



Review Article

Emerging Analytical Techniques for Detection of Environmental Pollutants: A Review

Phanindra Erukulla¹, Pericharla Venkata Narasimha Raju², Konatham Teja Kumar Reddy^{3*}, Venkata Ramana Singamaneni⁴, Ashutosh Pathak⁵, Sunil Kumar Yadav⁶, M. Sandeep Kumar⁷, Abdul Ajeed Mohathasim Billah^{7*}

¹ Department of Regulatory Affairs, Ricon Pharma LLC, 100 Ford Rd, Suite #9, Denville, NJ 07834, United States

² Department of Regulatory Affairs, Hikma Pharmaceuticals USA Inc., 2 Esterbrook Lane, Cherry Hill, NJ 08003, United States

³ Department of Pharmaceutical Analysis, Malla Reddy Institute of Pharmaceutical Sciences, Malla Reddy Vishwavidyapeeth (Deemed to be University), Secunderabad, 500100, Telangana, India

⁴ Department of Analytical Research and Development, Cambrex, Charles City, Iowa- 50616, United States

⁵ Department of Pharmacy Practice, Teerthanker Mahaveer College of Pharmacy, Teerthanker Mahaveer University, Moradabad, U.P. 244001, India

⁶ Department of Chemistry, SRM Institute of Science and Technology, Delhi-NCR Campus, Modinagar, Ghaziabad 201204, Uttar Pradesh, India

⁷ Department of BBA, Koneru Lakshmaiah Education Foundation, Green Fields, Vaddeswaram, Guntur, Andhra Pradesh 522 502, India

⁸ Department of Pharmacy Practice, Sri Ramachandra Faculty of Pharmacy, Sri Ramachandra Institute of Higher Education and Research, Deemed to be University, Porur, Chennai - 600116, Tamil Nadu, India

ARTICLE INFO

Article history

Submitted: 2025-11-20

Revised: 2025-12-19

Accepted: 2025-12-30

ID: AJCA-2511-1973

DOI: [10.48309/AJCA.2026.561017.1973](https://doi.org/10.48309/AJCA.2026.561017.1973)

KEYWORDS

Environmental pollutants

Analytical techniques

Nanomaterial-based sensors

Spectroscopy

Microfluidics

Machine learning

ABSTRACT

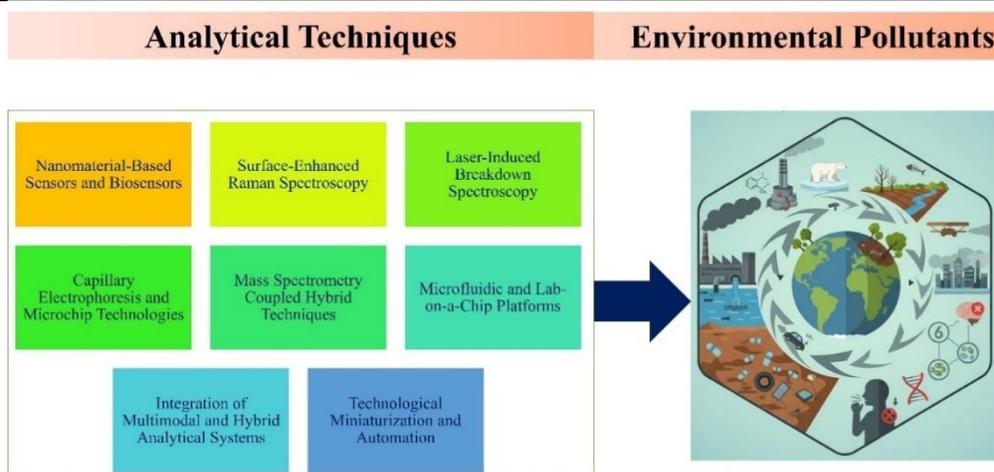
Environmental pollution is one of the most challenging issues for the sustainability of our planet, human health, and ecosystem integrity. Increasing evidence of the release of organic, inorganic, and emerging contaminants necessitates measures for more accurate, rapid, and inexpensive techniques for contamination detection. Although traditional analytical methodologies yield reliable results, they are often hampered by time-consuming sample preparation, high operational costs, and low applicability in the field. Recent developments in analytical science have provided a host of innovative technologies that can overcome these limitations. This review provides a thorough examination of emerging analytical techniques for the detection of pollutants in the environment, including nanomaterial-based sensors, surface-enhanced Raman spectroscopy (SERS), laser-induced breakdown spectroscopy (LIBS), and mass spectrometry-coupled hybrid systems GC-GC-MS and LC-MS/MS. Portable applications have also been developed by integrating microfluidic and lab-on-a-chip devices for convenient real-time analysis. Finally, the inclusion of machine learning (ML) and artificial intelligence (AI) algorithms has dramatically changed the data interpretation process to include predictive modeling and automated environmental monitoring. There is also an emphasis on environmentally friendly and sustainable analytical techniques, including miniaturized, solvent-free, and bioanalytical procedures, that conform to green chemistry guidelines. Despite these achievements, there are significant obstacles in terms of standardization, analytical performance, and scalability. The objectives of this review are to discuss the present advancements, address the identified limitations, and offer future research strategies on smart, integrated, and sustainable analytical methodologies for the rapid detection and management of environmental contaminants.

* Corresponding author: Kumar Reddy, Konatham Teja; Mohathasim Billah, Abdul Ajeed

✉ E-mail: tejakumarreddy.konatham@mrvv.edu.in; billahs@yahoo.co.uk

© 2026 by SPC (Sami Publishing Company)

GRAPHICAL ABSTRACT



Introduction

Environmental pollution has become one of the most significant global threats in the 21st century, placing the health of ecosystems, biodiversity, and human populations at risk. Rapid industrialization, urbanization, and agricultural intensification have resulted in unprecedented levels of diverse pollutants entering air, water, and soil systems. Pollution can occur from human and primary biological sources, manifesting as heavy metals, polycyclic aromatic hydrocarbons (PAHs), pharmaceuticals, and microplastics among other modern contaminants. Pollution is often characterized by persistence, bioaccumulation, or toxicity, which may occur at very low concentrations, making its detection, quantification, and monitoring key aspects of modern environmental science [1]. The ability to accurately monitor the level of pollutants represents not only the critical foundation for any environmental risk assessment, but also provides a scientific basis for establishing mitigation or regulatory policies. Analytical chemistry plays an essential role in the methods used to provide environmental safety through developing sensitive, selective, and rapid detection methodologies [2]. Environmental pollution is characterized by the release of toxic chemical,

physical, and biological substances into the natural environment, causing problems for human beings, other living organisms, and natural resources. Human activities, including burning fossil fuels, mining, industrial discharge, agricultural runoff, and dumping waste, are major contributors to air, water, and soil pollution. Global reports to organizations such as the United Nations environment programme (UNEP) and the world health organization (WHO) indicate a worrying increase in the concentrations of pollutants across different compartments of the environment. For example, approximately 9 million people die prematurely each year from pollution-related causes, representing one of the greatest global health challenges [3]. Pollution has broad implications for human health. It affects aquatic and terrestrial ecosystems, disrupts nutrient cycling, and results in biodiversity loss. The transboundary nature of many pollutants, especially persistent organic pollutants (POPs) and microplastics, has made pollution a global problem that requires international cooperation and sophisticated monitoring approaches. Climate change further complicates this concern because pollution processes increasingly rely on climate-dependent drivers that influence pollutant distribution, transformation, and

