, underscoring their transport potential and global reach. Prolonged exposure also drives biodiversity loss, eroding genetic diversity and reducing species resilience, ultimately threatening ecosystem stability (Table 2).

The socioeconomic consequences of ECs add further complexity. Healthcare systems face rising costs from chronic illnesses, endocrine disorders, and antimicrobial resistance,

while monitoring and remediation strain public budgets (Table 2). Agriculture and fisheries suffer reduced yields and food quality, tourism and recreation decline under ecosystem degradation, and utilities must invest in advanced treatment technologies, raising consumer costs. Contamination also lowers property values and imposes liability risks on industries [30]. Importantly, these burdens fall disproportionately on low-income communities, deepening health disparities and environmental injustice. ECs impose interconnected human, ecological, and economic challenges that require coordinated monitoring, regulation, and policy innovation.

Table 1. Overview of major categories of emerging contaminants (ECs) including their key characteristics, representative examples, major sources and environmental pathways, and associated environmental and health impacts.

Type of Emerging Contaminant	Key Characteristics/Description	Representative Examples	Major Sources and Environmental Pathways	Potential Environmental and Health Impacts	References
Pharmaceuticals and personal care products (PPCPs)	Broad group of prescription/OTC medicines and personal care products (e.g., lotions, cosmetics, fragrances); useful for health/hygiene but cause ecological disturbance when released	Antibiotics, antidepressants, hormonal contraceptives, analgesics, sunscreens, fragrances	Improper disposal, wastewater effluents, agricultural runoff	Ecological risks, bioaccumulation, endocrine disruption, potential human health impacts	[31,32]
Endocrine-disrupting chemicals (EDCs)	Substances that mimic, block, or disrupt hormones, interfering with physiological regulation (growth, reproduction, development)	BPA, dioxins, perchlorate, PCBs, alkylphenols, phthalates, atrazine, DDT	Plastics and resins, pesticides, personal care products	Reproductive disorders, obesity, reduced fertility, altered behaviors, developmental toxicity in wildlife and humans	[33–35]
Polyfluoroalkyl substances (PFASs)	Synthetic "forever chemicals" with strong C–F bonds; resistant to heat, water, and oils; highly persistent	PFOS, PFHxS, PFOA, GenX, PFNA, PFDA, PFBS	Industrial uses, food processing, migration from packaging/contact materials	Male reproductive disruption, endocrine effects, contamination in edible oils, obesogenic effects linked to childhood obesity	[36,37]
Microplastics (MPs)	Plastic fragments <5 mm from degradation of larger plastics or microbeads; widely distributed across ecosystems	Secondary MPs, microbeads	Freshwater, marine, terrestrial, and airborne environments	Digestive blockage, tissue damage, oxidative stress in organisms; inhibited seed germination, nutrient uptake in plants	[27,28]
Nanomaterials	Nanoscale particles with high surface-to-volume ratios; high reactivity and potential toxicity	Rare earth nanoparticles, mesoporous carbon nanoparticles	Industrial processes, consumer products, electronic/medical applications	Mutations in soil organisms (e.g., earthworms), phytotoxicity in plants (e.g., rice seedlings), particle size-dependent toxicity	[38,39]
Industrial chemicals and by-products (ICBs)	Persistent, toxic chemicals from industrial manufacturing and waste streams	Lead, mercury, dioxins, organic solvents, pesticides	Industrial emissions, improper disposal, waste mismanagement	Soil and water contamination, ecological harm, neurological and developmental effects in humans	[40]

Table 2. Summary of human health, ecological, and socioeconomic effects of emerging contaminants (ECs).

Category	Key Effects/Description	Representative Examples	Health, Ecological, or Socioeconomic Impacts	References
Human health risks (general)	Hormonal disruption, antibiotic resistance, and long-term chronic health effects	Various pharmaceuticals, EDCs, PFASs, industrial by-products	Increased disease burden, pressure on healthcare systems, need for updated regulations	[41,42]
Neurological effects	Neurotoxic pesticides and chemicals disrupt neurotransmission and cause oxidative stress and neuronal injury	Pesticides, industrial chemicals	Neurodevelopmental abnormalities, Alzheimer's, Parkinson's, chronic neurotoxicity	[43,44]
Carcinogenic effects	PFASs and other ECs linked to endocrine disruption and hormone-driven tumor growth	PFASs (e.g., PFOA, PFOS)	Elevated cancer risk, especially breast cancer, via estrogen signaling disruption	[36,45]
Immune system impacts	Heavy metals and by-products impair immunity, alter tolerance, and disrupt gut–immune axis	Trichloroethylene, cadmium, lead, mercury	Autoimmune disorders, infections, allergies, inflammatory states, epigenetic effects	[24,25]
Cardiovascular and metabolic effects	Oxidative stress and inflammation disrupt endocrine and metabolic functions	PFASs, EDCs	Hypertension, atherosclerosis, myocardial infarction, obesity, diabetes, NAFLD	[46]
Respiratory effects	Particulate pollutants cause pulmonary stress and chronic disease	Fine particulates, industrial pollutants	Asthma, COPD, severe exacerbations, pediatric asthma, worsened adult COPD	[47]
Ecosystem effects (general)	Pollutant and nutrient interactions alter ecosystem functions and nutrient cycling	Nutrient-rich runoff, microplastics	Eutrophication, algal blooms, oxygen depletion, soil nutrient imbalance	[48,49]
Impacts on wildlife	EDCs and pharmaceuticals disrupt reproduction and survival; industrial toxins raise mortality	Diclofenac, ivermectin, DDT, BPA, phthalates, PFASs, heavy metals	Endocrine disruption, reproductive failure, population decline, toxicity across taxa (fish, amphibians, birds)	[50,51]
Impact on biodiversity	Toxic pollutants reduce sensitive species, alter gene expression, and erode genetic diversity	Aquatic and terrestrial EC exposure	Species loss, reduced resilience, weakened ecosystems	[42,52]
Socioeconomic impacts	ECs drive healthcare, treatment, remediation, and monitoring costs; degrade ecosystem services	Water utilities, fisheries, agriculture, tourism	Higher healthcare/treatment costs, food insecurity, reduced tourism, property devaluation, environmental injustice	[47]

3. Detection and Monitoring of Emerging Contaminants

Emerging contaminants lack typical regulation and monitoring protocols due to the lack of comprehensive toxicological data or long-term environmental fate studies. Due to their occurrence in natural ecosystems, their identification among other components has become a major task that leads to being a high-risk cause for both environmental and human health [53]. Due to the higher EC proliferation among diverse environments (surface and ground water, sediments, soils, biota), many mitigation and management concerns are raised among environmental scientists, regulatory agencies, and public health

ministries. Research has shown that the release and persistence of ECs is marked by rapid urbanization, increasing pharmaceutical consumption, industrial development, and inefficient wastewater treatment technologies [54]. The inappropriate functioning of municipal wastewater treatment plants prior to ECs' release into the ecosystem is also a concern. Hence, compounds such as antibiotics, analgesics, antiepileptics, hormones, and cosmetic ingredients that can enter aquatic ecosystems are left behind in plants, causing contamination [55]. Their nature in the environment is influenced by adsorption, hydrolysis, photodegradation, redox reactions and biodegradation. However, many ECs, such as carbamazepine and triclosan, resist degradation and persist in water and soil. Moreover, transformation products formed during water treatment, including chlorinated derivatives, may exhibit a greater toxicity than their parent compounds [56]. The bioaccumulation of hydrophobic ECs (PFASs and brominated flame retardants) is one of the major concerns, as they can be easily consumed by living organisms via the food web. Microplastics also act as carriers for hydrophobic contaminants, increasing the risk externally. These pathways raise concerns regarding chronic human health effects, including endocrine disruption, neurotoxicity, and antibiotic resistance [57]. Figure 2 presents an integrated monitoring framework for emerging contaminants, linking wastewater treatment plant effluents with advanced analytical platforms such as high-performance liquid chromatography and complementary detection systems. These directly emphasize the progression from source identification to environmental surveillance, supporting the assessment of contaminant fate, transport, and ecological exposure in aquatic and terrestrial systems.

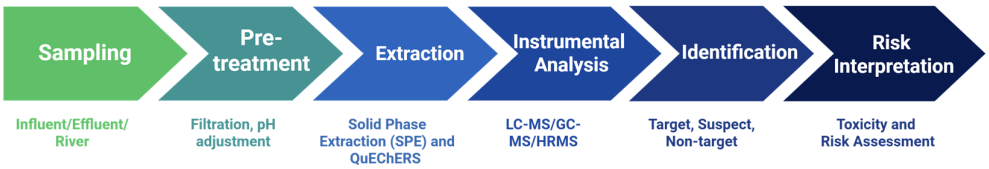


Figure 2. Analytical monitoring of emerging contaminants from wastewater to the environment.

3.1. Analytical Techniques for Detecting Emerging Contaminants

The identification and monitoring of ECs is dependent on understanding their core effects on the environment and public health. Liquid chromatography–mass spectrometry (LC-MS) and gas chromatography–mass spectrometry (GC-MS) are the analytical techniques most preferably used due to their highly selective and specific nature. Sample preparation is the most critical step in performing EC analysis; the solid-phase extraction (SPE) method is one of the most commonly employed methods to estimate the concentration and purify the analytes of specified aqueous samples [58]. Along with SPE, liquid–liquid extraction and solid-phase microextraction are also used, especially for the extraction of volatile compounds extracted using minimal solvent volumes. For better EC detection and separation analysis, high-performance liquid chromatography (HPLC), gas chromatography (GC), and mass spectrometry (MS) are used alone or in conjunction. Among these separation techniques, GC-MS is ideal for volatile and thermally stable compounds, whereas HPLC-MS or simple MS is usually preferred for polar and thermolabile analytes [59].

Tandem MS and high-resolution MS (HRMS) enables the identification of ECs and their transformation products at ultra-trace levels [60]. Non-target and retrospective analyses are usually facilitated by time-of-flight and orbitrap analyzers. LC-MS is a powerful analytical technique that combines the physical separation capabilities of LC with the mass analysis capabilities of MS. It is widely used in pharmaceutical analysis, environmental monitoring, proteomics, metabolomics, and the detection of ECs due to its sensitivity, specificity, and versatility. LC relies on separation based on interactions with both the