toxicity, resulting in complex interdependencies [4]. Consequently, accurate detection and ongoing monitoring of pollutants are crucial to achieving sustainable development goals (SDGs), especially those related to clean water and sanitation (SDG 6), climate action (SDG 13), and life underwater on land (SDG 14 and 15). Nonetheless, the current pollution scenarios are complex and require analytical methods capable of addressing multiple matrices, low analyte levels, and complex chemical interactions [2]. Pollutants can be broadly categorized into three groups based on their chemical nature, source, or persistence: organic, inorganic, and persistent. Organic pollutants include pesticides, polychlorinated biphenyls (PCBs), PAHs, dyes, and pharmaceutical residues. These compounds are generally carbon-based, and can persist in the environment for long periods, bioaccumulate, and exhibit mutagenic properties. Inorganic pollutants include heavy metals (*e.g.*, lead, mercury, cadmium, and arsenic), nitrates, phosphates, and fluoride ions that frequently originate from industrial effluents, mining operations, and agricultural additions [5]. A relatively new class of contaminants, known as emerging contaminants of concern (ECCs), includes substances such as personal care products, endocrine disruptors, perfluorinated compounds, and nanomaterials. Often, these compounds are not considered contaminants or are rarely monitored because they are relatively new and challenging contaminants to detect. Micro- and nanoplastics are another class of pollutants, and much attention has been paid to them because of their pervasiveness and risk of lasting environmental impacts. Microplastics are microscopic products of large plastic items that break down or smaller-sized materials that are intentionally manufactured for industrial use [6]. Each class of pollutant poses unique analytical issues. For example, organic compounds are challenging to analyze because they are often insoluble in water and present at trace levels. Generally, organic compounds require extraction

and precision for both quantitative and qualitative confirmation. Inorganics pose challenges for quantification, and therefore, speciation. Microplastics and nanoplastics require complementary approaches that combine spectroscopy, microscopy, and thermal analysis to determine the morphology and size distribution of the polymers or fibers. Therefore, these unique classes of pollutants create a need for suites of analytical approaches that can characterize each contaminant type, as well as pollutant diversity [7]. The techniques included in this review were selected based on their recent advancements in environmental analytical research, growing adoption in contemporary monitoring studies, and their demonstrated potential to overcome the limitations of traditional methods. This review also differs from the existing literature in that it provides an integrated perspective that combines emerging analytical technologies with machine learning-driven data interpretation, green and sustainable analytical approaches, and smart sensing systems. By synthesizing these domains, this review offers a comprehensive framework that reflects the future direction of environmental pollutant detection, beyond traditional technique-specific discussions.

Necessity of advanced analytical techniques

The correct identification of environmental contaminants is more than a research focus; it matters to health policies, industry regulations, and ecosystem restoration. Traditional environmental monitoring methods are usually trustworthy, but do not possess sufficient sensitivity and selectivity to identify new pollutants and contaminants in ultra-trace amounts. There is still a key analytical challenge when working with environmental samples due to their complexity, which includes a blend of organic compounds, inorganic ions, and particulates that commonly interfere with

detection limits. Thus, sufficient analytical innovations are needed to eliminate matrix effects, minimize detection limits, and support rapid field analysis [8]. New analytical techniques are based on recent developments and innovations in nanotechnology, spectrometry, electrochemistry, and data analysis technologies for improved performance. For example, nanomaterial-based sensors have exceptional sensitivity due to the high surface-to-volume ratio of the nanostructures, resulting in the detection of pollutants at the picomolar level.

Similarly, Surface-Enhanced Raman Spectroscopy (SERS) takes advantage of the plasmonic properties of metallic nanostructures to enhance Raman signals by several orders of magnitude, allowing users to detect molecular fingerprints at low concentrations [9]. Hybrid technologies based on mass spectrometry (MS), such as gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-tandem mass spectrometry (LC-MS/MS), have revolutionized pollutant analysis by enabling accurate qualitative and quantitative determinations. Microfluidic and lab-on-a-chip systems are advancing the field of portable environmental monitoring by enabling real-time detection with minimal reagent consumption and waste production [10]. Moreover, the use of machine learning (ML) and artificial intelligence (AI) with analytical devices has changed data interpretation and pattern recognition. These computational analytical methodologies can analyze large datasets, identify complex pollutant signatures, and predict contamination trends for smarter and more adaptive environmental monitoring systems as the intersection of analytical chemistry, materials science, and computational intelligence evolves the future of environmental pollutant detection [11].

Limitations of conventional detection methods

Although considerable advances have been made, conventional analytical techniques such as atomic absorption spectroscopy (AAS), UV-Vis spectrophotometry, and gas/liquid chromatography have intrinsic limitations in meeting the ever-growing analytical demands. These approaches usually require timely, labor-intensive preparation of samples and the use of hazardous solvents or interventions, with the necessary aspect of portability hypertrophying the in-field area or the needs of the client. Furthermore, they are typically prescriptive in their design for analyte detection for target analysis and may not detect unknown pollutants or pollutants with similar structures unless the analyte is known beforehand [12]. For example, chromatography-based approaches are strong for separating complex mixtures, but because of the time-consuming nature of the laborious extraction and pre-concentration steps, analyte loss and contamination are possible. Spectroscopic approaches often encounter limitations in terms of detection limits and interference from sample matrices. Electrochemical methodologies, although very promising, sometimes face electrode fouling or poor reproducibility [13]. Another major limitation was the concurrent detection of multiple pollutants. Field environmental samples typically exhibit heterogeneous mixtures of pollutants at various concentrations. Standard procedures traditionally involve assaying one or a few analytes at a time, which is inadequate for a full environmental assessment. Moreover, many traditional methods may depend on a centralized lab infrastructure that is not suitable for real-time environmental monitoring [14]. These methods may also raise concerns regarding sustainability given the economic and environmental costs associated with their use.

Analytical workflows that require large volumes of toxic solvents or create significant waste are contradict the call for better solutions under the green chemistry movement. Future solutions for environmental monitoring must provide more sustainable and cost-effective analytical systems for use at both larger and smaller scales. Novel approaches are also emerging, such as using solvent-free extraction methods, microfluidic devices, and biosensing tools, to address the challenge of delivering quick, sensitive, and environmentally appropriate methods [15].