mobile and stationary phases, employing the reversed phase, whereas non-polar analytes remain longer in a hydrophobic stationary phase [61]. First, chromatographic separation occurs; later, the molecules enter the mass spectrometer for further separation, where the molecules are ionized using techniques like electrospray ionization (ESI) or atmospheric pressure chemical ionization (APCI) [62]. This is followed by ion detection based on their mass-to-charge ratio, which provides qualitative and quantitative data. LC-MS is applied in pharmaceuticals for drug discovery, pharmacokinetics, and metabolite identification, and it is also vital in diagnostics for detecting biomarkers, therapeutic drug monitoring in medical sciences, and identifying trace levels of contaminants and emerging pollutants in environmental sciences [63]. Similarly, GC-MS is highly effective for analyzing volatile and semi-volatile organic compounds (VOCs and SVOCs), polycyclic aromatic hydrocarbons (PAHs), and drug residues [64]. In GC-MS, analytes are volatilized and transported by an inert gas (typically helium or nitrogen) through a capillary column, where they separate according to their specific boiling points and polarity [65]. The separated compounds are subsequently ionized in the mass spectrometer, usually through electron ionization (EI), producing fragmentation patterns that are detected and quantitated based on their mass-to-charge (m/z) ratios [59]. In environmental science, it serves as a gold standard for finding pollutants in air, water, and soil. It is also crucial in forensic toxicology to identify narcotics and toxins [66].

3.2. Biosensors Used in the Management and Mitigation of ECs

Biosensors are sensitive analytical tools that pair a biological recognition component (e.g., enzymes, antibodies, nucleic acids, or microbial cells) with a physicochemical transducer to identify analytes with excellent sensitivity and selectivity, providing an effective method for in situ and real-time EC monitoring. The biorecognition moiety binds or interacts selectively with target ECs (pharmaceuticals, endocrine-disrupting chemicals, pesticides, and industrial pollutants), where the transducer converts these interactions into measurable signals (electrochemical, optical, piezoelectric, or thermal) [67]. Electrochemical biosensors are especially popular for environmental use because of their mobility, low expense, and high level of analytical performance. Various classes of biosensors are designed for particular ECs: enzyme biosensors recognize organophosphates and phenols through the inhibition of an enzyme; immunosensors utilize antigen–antibody binding to detect antibiotics, hormones, and POPs; DNA biosensors (geno-sensors) evaluate genotoxic contaminants by identifying hybridization or DNA damage; and whole-cell biosensors employ genetically modified microorganisms that produce luminescent or fluorescent signals in response to contaminant exposure [68,69]. These biosensors offer a rapid, selective, and sensitive response in complex media such as water, soil, and air, and can be used to facilitate early warning systems and bioremediation monitoring through the assessment of contaminant bioavailability and microbial degradation activity [68]. While biosensors are superior to traditional chromatographic techniques in the aspects of speed, expense, and field use, constraints in the form of a narrow target specificity, environmental variability sensitivity, and limited long-term stability remain. Yet developments in synthetic biology and nanotechnology are increasingly improving their signal amplification and multiplexing capability, as well as their robustness for extensive environmental monitoring.

3.3. Remote Sensing Used in the Management and Mitigation of Emerging Contaminants in Environment

Remote sensing is a contactless geospatial technology that employs satellite- or airborne-based sensors to identify electromagnetic radiation reflected or emitted from the earth's surface and monitor the environment continuously without physical contact. In the case of ECs, remote sensing provides indirect yet essential environmental risk and

pollutant dynamics assessments [70]. Techniques like multispectral, hyperspectral, and thermal infrared sensors are used to measure spectral differences in land and water bodies, which can be linked with contamination events. While remote sensing cannot directly detect trace-level ECs because of their very low environmental concentration levels, it offers useful proxy indicators [71,72]. Some of these include land use/land cover (LULC) analysis to delineate agricultural runoff or industrial effluent discharges, chlorophyll-a estimation for observing algal bloom due to nutrient and pharmaceutical discharge (e.g., from Sentinel-2 or MODIS), and thermal anomalies indicative of unauthorized wastewater release. Furthermore, remote sensing facilitates the observation of hydrological parameters like turbidity, surface temperature, and total suspended solids, which are associated with contaminant transport and distribution [73]. Advances in recent hyperspectral imaging (HSI) technology have provided increased spectral resolution for monitoring dissolved organic matter (DOM) and other EC surrogates. Coupled with Artificial Intelligence (AI) and machine learning algorithms, predictive modeling and early warning systems are further enhanced in risk assessment for EC [71,74,75]. While there are limitations, namely the inability to monitor ECs at a molecular concentration, integrating remote sensing information with ground sampling, biosensors, in situ measurements, and GIS-based modeling greatly enhances its utility in environmental monitoring and contaminant control measures.

3.4. AI-Driven Monitoring in the Management and Mitigation of ECs

Artificial Intelligence (AI) has become a revolutionary computational strategy for monitoring, predicting, and mitigating ECs like pharmaceuticals, endocrine-disrupting compounds, and microplastics that usually exist at trace concentrations with a complex spatiotemporal variability [76–78]. Conventional analysis techniques are not capable of managing such multifactorial datasets; yet AI-based procedures, specifically machine learning (ML) algorithms like support vector machines (SVM), random forests, and artificial neural networks, enable pattern and trend recognition in EC distribution through an integration of environmental factors such as land use, hydrological regimes, and climatic conditions [79]. Deep learning structures, specifically convolutional neural networks (CNNs), improve the machine-based examination of remote sensing images and sensor readings, providing an early warning for signals of contamination. AI-enabled Internet of Things (IoT)-based sensor platforms enable real-time environmental monitoring, allowing the dynamic monitoring of pollutant sources, contamination risk forecasting, and decision-making in remediation planning [75]. In addition, AI is increasingly being applied in non-target screening pipelines, where it helps to detect unidentified chemical properties from intricate LC-MS and GC-MS datasets, thus extending the coverage of EC detection beyond known analytes. Although there are known limitations with data heterogeneity, model generalizability, and interpretability, AI offers an adaptable and scalable solution for furthering environmental informatics and the proactive management of ECs [75].

3.5. Challenges in Detection for Management and Mitigation of ECs

The detection of ECs in environmental matrices is scientifically demanding because of the variability in their physicochemical characteristics and presence at ultra-trace concentrations [59]. Most ECs are polar, thermolabile, and non-volatile, making them incompatible with conventional gas chromatography (GC) methods. While liquid chromatography with tandem mass spectrometry (LC-MS/MS) offers a higher sensitivity and specificity, it is beset by challenges like matrix effects, co-elution, and ion suppression that affect quantitative accuracy and reproducibility [80]. The identification of unknown or transformation products that form during processes of environmental degradation and are not accessed through traditional targeted analysis is another key challenge. Sophisticated meth-

ods such as high-resolution mass spectrometry (HRMS) facilitate suspect and non-target screening, but data processing and compound annotation are still time-consuming and need advanced computational systems. In addition, ECs tend to interact with natural organic matter, sediments, and microbial consortia, which impact their bioavailability, persistence, and sensitivity to detection [81,82]. Their temporal and spatial heterogeneity also makes environmental monitoring and risk assessment even more challenging. The absence of harmonized analytical guidelines, reference materials, and regulatory limits for most ECs hinders cross-comparability and restricts the creation of effective environmental management strategies.

3.5.1. Low Concentration

ECs such as pharmaceuticals, endocrine-disrupting compounds, and personal care products are usually present at ultra-trace concentrations (ng/L to pg/L) in environmental matrices like surface water, ground water, and effluents [83]. Low concentrations make it difficult for conventional detection methods because extremely sensitive and selective analytical tools are required. Techniques like LC-MS/MS and HRMS are used widely to detect and quantify ECs at such trace concentrations. But even this sophisticated equipment is prone to ion suppression, poor recovery, and signal noise, especially for complex samples [84]. The long-term persistence of ECs at low levels can result in chronic toxicity, bioaccumulation, and sub-lethal ecological impacts that are challenging to track without constant, sensitive real-time methods [59]. Therefore, low concentrations not only hinder detection but also make it difficult to assess risk and implement environmental policies, indicating the requirement for sophisticated pre-concentration technologies, sensor miniaturization, and data-enhanced monitoring frameworks.

3.5.2. Complex Matrices

Environmental samples like wastewater, sludge, river sediments, and biological tissues are extremely complex matrices that hamper the precise detection and quantification of ECs [83]. These matrices are composed of a range of dissolved organic matter (DOM), particulate matter, humic substances, and microbial biomass, which can co-elute or interact with analytes and cause matrix effects like ion suppression or enhancement during LC-MS/MS or GC-MS analysis [85]. Some of the physicochemical interactions between ECs and matrix constituents are sorption behavior, mobility, and bioavailability, making it more compactable for environmental fate modeling and risk assessments. Most preferred sample preparation techniques like solid-phase extraction (SPE), QuEChERS, and ultrafiltration are usually required to minimize the matrix interference, but the risk of analyte loss or degradation is high [86]. Matrix complexity requires a time- and resource-consuming process called method validation for many environmental categories. For seasonality, geography, and contamination, the variability of these matrices requires adaptive, matrix-matched calibration procedures and multi-residue analytical procedures, mainly to enhance reliability and comparability in EC monitoring and mitigation.

One of the issues most considered in EC management is the lack of standardized methods for sample preparation, analysis, risk assessment, and regulation compliance [87]. In contrast to traditional pollutants, most ECs do not have compatible analytical guidelines in research laboratories, resulting in data variability, irreproducibility, and non-comparability [88]. The heterogeneity of emerging EC classes, ranging from antibiotics and synthetic hormones to nanomaterials, complicates the establishment of uniform detection limits, standardized sampling rates, and consistent pretreatment procedures. A lack of reference materials and certified standardized protocols for most ECs complicates calibration and quality control in any of the analytical processes [83,89]. Major regula-

tory approaches like the EU water framework directive (WFD) and U.S. EPA contaminant candidate list (CCL) only cover a subset of ECs, and this is identified with more data on toxicology [84]. This can lead to the under-regulation and underreporting of new and less-studied contaminants. Harmonized protocol development is key for designing inter-laboratory studies, international surveillance schemes, and evidence-led policy choices in environmental management.