Evolution toward next-generation detection technologies

The development of environmental analytical chemistry has been motivated by the dual objectives of improved analytical capabilities and sustainability. The 21st century has witnessed a shift from traditional bulk-scale instrumentation to miniaturized, integrated, and automated systems. Developments in materials science, nanomaterials, polymers and hybrid composites, photonics, and microfabrication technologies have facilitated this transition [16]. Nanotechnology has also introduced new sensing mechanisms and has enhanced transduction efficiency. More specifically, there is a growing trend toward incorporating metal nanoparticles, carbon nanotubes, quantum dots, and graphene-based nanomaterials into sensors for ultrahigh sensitivity and selectivity. The surface chemistry associated with these nanomaterials allows for the immobilization of biorecognition elements, such as enzymes, antibodies, and DNA probes for highly specific pollutant detection [17]. Simultaneously, using a combination of techniques or hybrid (or hyphenated) approaches has substantially enhanced the ability to identify and, in some cases, quantify more complex pollutants (*i.e.*, multimedia and multi-compound pollutants). For instance, the use of techniques such as GC-MS, LC-MS/MS, and ICP-MS

(inductively coupled plasma-mass spectrometry) offers exceptionally strong multi-element and multi-compound analysis capability. Other techniques, such as Laser-Induced Breakdown Spectroscopy (LIBS) and SERS, are no longer emerging methods and are now vital for rapid and non-destructive detection [18]. The introduction of microfluidic and lab-on-a-chip systems is another important advancement. These platforms integrate multiple analytical steps (sample collection, separation, reaction, and detection) within a single miniaturized platform that aids both the analysis and sample throughput. These systems significantly decrease both reagent consumption and waste, complying with the principles of green analytical chemistry (GAC). Additionally, when combined with wireless data transmission and internet of things (IoT) technologies, these systems allow real-time network environmental monitoring [19].

Integration of digital and smart analytical systems

A newly emerging mainstay in environmental assessment is the merger of digital technologies with analytical instruments. The combination of AI, ML, and big data analytics with sensing systems enables intelligent data processing, noise reduction, and predictive modeling. Smart analytical systems can now autonomously recognize abnormal pollutant behaviors, optimize calibration suggestions, and predict future contamination based on environmental electronics trends [20]. Using ML, algorithms can classify spectroscopic data to differentiate between pollution types with indistinguishable spectral signatures. AI predictive models are utilized to simulate pollution dispersal patterns and to enact pre-emptive methods for pollution control. This creates interoperability between IoT and cloud-based systems by allowing near real-time availability of data from multiple monitoring networks to enable quick data-informed actions by environmental authorities [21]. This

represents a change from reactive to pre-environmental management, where analytical systems both identify pollution and predict or prevent its escalation. However, executing these systems comes with the challenge of harmonizing the proposed data formats, securing communication standards, and developing cooperation toward multidisciplinary approaches across programs [22].

Toward Sustainable and green analytical chemistry (GAC)

Sustainability is becoming an essential element in the development of analytical disciplines. GAC reduces the environmental detriment in every aspect of the analytical process, minimizing the use of solvents, energy, and waste generation. GAC is characterized by solid-phase microextraction (SPME), dispersive liquid-liquid microextraction (DLLME), and microwave-assisted extraction (MAE), which are leading the green movement in analytical sciences to minimize analytical use and maximize the added benefits of reducing the environmental impact [23]. The use of bioanalytical systems has been demonstrated in enzyme-based assays, microbial biosensors, and immunoassays, which utilize biodegradable, non-toxic, and renewable chemicals instead of traditional chemical reagents. Many bioanalytical systems operate under mild conditions and are, therefore, ideal for ongoing environmental monitoring. Implementing additional criteria (or methodologies), such as pairing green methods with portable devices for field measures and assessing the analytical process as a tool to reduce laboratory measures [24].

In addition to sustainability defined in terms of broader societal environmental protection agendas, sustainable analytical chemistry also supports industries and regulatory authorities through local compliance within global

sustainable frameworks. Therefore, GAC paired with innovative methodologies is the way of the future for environments and denigration of the analytical process when selecting out the chemicals [25].

Types of Environmental Pollutants and their Impact

Environmental pollutants exist as unique and diverse chemical, physical, and biological materials released into the environment by natural and human activities. Environmental pollutants may occur in air, water, and soil ecosystems, disrupt the ecological balance, and present extreme potential for harm to humans and animals. The complexity of environmental pollution reflects the diversity of its contaminants, including organic and inorganic materials, micro- and nanoplastics, and emerging contaminants, all of which have differing physicochemical properties, ecological behaviors, and toxicological risks. Understanding the impacts of pollutants on ecosystems is critical for developing new and improved analytical methods that can detect, quantify, and monitor environmental contaminants across different environmental matrices [26]. Pollutants include, but are not limited to, organic pollutants, inorganic pollutants, micro- and nanoplastics, and ECCs (Table 1). An overview of these major pollutant categories may reveal their ecological and toxicological impacts. As shown in Figure 1, each pollutant category demonstrates how pollutants enter ecosystems and disrupt biological systems, thereby contributing to long-term ecohealth and human health concerns. Figure 1 also depicts the overall toxicological and ecological considerations as ecological and human health concerns increase, and climate change advances the need for sustainable pollutant control and remediation.

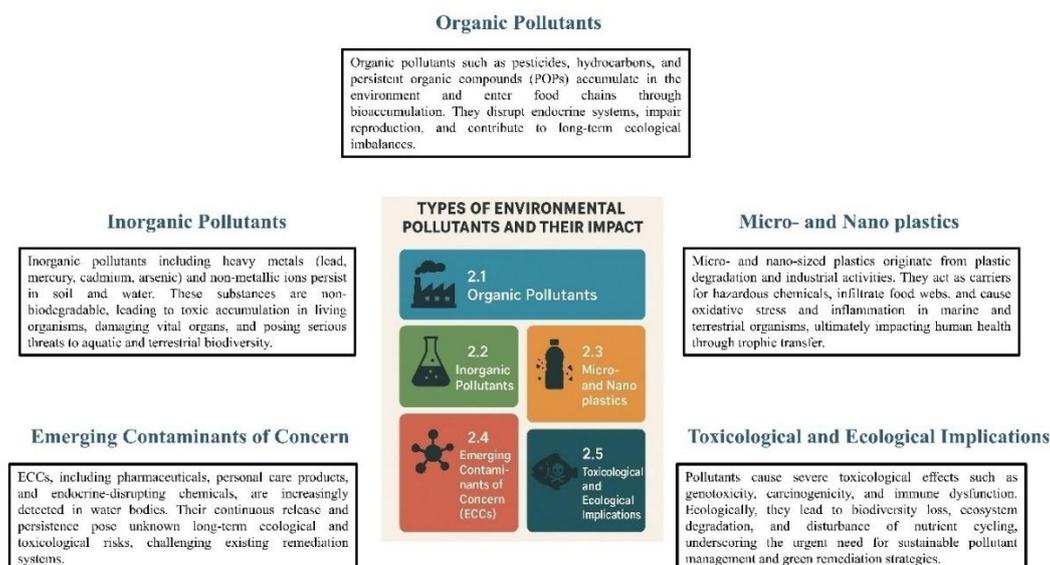


Figure 1. Types of environmental pollutants and their associated impacts [26]