3.6. Emerging Tools for Real-Time Monitoring

Real-time monitoring technologies have emerged as a linchpin in the management and control of ECs, which encompass pharmaceuticals, personal care products, endocrine-disrupting compounds, and microplastics [5,15,89]. Conventional techniques, though strong, tend to be cumbersome, time-consuming, and unable to reflect temporal variability. The latest innovations in sensor technologies, biosensing platforms, and data analytics now allow for the near-real-time detection and characterization of ECs in intricate environmental matrices like surface water, wastewater, and sediments. Electrochemical biosensors, containing enzymes, antibodies, or aptamers as the recognition element, provide the selective and rapid detection of pollutants like pesticides, antibiotics, and industrial chemicals [69]. They are portable and highly sensitive, making them ideal for field use. Likewise, optical biosensors based on surface plasmon resonance (SPR) or fluorescence permit continuous label-free monitoring with high specificity. Whole-cell biosensors, which are normally genetically engineered microbes, may emit luminescent or fluorescent responses to EC exposure, allowing integrative biological response detection. Integration with Internet of Things (IoT) platforms and wireless sensor networks (WSNs) increases data collection, transmission, and cloud-based analysis, enabling the real-time spatial and temporal mapping of pollution hotspots [54,68,69]. In addition, the integration of sensors with Artificial Intelligence (AI) algorithms enhances predictive ability and enables early warning systems for regulatory action. Lab-on-a-chip (LOC) and microfluidic devices are also being developed, offering miniaturized, multi-analyte detection platforms that minimize sample volume and response time. Despite selectivity-, environmental stability-, and standardization-related challenges, these new tools are transforming environmental monitoring and offering proactive EC risk assessment and mitigation frameworks [23,90].

3.7. Citizen Science

Citizen science involves non-expert participation in environmental observation and sampling using structured protocols and is increasingly recognized as a practical complement to emerging contaminant monitoring [91]. Within a tiered detection framework, citizen-generated data serve as an upstream screening layer, while compound-specific identification and regulatory-grade quantification remain dependent on accredited laboratory analyses such as LC–MS/MS. Citizen efforts can extend spatial and temporal coverage, enable the rapid reporting of episodic events (e.g., suspected discharges, unusual odors, foaming, or algal bloom onset), and supply contextual details on land use, potential sources, and local practices that guide confirmatory sampling [92]. When incorporated into formal workflows, these datasets can fill monitoring gaps and enhance situational awareness, particularly where surveillance resources are limited [93]. Data comparability may suffer from inconsistent sample handling, variable participant adherence, and differing observation practices. Calibration and traceability are persistent challenges, as most low-cost field tools lack compound specificity and are vulnerable to sensor drift and matrix interference, limiting defensible quantification without laboratory confirmation. Sampling bias may result from clustered participation, preferential site selection, or visibility-driven reporting, distorting spatial interpretation. Studies show that data can be fit for purpose when

supported by training and QA/QC procedures, though outputs should be interpreted as indicative rather than regulatory [94]. Best practice calls for standardized protocols, structured metadata, co-located validation, and transparent uncertainty reporting.

3.8. Sensor Networks

Sensor networks in wastewater and receiving waters enable high-frequency measurements that strengthen operational control and environmental surveillance. For ECs, their utility is best interpreted through a tiered framework that distinguishes proxy monitoring from compound-specific detection [95]. Most deployed networks rely on indicators such as UV254 absorbance, fluorescence, turbidity, conductivity, pH, redox potential, dissolved oxygen, temperature, and nutrients [96–98]. These parameters do not quantify individual ECs but can support event detection and trend screening by flagging abnormal influent conditions, overflow or dilution events, and process perturbations that may coincide with elevated EC loads. Because optical and bulk indicators are inherently nonspecific and sensitive to matrix effects, they are most defensible for triggering targeted sampling and prioritizing confirmatory laboratory analyses rather than reporting compound-specific concentrations [99]. Direct or semi-direct sensing approaches, including selective biosensors and field-deployable platforms, aim to enhance specificity for priority compounds or classes [54,68]. Sensor networks and IoT-enabled platforms increasingly provide high-frequency environmental data streams that support operational control and surveillance [74]. However, routine large-scale deployment is constrained by fouling, drift, cross-reactivity, limited analyte panels, and the intensive calibration and validation requirements of complex wastewater matrices. Consequently, direct sensing is best suited for focused applications at high-risk sites and continues to benefit from periodic cross-validation with accredited analytical methods.

3.9. Omics Technologies

Various omics technologies such as genomics, proteomics, and metabolomics are gaining more faces to explore the biological effects of ECs on organisms [100–102]. These systemic methods offer a holistic way of learning about the influence of ECs on biological systems at different levels, ranging from the molecular to the organism level.

3.9.1. Genomics

Genomics plays a major key role in unraveling and reducing the environmental footprint of ECs by providing guidelines for the microbial community's genetic potential and adaptability in process contaminant transformation [100,103]. Using methods like whole-genome sequencing (WGS) and metagenomic study, scientists can identify important functional genes and enzymatic pathways accountable for the biodegradation of pharmaceuticals, endocrine disruptors, and pesticides [103,104]. Genomic information focuses on the characterization of microbial taxa capable of degrading ECs, such as *Pseudomonas*, *Sphingomonas*, and *Deinococcus* species, as well as on estimating contaminant fate under varying environmental conditions [105]. Metagenomics, specifically, performs the investigation of non-culturable microorganisms and horizontal gene transfer routes to account for the spread of many antibiotic resistance genes (ARGs), a significant issue associated with EC pollution [106,107]. Furthermore, genomics facilitates the formation of bioaugmentation and engineered microbial consortia with superior degradation. When combined with bioinformatics and ecological modeling, genomics provides predictive insight for the identification of contamination hotspots and quantification of ecosystem balance. As sequencing becomes increasingly cheaper and scalable, genomics will increasingly enhance evidence-based bioremediation strategies and total risk assessment for the environment.

3.9.2. Proteomics

Proteomics provides clear insights into functional organismic and microbial community response to ECs like pharmaceuticals, pesticides, and endocrine-disrupting chemicals [100,108]. Through a systemic examination of the complete protein complement (proteome) produced under various activities such as contaminant stress, proteomics leads to the discovery of biomarker proteins, stress-response enzymes, and biodegradation-associated pathways [80]. Emerging methods such as two-dimensional gel electrophoresis (2-DE) and liquid chromatography–tandem mass spectrometry (LC-MS/MS) allow for the differential expression profiling of proteins in organisms such as *Pseudomonas putida* or *Escherichia coli* treated with ECs to check toxicity and adaptive response [109]. Functional proteomics also provides the identification of new enzymes such as laccases, monooxygenases, and peroxidases that are inculcated in the biotransformation of recalcitrant ECs and are much more valuable candidates for bioaugmentation and biocatalytic remediation approaches [103,110]. Proteomics also assists in ecotoxicological analysis, closing mechanisms through which ECs affect cellular metabolism, redox homeostasis, and signal transduction. When performed with genomics and metabolomics, proteomics improves systems-level response understanding, informing the design of sustainable mitigation models [111].

3.9.3. Transcriptomics

Transcriptomics provides a comprehensive window into how organisms recalibrate gene expression when they encounter emerging contaminants, including pharmaceuticals, personal care products, and endocrine-disrupting chemicals [112]. By leveraging RNA sequencing (RNA seq) and microarray analysis, researchers can pinpoint differentially expressed genes that signal exposure, cellular stress responses, and the activation of detoxification pathways in exposed organisms [113]. These datasets illuminate molecular toxicology in practice, clarifying how contaminants disrupt signaling cascades, tip redox balance toward oxidative stress, alter xenobiotic metabolism, and interfere with endocrine regulation across species and biological scales [114]. In aquatic ecotoxicology, established models such as *Danio rerio* (zebrafish) and *Daphnia magna* are widely used to track transcriptional shifts following exposure; hallmark responses include elevated cytochrome P450 enzymes and heat shock proteins, which together indicate metabolic activation and mounting cellular stress [115]. Beyond diagnosis, transcriptomic profiles accelerate biomarker discovery, inform dose response modeling, and strengthen quantitative risk assessment frameworks that guide regulatory decision-making and remediation priorities [116]. When integrated with proteomics and metabolomics, transcriptomics anchors a systems biology approach, linking gene level changes to protein activities and metabolite fluxes, and ultimately to phenotypic outcomes and ecosystem-level effects [117].

3.10. Mitigation of Arising Contaminants

Proper wastewater and solid waste management is important in curbing the dissemination of adulterants into the environment and blocking their intrusion into food, water, and the larger ecosystem [118]. Unsound waste handling procedures are one of the main drivers of contamination, which may lead to long-term damage to human health and biodiversity [119]. The rollout of strategic waste management systems is therefore a key measure to curb adulterant-generated threats. Wastewater management entails the collection, treatment, and proper disposal or reuse of water that has been contaminated due to industrial, agricultural, or domestic processes [120]. Most industries release untreated or partially treated effluents into water bodies directly, adding heavy metals, synthetic dyes, and pharmaceutical residues that can subsequently contaminate drinking water or be utilized for irrigation [121]. For this purpose, effluent treatment plants (ETPs) and

sewage treatment plants (STPs) are currently outfitted with sophisticated technologies such as membrane filtration, activated carbon adsorption, and UV disinfection to eliminate chemical and biological contaminants [97]. Zero liquid discharge (ZLD) systems are gaining importance in industries such as textiles, pharmaceuticals, and food processing. These systems recycle all water used in manufacturing, ensuring that no contaminated water is released into the environment [122]. Additionally, decentralized wastewater treatment systems (DEWATSs) are being adopted in rural and semi-urban areas to treat wastewater close to its source, minimizing environmental damage and improving local sanitation [123]. However, solid waste management emphasizes the segregation, collection, treatment, and disposal of waste. Inadequately disposed packaging waste, out-of-date products, and industrial waste can lead to adulterants in the soil and water [124]. An adherence to stringent waste sorting protocols for biodegradable, recyclable, and hazardous fractions helps reduce cross contamination [125]. Technologies such as composting, biogas production, and waste-to-energy plants provide environmentally friendly options for organic waste disposal while minimizing adulteration. Chemical industry hazardous waste is treated through incineration or safe landfill disposal under strict regulation to avoid leaching into ground or nearby water [126]. Public awareness and community involvement are equally important. Encouraging households and businesses to follow proper disposal practices, reduce plastic use, and participate in recycling initiatives helps build a sustainable system [82].