Table 1. Types of environmental pollutants and their impact

Type of pollutant	Sources	Environmental impact	Human health & ecological implications	Ref.
Organic pollutants	Pesticides, industrial chemicals, petroleum hydrocarbons, dyes, and pharmaceuticals	Persistent contamination of soil and water; Bioaccumulation in food chain	Endocrine disruption, carcinogenicity, reproductive toxicity, and ecosystem imbalance	[27]
Inorganic pollutants	Heavy metals (Hg, As, Pb, and Cd), nitrates, phosphates, and acids	Long-term soil and water toxicity; and alteration of pH;	Neurotoxicity, organ failure, developmental issues, and eutrophication in	[28]
Micro- and nanoplastics	Plastic degradation, synthetic textiles, cosmetics, and packaging waste	Ubiquitous distribution; long-term persistence; and transport of adsorbed toxins	Oxidative stress, inflammation, cellular toxicity, and ingestion by aquatic organisms disrupting food webs	[29]
ECCs	Pharmaceuticals, personal care products, pfas, hormones, and nanomaterials	Difficult to degrade; unknown long-term fate; and increasing environmental loads	Antibiotic resistance, endocrine disruption, chronic toxicity, and unknown synergistic effects	[30]

Toxicological and ecological implications	Combined impact of all pollutant classes	Habitat degradation, biodiversity loss, and reduced ecosystem resilience	Multi-organ toxicity, immune suppression, increased disease susceptibility, and ecosystem collapse risk	[31]
--	--	--	---	------

Organic pollutants

Organic pollutants are among the most important environmental contaminants in the world. They include a wide range of chemicals, such as PAHs, pesticides, pharmaceuticals, personal care products (PPCPs), volatile organic compounds (VOCs), and industrial solvents. Many of these compounds are hydrophobic, chemically stable, and persist in the environment, leading to bioaccumulation and biomagnification in the food chain [32]. PAHs are primarily produced from the incomplete combustion of organic matter, fossil fuels, and biomass. These sources include, but are not limited to, vehicle exhaust, industrial emissions, coal tar, and cigarette smoke. PAHs are highly lipophilic and accumulate in the sediments and biota. Some compounds, such as benzo[a]pyrene, are well-documented carcinogens and mutagens that induce oxidative stress and DNA damage in living organisms. The persistence of these compounds in the environment and their low biodegradability means that a sensitive detection method, such as GC-MS or SERS, is necessary [33]. Agricultural practices have resulted in extensive use of organophosphates, organochlorines, carbamates, and pyrethroids. These compounds are critical for safeguarding crops, yet they remain persistent and toxic to the environment. Organochlorine pesticides, such as DDT, aldrin, and dieldrin, are particularly infamous for their tendency to degrade slowly and bioaccumulate in marine and terrestrial food webs. Chronic exposure is associated with endocrine disruption, reproductive toxicity, and neurotoxicity. Pesticide residues are often detected in soils, groundwater, and atmospheric particulates, suggesting that

they are dispersed globally [34]. Pharmaceuticals, such as analgesics, hormones, and antibiotics, enter aquatic systems through excretion into water, insufficient disposal and flushing of unused pharmaceuticals, and effluents from wastewater treatment plants. Many pharmacologically active compounds resist conventional water treatment processes, leading to low-level contamination of the surface and drinking water. Routine exposure to and release of antibiotics are driving the evolution of antibiotic-resistant bacteria, which presents a significant public health issue. In addition, hormones such as ethinylestradiol can be considered endocrine disrupting compounds (EDCs) and will affect reproductive behavior in aquatic organisms at nanogram levels and perhaps even lower [35]. VOCs (volatile organic compounds) such as benzene, toluene, and formaldehyde are important contributors to air quality degradation and ground-level ozone. Chronic inhalation exposure has been linked to adverse health effects, including respiratory and neurological illnesses, as well as cancer. Semi-volatile compounds such as phthalates and flame retardants are present in both indoor and outdoor environments and can accumulate in dust and human tissues. Emerging analytical detection techniques utilizing high-performance liquid chromatography (HPLC) and GC-MS have become important tools for monitoring the trace levels of these pollutants [36].

Inorganic pollutants

Inorganic pollutants, particularly heavy metals, metalloids, and inorganic ions, represent another significant class of contaminants with negative effects on environmental and human health. In

contrast to organic pollutants, metals do not biodegrade and can persist in ecosystems for centuries while continuing to cycle through different environmental compartments. Elements such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) enter the environment through industrial discharge, mining, smelting, fertilizers, and wastewater effluents. Heavy metals accumulate in sediments, plants, and animal tissues and cause chronic toxicity. For example, lead causes neurological and developmental problems in children, cadmium causes renal dysfunction, and mercury affects the functioning of the central nervous system. Arsenic-contaminated groundwater, particularly in South and Southeast Asia, has become a global public health emergency, leading to skin lesions and cancers. Chromium (VI) is another metal known to be a carcinogen that is typically found in areas near the tannery and electroplating industries. Analyzing the presence of these metals requires the use of highly sensitive analytical techniques (e.g., such as ICP-MS, AAS, and X-ray fluorescence (XRF) [37]. Agricultural runoff, which contains nitrogen fertilizers and animal wastes, results in nitrate contamination of the surface and groundwater. High levels of nitrate in drinking water can result in methemoglobinemia, or "blue baby syndrome," in infants, and is also linked with some gastrointestinal cancers. In aquatic ecosystems, elevated nitrate and phosphate levels can cause eutrophication or excessive algal growth, which depletes oxygen and disrupts aquatic biodiversity. The measurement of nitrate concentrations in water bodies through either UV-visible spectroscopy or ion chromatography is a common practice in the field of water quality [38]. Although fluoride at trace levels of exposure is beneficial to dental health, excessive fluoride exposure can cause dental and skeletal fluorosis. The presence of naturally occurring fluoride contamination in groundwater is still an ongoing environmental problem, especially in the arid

regions of India, China, and Africa. Other ions, such as sulfates, chlorides, and cyanides from industrial processes, both directly and indirectly, can change the chemical equilibrium of aquatic ecosystems and negatively impact their water quality. Continuous monitoring via ion-selective electrodes and microfluidic sensors can allow real-time detection of various inorganic contaminants in water [28].

Micro- and nanoplastics

Microplastics (MPs) and nanoplastics (NPs) have recently been recognized as ubiquitous pollutants that can be found throughout marine, freshwater and terrestrial environments. MPs can either be the result of the degradation of larger plastics, referred to as secondary MPs, or they can be produced for cosmetic and industrial purposes as microbeads, referred to as primary MPs. The small size of microplastics (less than 5 mm) and nanoplastics (nanoplastics are less than 100 nm) facilitates their entry into the ecosystem, where they bioaccumulate in organisms and translocate across biological membranes [39]. Microplastics also transport related pollutants, such as hydrophobic organic contaminants, heavy metals, and pathogens, which can enhance their bioavailability and toxicity. Other researchers have detected MPs in food, drinking water, and air, which are related to their global prevalence. Once plastic particles are ingested, they can cause inflammation, oxidative stress, and other metabolic disruptions for fauna in aquatic systems and mammals. Furthermore, due to the large surface area and reactivity of nanoparticles, NPs may cross cellular membranes, allowing the introduction of genotoxicity and immune dysfunction [40]. Examining environmental MPs and NPs can be difficult because they are heterogeneous mixtures and are small in size. Thus, emerging technologies, such as Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, pyrolysis-GC-MS-MS, and

nanoparticle tracking analysis (NTA), are being applied to identify and quantify plastic particles from complex matrices. The potential for negative impacts on living organisms and persistence in the environment highlights the need for continuous improvements in the detection of micro- and nanoplastics in ecosystems, classification, and risk assessment methodologies [41]. While micro- and nanoplastics represent a rapidly expanding class of particulate pollutants, another increasingly significant group comprises chemically diverse emerging contaminants, whose environmental behavior and long-term risks remain poorly understood.

Emerging contaminants of concern

ECCs are a large and expanding class of contaminants that were not previously considered for purposes of systematic planetary monitoring or regulation but are now increasingly recognized as potentially harmful contaminants with environmental and human health implications. The ECC class includes perfluoroalkyl substances (PFASs), endocrine-disrupting compounds (EDCs), nanomaterials, cosmetics and personal care products, industrial additives, and drinking water disinfection byproducts. PFASs are synthetic fluorinated chemicals used in firefighting foams, nonstick cookware, and coatings for water repellency. PFASs have very strong C-F bonds that produce exceptional thermal and chemical stability, contributing to their almost non-degradability; hence, they are often referred to as "forever chemicals." Some PFASs have been linked to immunotoxicity, thyroid dysfunction, and cancer. PFASs can be detected at extremely low levels (ng/L) using sensitive methods such as high-resolution LC-MS/MS and time-of-flight mass spectrometry (TOF-MS) [42]. EDCs interfere with hormone-mediated signaling pathways and act as hormone mimics or blockers. Common EDCs include bisphenol A (BPA), phthalates, and certain

pharmaceuticals. EDCs have the potential to impact reproductive health, metabolism, and the development of humans and wildlife, and they are of concern because of their environmental persistence and potential for bioaccumulation [43]. The rapid growth of nanotechnology has resulted in the entry of engineered nanomaterials (ENMs) such as silver, titanium dioxide, and zinc oxide nanoparticles into the environment. These engineered particles have favorable properties for various uses in industry and biomedicine; however, uncontrolled release could present challenges for cytotoxicity, genotoxicity, and the induction of oxidative stress in aquatic and terrestrial systems. Traditional analytical methods usually do not have the capacity to fully characterize nanoparticles in environmental samples because of their ultrasmall size, complex matrices, and continuously changing nature. Consequently, new analytical strategies, such as single-particle ICP-MS, electron microscopy, and nanoparticle-resolved spectroscopy, are imperative for evaluating these nanomaterials. Water disinfection processes that utilize chlorine or chloramines can degrade them into disinfection byproducts (DBPs), including trihalomethanes (THMs) and haloacetic acids (HAAs), which are all thought to be potentially carcinogenic. With the increasing trend toward the reuse and desalination of water compounds, it is important to track the formation of DBPs by minimizing human exposure using advanced analytical control strategies [44].

Toxicological and ecological implications

The impacts of environmental pollutants can be seen both ecologically and toxicologically, and can take the form of acute and chronic effects on organisms, ecosystems, and human populations. Toxicity can be attributed to mechanisms such as oxidative stress, genotoxicity, endocrine disruption, neurotoxicity, and immunosuppression [45]. Pollutants may modify

gene expression, alter signal transduction pathways, and damage cellular macromolecules. Many pollutants lead to oxidative stress, whereby reactive oxygen species (ROS) are generated and ultimately contribute to lipid peroxidation, DNA strand breaks, and protein oxidation. For example, PAHs and heavy metals can activate cytochrome P450 enzymes, leading to the formation of reactive intermediates that initiate carcinogenesis. On a broader scale, systemic exposure to pollution alters metabolic, reproductive, and developmental outcomes. For instance, while aquatic effects are not the only synonyms for pollution, sub-lethal exposure to pesticides and pharmaceuticals can influence the growth rates, behavioral patterns, and enzyme activity of aquatic organisms. Furthermore, endocrine disruptors can feminize male fish and affect the reproductive success of amphibians, whereas heavy metals may accumulate in the tissues of fish, creating a toxicological hazard through the consumption of these fish from a human dietary exposure assessment standpoint. [46]. Pollutants disrupt nutrient cycling, decrease biodiversity, and hinder ecosystem functionality at the ecosystem level. Eutrophication from nitrates and phosphates causes hypoxic “dead zones,” while acid rain from industrial sources causes forest and aquatic habitat loss. POPs, which are highly complex chemical mixtures, have reached remote areas of the Arctic because of long-range atmospheric transport. From a human health perspective, chronic exposure to pollutants is linked to a long list of diseases, such as cancers, cardiovascular disease, respiratory diseases, disruption of the endocrine system, and even neurodevelopmental delays. Children and pregnant women from disadvantaged areas are most severely affected by a lack of regulations and exposure mitigation to address environmental pollution [47]. Synergistic and cumulative effects from mixed pollutants further complicate risk assessments. For example, co-exposure to heavy metals and organic contaminants may produce

either additive or synergistic toxicity, increasing the human health risk more than each contaminant on its own. Modern environmental monitoring should evolve quickly from the assessment of single compounds to integrated multi-pollutant assessments using new analytical and computational tools [48].

Emerging Analytical Techniques and Technological Advancements

The ongoing advancement in environmental pollution has produced a great need for research into analytical methods that are more sensitive, selective, and rapid for the analysis of pollutants. Traditional methods, including UV-Vis spectrophotometry, flame atomic absorption spectroscopy (FAAS), and simple chromatography, are generally reliable but frequently lack sensitivity, portability, and versatility, and thus cannot be applied to modern environmental monitoring applications. In the past two decades, the revolution in nanotechnology, spectroscopy, microfluidics, and artificial intelligence has not only transformed analytical chemistry, but has also given rise to a multidimensional discipline that is capable of addressing complex environmental problems. The following sections focus on recent, impactful analytical technologies for the detection and quantification of environmental pollutants with greater accuracy, precision, and sustainability [49].

Nanomaterial-based sensors and biosensors

Nanomaterials have changed the field of environmental analysis with an increased level of sensitivity, surface area to volume ratios, and tunable physicochemical properties. Nanomaterial-based sensors rely on engineered nanostructures such as gold nanoparticles (AuNPs), carbon nanotubes (CNTs), graphene, metal-organic frameworks (MOFs), and quantum dots (QDs), which amplify signals and improve

detection limits. Metal and metal oxide nanoparticles (*e.g.*, ZnO, TiO₂, and Fe₃O₄) serve as electron mediators in electrochemical nanosensors, increasing the current response for analytes such as heavy metals, nitrates, and pesticides. For example, chemical sensors consisting of gold nanoparticle-modified electrodes are directly applicable for the detection of mercury ions at concentrations as low as 1 ppb, which is far superior to conventional analytical techniques. Similarly, graphene-based field-effect transistors (GFETs) provide a direct platform for monitoring organic contaminants in real time, which is faster than most traditional methods due to their high electrical conductivity and fast electron transfer [50]. The term biosensor refers to a biologically based material (such as enzymes, antibodies, and nucleic acids) integrated with nanomaterials and has demonstrated high specificity and selectivity. Existing studies have utilized enzyme-based (*e.g.*, acetylcholinesterase (AChE)-modified CNT sensors) nanobiosensors for the detection of organophosphate pesticides. DNA-based biosensors employing complementary base-pair hybridization are increasingly being utilized in the detection of mutagenic and genotoxic pollutants in water. Additionally, plasmonic nanosensors based on localized surface plasmon resonance (LSPR) exhibit unique optical signals when a substance of interest interacts with the nanosensor, allowing for the detection of pollutants without the need for labeling. The incorporation of nanotechnology in the development of portable miniaturized detection platforms has made it possible to conduct on-site environmental assessments using mobile interfaces. The combination of nanosensors with Internet-of-Things (IoT) technologies represents the next generation of smart environmental monitoring [51]. Biosensors enhanced with nanomaterials are summarized in this schematic by showing their components, target analytes, and types of applications. The schematic describes the