Nature-based solutions (NBSs) provide sustainable, low-impact pathways to prevent adulteration and remediate contamination, aligning human health goals with ecological resilience [127]. Bioremediation harnesses microorganisms, fungi, and plants to degrade or sequester pollutants in soil, water, and food matrices; certain bacteria break down pesticide residues and solvents, while plants such as vetiver grass can accumulate heavy metals from contaminated water, reducing exposure at the source and lowering downstream treatment burdens [128]. Phytoremediation is particularly attractive for rural and peri-urban settings because it is cost-effective, scalable, and minimally disruptive to local ecosystems [129]. In parallel, natural antimicrobials and preservatives derived from plants offer safer alternatives to synthetic additives sometimes implicated in adulteration [130]. Essential oils from clove, cinnamon, and oregano, along with neem extracts and curcumin, can inhibit spoilage and enhance food safety without introducing toxic residues [131]. Traditional preservation methods including fermentation, solar drying, and smoking extend shelf life and reduce the reliance on chemical preservatives; supporting small-scale producers to adopt and refine these practices improves product integrity while preserving culinary heritage [132]. On the production side, agroecological approaches limit contamination pathways by minimizing synthetic inputs and emphasizing soil health [133]. Organic farming, crop rotation, companion planting, and biological pest control reduce the need for chemical interventions that may elevate adulterant risks, while also improving biodiversity and long-term productivity [134]. For water quality, constructed wetlands and vegetated buffers filter contaminants through plant–microbe interactions, removing heavy metals, pathogens, and nutrients in low-maintenance systems suited for diverse climates and land uses [135]. Microalgae-based wastewater treatment (phyco-remediation) is also emerging as a nature-based option for the simultaneous removal of nutrients and selected ECs, with co-benefits such as biomass generation for downstream valorization [136]. Community stewardship also matters, planting and maintaining trees, grasslands, and riparian buffers reduces airborne and waterborne pollutant loads by trapping dust, particulates, and microplastics before they reach homes, fields, and waterways [137]. Together, these nature-grounded strategies complement technological and regulatory measures, offering a portfolio of solutions that are adaptable, equitable, and durable across varied environmental and economic contexts.

To strengthen the integrated-management perspective without expanding length substantially, this section provides a compact, feasibility-oriented comparison of representative chemical (ozonation/advanced oxidation processes, AOPs), physical (adsorption and membranes), and biological (post-treatment/nature-based) options for EC control. Chemical oxidation can achieve broad micropollutant abatement but typically requires post-treatment and the careful management of transformation by-products [138–140]. Adsorption polishing (e.g., powdered activated carbon, PAC) is widely deployable but is strongly influenced by bulk organic matter competition and carbon consumption, making operational expenditure (OPEX) site-specific [141]. Membrane trains (nanofiltration/reverse osmosis; NF/RO) provide a strong separation for many ECs, yet the feasibility bottleneck often becomes concentrate management (Table 3). Overall, the most implementable solutions are usually integrated treatment trains, and transparent criteria-based selection helps align performance with cost and sustainability targets.

Table 3. Compact comparative assessment of EC mitigation options: feasibility, burden, and key constraints.

Process Class (Typical Role)	EC Control Potential	Implementation Feasibility	Relative Burden	Key Limitations	References
Ozonation/AOP + post-treatment (tertiary polishing)	High	High	High (energy/chemicals; by-products)	Transformation by-products; requires post-treatment and monitoring	[138,140]
Powdered activated carbon (PAC) (polishing/capture)	Medium–high	High	Medium–high (carbon demand; sludge handling)	Competition from background dissolved organic matter; media consumption/regeneration	[141]
NF/RO membranes (separation for reuse)	High	Medium–high	High (energy; concentrate handling)	Concentrate/brine management can dominate feasibility and cost	[141,142]
Biological polishing (biofiltration/post-treatment)	Low–medium	High	Low–medium	Compound-specific and matrix-dependent performance; best as complementary barrier	[140,142]
Criteria-based selection of treatment trains	—	High	Low	Requires local data and transparent criteria; improves fit-to-context	[142]

To demonstrate the advantages of an integrated process approach for sustainable ECs mitigation, we propose a concise decision algorithm that links monitoring to management actions in an adaptive loop (Figure 3). The pathway begins with defining compliance/reuse objectives, followed by Tier-1 screening using high-frequency indicator data to flag hotspots and Tier-2 confirmatory analysis (targeted LC–MS/MS and/or HRMS) to identify priority ECs and relevant transformation products. A local priority watch list is then developed through risk-based ranking, after which upstream prevention measures are implemented where feasible (e.g., discharge control, pretreatment, stewardship/substitution). The remaining risks are addressed through the selection of a multi-barrier treatment train (biological core plus targeted polishing such as adsorption, AOP/ozonation, and/or membranes) based on feasibility, resource demand, and residual/by-product handling. Performance is verified, and the system is iteratively updated by adjusting operations or retrofitting processes as EC profiles and regulatory needs evolve.