fundamental biosensing mechanism, whereby a biocomponent interacts with an analyte and subsequently generates a measurable signal using a transducer. All biosensors can detect different types of complex organic (toxins, pesticides, and antibiotics) and inorganic (metals, phosphates, and nitrates) pollutants using biocomponents, such as enzymes, antibodies, nucleic acids, and whole cells. Technologies using nanomaterials can improve the sensitivity, specificity, and speed of detection, and provide analytical tools for clinical and performance diagnostic tests, environmental compliance assessments, and food quality monitoring (Figure 2).

Surface-enhanced Raman spectroscopy

SERS has become one of the most effective vibrational spectroscopic techniques for detecting environmental pollutants because of the combination of the molecular specificity and ultrahigh sensitivity of SERS. SERS works through the enhancement of Raman scattering signals of analyte molecules adsorbed onto roughened metallic surfaces, usually silver (Ag), gold (Au), or copper (Cu) nanostructures, through LSPR. This enhancement can be increased by 10⁶–10¹⁴ times, and SERS may allow the detection of single molecules. SERS is particularly useful for detecting PAHs, pesticides, and industrial dyes in aqueous samples, with minimal sample processing. In practice, Au–Ag bimetallic nanostructures can detect rhodamine B and malachite green with detection limits below nanomolar concentrations [52]. Recent progress has included portable SERS gadgets and fiber-optic SERS probes that provide real-time and in situ monitoring capabilities in remote or hazardous environments. When combined with microfluidic devices, these techniques measure the sample streams and provide reproducible enhancement conditions. Spectral pattern discovery using ML is combined with SERS to automate pollutant classification and reduce

human interpretation and measurement errors. Finally, SERS will benefit from multiplex detection using multiple spectrally distinct reporters to simultaneously detect multiple contaminants at

the same time, which is a significant jump toward more complete environmental monitoring systems [53].

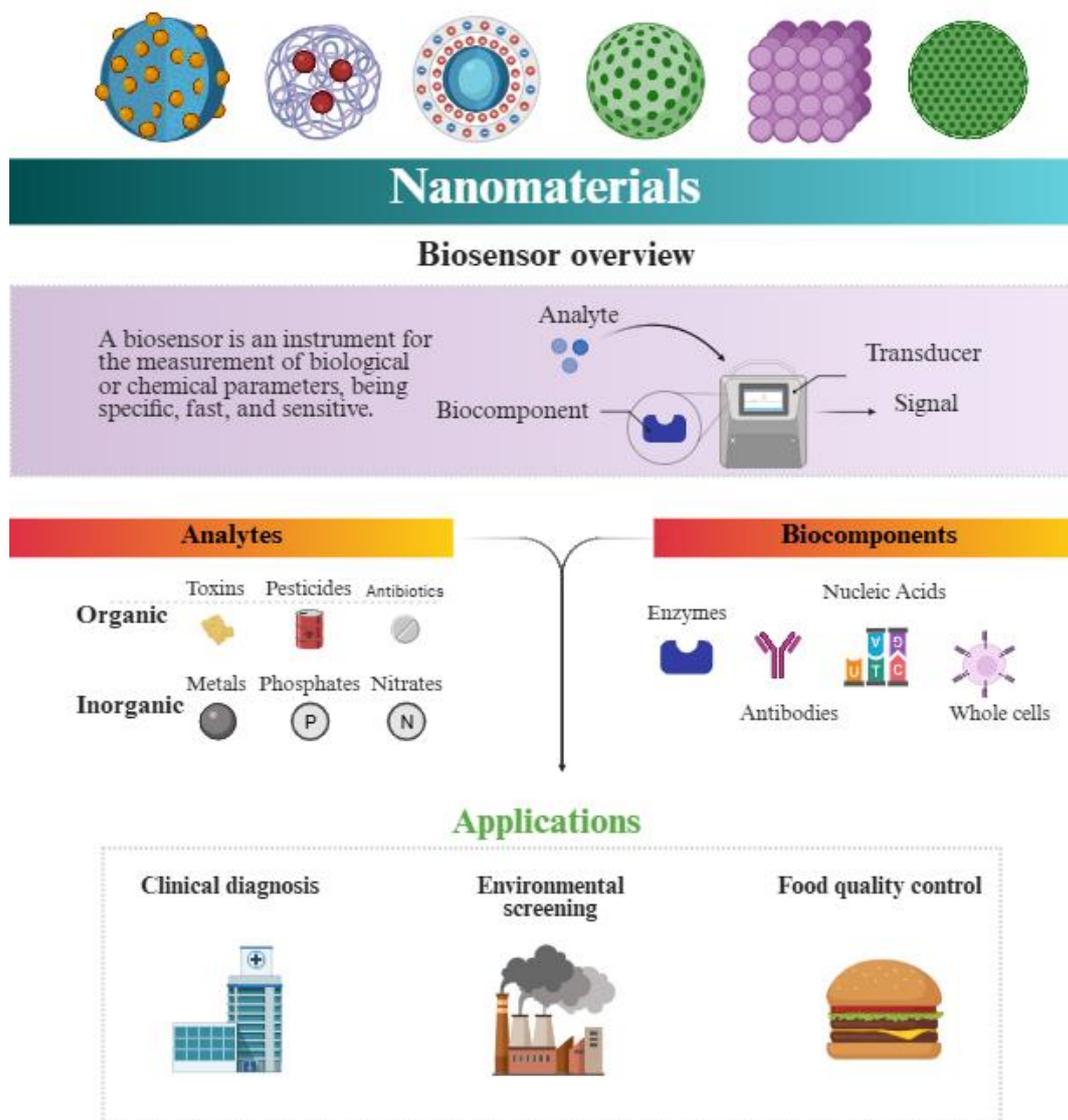


Figure 2. Schematic representation of nanomaterial-enhanced biosensor components and their mechanism for detecting organic and inorganic environmental pollutants

Laser-induced breakdown spectroscopy

LIBS is a rapid, multi-element, and almost no sample preparation analytical method that is being increasingly used for the analysis of environmental contaminants. LIBS is based on focusing a high-energy laser pulse onto the target

surface to generate a microplasma that emits light, which is representative of the atomic composition of the sample. One of the main strengths of LIBS is its ability to analyze samples in real time, which is especially useful for heavy metals (Pb, Cd, As, and Cr) in soils and sediments. LIBS can analyze solid, liquid, and gas samples,

with little to no sample pretreatment. With advances in double-pulse and femtosecond LIBS systems, the detection limits have improved, achieving detection limits below ppm in complex matrices. LIBS instruments are now paired with computational chemometric algorithms and ML models to improve accuracy and reduce matrix effects, allowing quantitative analysis of samples. With advancements and lower technology costs, the portability of LIBS has allowed for field-deployable instruments useful for industrial effluent analysis and environmental remediation monitoring. LIBS can also be interfaced with Raman or Laser-Induced Fluorescence (LIF) systems to provide complementary molecular and elemental analyses, allowing for a better understanding of the pollutant composition and transformations [54]. A schematic shows how LIBS, a new analytical method, is receiving more attention for the rapid and multi-element detection of environmental contaminants. A high-energy laser pulse strikes the sample, creating a microplasma that produces characteristic light, and the emitted radiation is collected at an angle (θ) and converted to spectral data displayed on the computer after the optical signal is captured by the detector. LIBS can analyze solids, liquids, and aerosols with little or no sample preparation in real time, making it an ideal method for

monitoring contaminants in environmental matrices (Figure 3).

Capillary electrophoresis and microchip technologies

Capillary Electrophoresis (CE) has emerged as an essential analytical technique for environmental analysis because of its high separation efficiency, low sample and solvent consumption, and fast analytical time. CE functions in the separation of analytes according to their charge-to-mass ratio under an electric field, which is well suited to ionic pollutants such as nitrates, phosphates, and heavy metals. The development of micellar electrokinetic chromatography (MEKC) and capillary zone electrophoresis (CZE) has expanded the use of CE to nonpolar and neutral pollutants, such as pesticides and pharmaceuticals. Ultimately, CE combined with a UV-Vis, NIR, or mass spectrometric detector (CE-MS) increases the sensitivity and structural elucidation capabilities [55]. Recent trends involve microchip electrophoresis (ME) and lab-on-a-chip (LOC) devices that take the CE platform and miniaturize the CE system into a microfluidic chip, delivering rapid, automated, and simultaneous analyses.

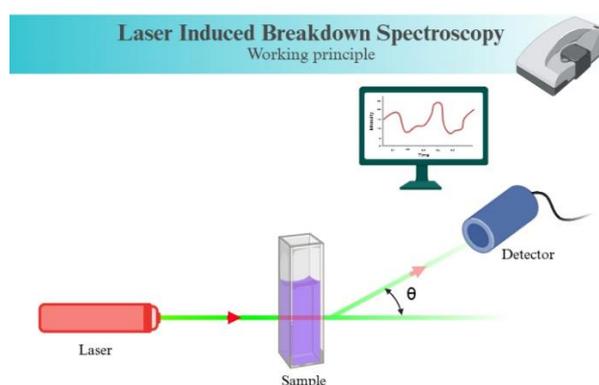


Figure 3. Working mechanism of LIBS showing laser-generated plasma and emission-based elemental analysis for rapid pollutant detection

These devices integrate sample pre-treatment, separation, and detection on the same platform,

decreasing the analysis time, required samples, and the amount of reagent needed. The

development of nanoparticle-modified microchannels in microchip CE can enhance analyte adsorption and facilitate control over the electroosmotic flow to achieve better resolution and reproducibility. Implementing CE with more recent microchip technologies is a significant step toward green, portable, and cost-effective environmental diagnostics [56]. Although CE-based platforms provide rapid and low-consumption separation capabilities, advanced pollutant characterization often requires coupling separation with high-resolution detection systems such as mass spectrometry.

Mass spectrometry coupled hybrid techniques (GC-MS, LC-MS/MS)

Mass spectrometry (MS) maintains its position as a fundamental analytical chemistry technique for toxicant analysis due to its unmatched sensitivity, selectivity, and structural characterization. To address the current environment, researchers define modern chemicals of concern via hybrid methodologies, such as Gas Chromatography-Mass Spectrometry (GC-MS) and Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS), which combine efficient separation and powerful detection capabilities. GC-MS is particularly useful for volatile and semi-volatile organic compounds, such as PAHs, pesticides, and hydrocarbons, while LC-MS/MS is particularly effective for non-volatile and thermally labile toxicants, such as pharmaceuticals and endocrine-disrupting chemicals (EDCs). High-resolution mass spectrometry (HRMS) analyzers and time-of-flight (TOF) mass spectrometers enable untargeted screening and recognition of ECCs

[57]. New techniques, including Orbitrap MS and Quadrupole-Time of Flight (QTOF), improve mass accuracy and resolution, enabling the identification of trace-level toxicants in complex environmental matrices. Uniform descriptors such as ambient ionization (DART-MS and DESI-MS) allow for minimal-to-no sample preparation for direct analysis, paving the way for unique *in situ* environmental sample monitoring. Automation, miniaturization, and data-driven reporting make MS-based methodologies an important platform for powder-monitoring assistance. The increasing combination of MS with microextraction methods and green sample preparation techniques addresses sustainability needs, while maintaining high-level analytical performance [58]. Mass spectrometry (MS), a highly sensitive analytical technique frequently applied to measure trace-level environmental contaminants, is based on the following principles. A sample is injected, vaporized, and subjected to an electron beam, which ionizes molecules to form charged ions. These ions were subsequently charged and propelled through an electromagnetic environment, where they were separated based on their mass-to-charge ratios (m/z). The ions are detected, counted, and quantified by the detector, which generates a characteristic set of spectra associated with a particular pollutant. Thus, MS can offer precise multi-component measurements of organic and inorganic pollutants in air, water, and soil samples, as shown in Figure 4. Despite the analytical power of MS-based methods, the need for portable, real-time, and resource-efficient approaches has accelerated the development of microfluidic and lab-on-chip platforms for onsite pollutant monitoring.

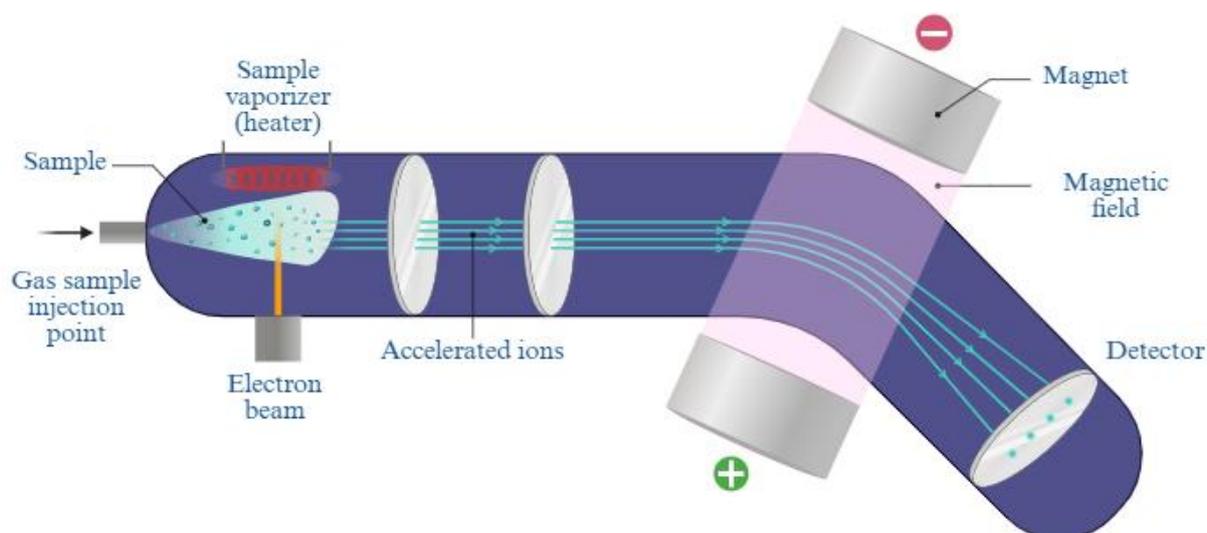


Figure 4. Schematic representation of mass spectrometry for environmental pollutant analysis