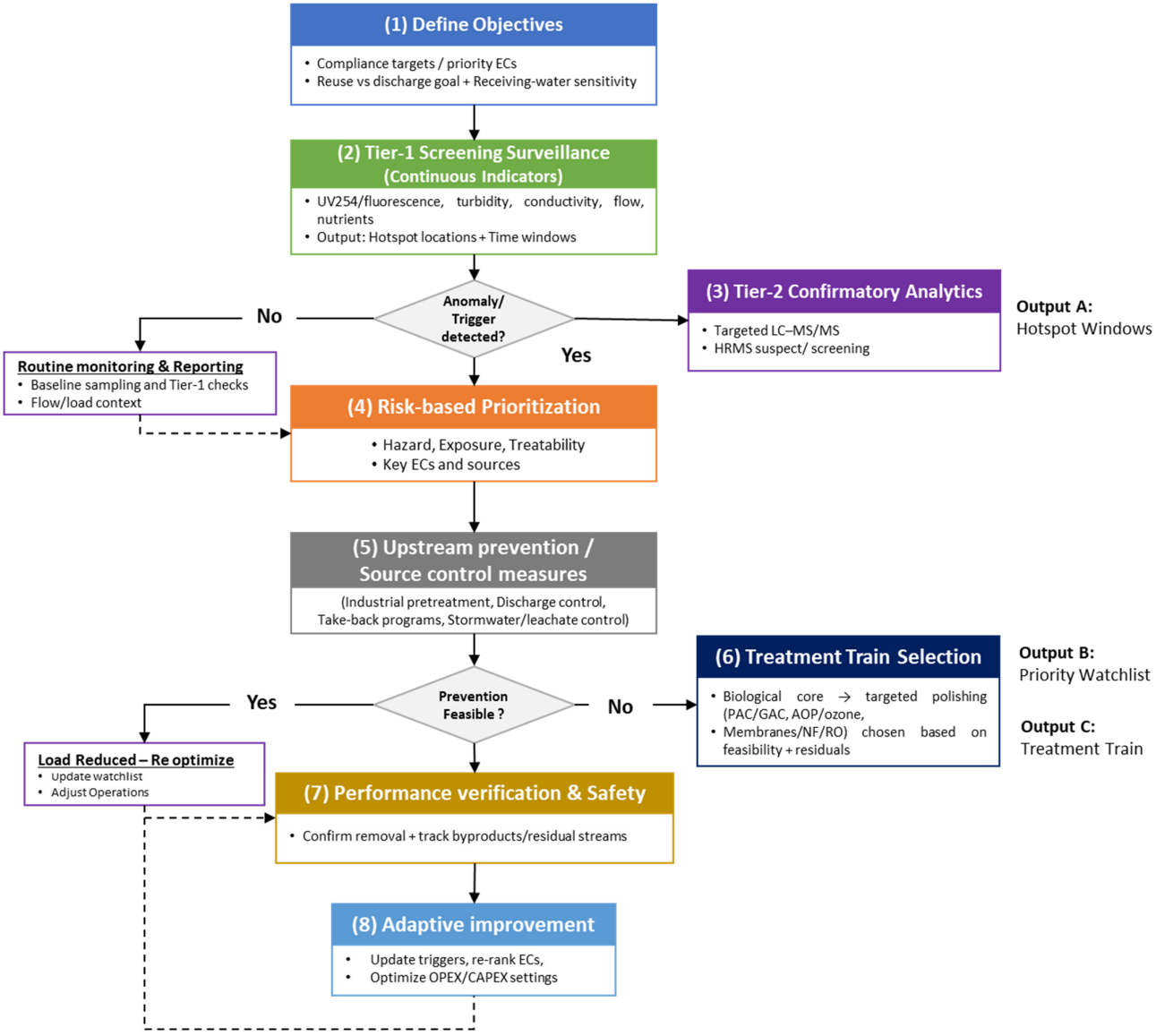


Figure 3. Proposed integrated adaptive management algorithm for EC mitigation in wastewater.

4. Future Directions

The future management of ECs will require multi-faceted integrative approaches that consider ECs' complexity, substance variety, and volume overloads. Next-generation systems would be feasible with a hybrid combination of engineering approaches and nature-based solutions that address a broad spectrum of contaminants. Emerging technologies, including catalytic- and nanomaterial-based processes, hold promise but must be assessed carefully for long-term safety and environmental compatibility. Artificial Intelligence and machine learning tools for coordinating advanced and real-time detection systems could add future dimensions by addressing EC problems. This would be reflected by allowing the contaminants to be identified more quickly and accurately, while providing enhanced capability, supporting timely interventions, and enabling better-informed management decisions. Portable sensor systems with targeted specificity and continuous monitoring networks could further improve the ability to track contaminants across different environmental media and respond before they reach critical levels. Sustainable solutions for ECs must balance technical feasibility, energy balance and economics to gain real-world traction while providing specific mitigation strategies to achieve broader regional and global goals. Citizen science through an outreach education program could shift behavior

toward safer disposal practices and an adaption to environmentally safer alternatives. The emphasis could reflect a sequential flow of prevention, technological innovation, and strong, coordinated policy-making, providing significant and precise problem-oriented solutions. The scientific understanding of ECs is advancing faster than the development of consistent, enforceable policy and regulations. A global coordinated framework is essential for portraying transparency, reflecting the nature of EC pollution, and prioritizing their management. The overarching aim is a proactive, integrated, and globally coordinated approach that embeds sustainability across a chemical's life cycle from design and production through use and end-of-life management. Aligning innovation with effective governance, enabling cross-sector collaboration, and centering the public in the process can substantially lower the risks from ECs and protect ecosystems and human health for the long term.

5. Concluding Recommendations

Future management strategies should prioritize the advancement and deployment of high-resolution analytical platforms, continuous environmental monitoring networks, and AI-assisted data analytics to enable early detection and predictive responses. Remediation approaches must integrate advanced engineered processes with nature-based solutions to maximize removal efficiency, while ensuring ecological sustainability. Strengthening governance through harmonized international standards, enforceable regulations, and extended producer responsibility will be essential for reducing emissions at the source. Targeted capacity building in resource-limited regions will further promote equitable global protection. To achieve lasting progress, multi-disciplinary collaboration among scientists, policy-makers, industry, and communities is imperative to co-design context-specific mitigation measures. Public engagement, supported by environmental education and citizen science initiatives, can foster behavioral changes such as responsible waste disposal and the adoption of sustainable products. Collectively, these interventions offer a pathway to significantly reduce the risks of emerging contaminants and safeguard environmental and human health for future generations. Sustainable mitigation should use integrated treatment trains and biological core treatment, followed by targeted polishing (adsorption/membranes/AOPs) aligned with reuse/discharge goals. Standardized monitoring and coordinated governance are needed to scale prevention-oriented EC management.

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