Microfluidic and lab-on-a-chip platforms

Microfluidic systems and lab-on-a-chip (LOC) technologies represent the latest trends in miniaturized analytical platforms designed for environmental monitoring. These systems integrate multiple laboratory functions into one microchip with microchannels, measuring tens to hundreds of micrometers, and include sample preparation, reaction, separation, and detection. The benefits of LOC systems are their minimum sample volume, high throughput, and real-time monitoring. LOC devices have been developed to measure heavy metals, pesticides, and microbial contamination in water using electrochemical or optical detection methods. Further advances in performance have come from integrating nanomaterials; for example, gold nanoparticles and graphene oxide have been added to microfluidic channels to improve conductivity, sensitivity, and specificity for target analytes. The use of droplet-based microfluidics enables the digital control of discrete sample volumes, thus allowing rapid analysis that is reproducible and accurate for variable, dynamic environmental

systems [51]. Paper-based microfluidic devices (μ PADs) are rapidly becoming low-cost and eco-friendly alternatives for detecting pollutants, which can conveniently be used in low-resource settings. μ PADs are amenable to use with smartphones for colorimetric or fluorescence readings, providing low-cost, easy-to-use instruments for on-site use. The combination of microfluidics, nanotechnology, and artificial intelligence is creating autonomous environmental monitoring systems that self-calibrate and allow for continuous and distributed sensing within smart cities and industrial ecosystems [59]. Building on the strengths of microfluidic miniaturization, recent studies have increasingly integrated multiple complementary techniques to create hybrid systems with improved analytical breadth and precision.

Integration of multimodal and hybrid analytical systems

One emerging trend is the development of multimodal analytical platforms that integrate complementary techniques to take advantage of

their higher analytical capabilities. These include SERS–LC–MS systems that combine molecular fingerprinting with quantitative mass analysis and LIBS–Raman systems that combine elemental and molecular information. These hybrid systems enable concurrent detection of multiple classes of pollutants (organic, inorganic, and biological) and cross-validate the results to strengthen accuracy and support claims. While less straightforward, sensor arrays described as “electronic tongues or noses” utilize networks of multisensor arrays to recognize patterns in complex environmental mixtures. When combined with ML algorithms, these sensors can classify the sources of pollutants and provide information on concentration levels and gradients to help with regulatory decisions. Developments of hybrid instruments that also rely on AI have begun to use deep learning to help identify specific pollutants in spectral or chromatographic assessments, which can provide a method of increased automation and reliability in data-hungry environmental work [60].

Technological miniaturization and automation

The environmental monitoring landscape is undergoing radical shifts due to miniaturization and automation, which facilitate portable, affordable, and real-time analytical devices. Portable gas chromatographs, online Raman spectrometers, and nanosensors coupled with smartphones now allow for the democratized detection of pollutants in the field. Automated sample preparation modules and robotic arms enable consistent, high-throughput analyses, protect humans from hazardous environments, and reduce uncertainty related to human interactions. The trend of Internet-connected analytical devices (*e.g.*, IoT-based analytics) enables continuous remote monitoring of air, soil, and water quality. By coupling cloud-based data management systems, remote analyses can be synchronized for cross-datum time-series

analyses, pattern recognition, and the predictive modeling of environmental conditions. Collectively, these advancements contribute to sustainable, decentralized monitoring infrastructure [51].

Application of ML and AI in Pollutant Detection

The use of ML and AI has led to a paradigm shift in environmental pollution monitoring. With environmental data growing exponentially from analytical instruments, sensors, and remote monitoring, computational models must accommodate complex, nonlinear, and multidimensional datasets. Traditional analytical and statistical models are often not sufficiently sensitive to detect the complexity and interrelationships in environmental data. Thus, ML and AI have the potential to improve detection efficacy, maximize sensor applications, predict pollution behavior over time, and allow for automatic environmental monitoring systems. The synthesis of these techniques with purposeful analytical platforms (*e.g.*, spectroscopy, chromatography, and sensor-based systems) represents a new era in the detection and quantification of environmental pollutants, which can increase analytical accuracy and permit real-time and remote monitoring of the environment in response to growing global pollution challenges. This section reports the foundational applications of ML and AI for pollutant detection regarding their ability to process and recognize patterns in data, develop predictive models, and synthesize IoT-enabled sensor networks [61].

Data processing and pattern recognition

Assessment of environmental contaminants usually includes extracting information from large volumes of heterogeneously distributed data generated by various analytical instruments that often differ in specialized techniques (*e.g.*, gas chromatography–mass spectrometry (GC–MS),

liquid chromatography–tandem mass spectrometry (LC–MS/MS), FTIR, and SERS. These datasets show variability arising from environmental effects, instrument sensitivity, or sampling complexities. ML algorithms facilitate and exhibit better data preprocessing, feature extraction, and classification, thus improving the analytical accuracy. Dimensionality reduction and visualization methods, such as Principal Component Analysis (PCA), Independent Component Analysis (ICA), or t-distributed Stochastic Neighbor Embedding (t-SNE), are two common approaches for pollutant datasets among other dimensionality reduction methods. PCA converts large datasets into uncorrelated linear combinations known as principal components to facilitate pattern recognition while removing experimental noise. PCA (for image or spectral features) was successfully combined with support vector machines (SVMs) for the discrimination of multiple heavy metals from water samples using mixed-mode spectral and imaging data. Similar uses of Partial Least Squares (PLS) regression and autoencoders can be employed to compress sensor data, further facilitating the identification of pollutants with minimal computational load [62].

Pollutant classification projects commonly utilize supervised learning algorithms such as support vector machines (SVM), random forests (RF), k-nearest neighbors (k-NN), and artificial neural networks (ANN). For instance, ANN-based models trained using fluorescence or UV-Vis spectral data can differentiate between organic pollutants (*e.g.*, PAHs and pesticide contamination). Likewise, convolutional neural networks (CNN) capable of processing complicated, image-based data (*e.g.*, hyperspectral or satellite images) can assist in detecting spatial patterns of contaminants in water bodies and soils. Unsupervised learning algorithms, such as k-means clustering, hierarchical clustering, and self-organizing maps (SOM), are also helpful in revealing hidden

patterns in datasets and classifying unknown pollutants without pre-labeled data. These methods can be particularly useful in exploratory data analyses of environmental datasets and can be used to identify pollutant types, concentrations, or an unknown mix of ketones, phenolics, or aromatic compounds. For example, clustering algorithms have been used in air quality index (AQI) decomposition by geographic region to develop and analyze pollution hotspots over time [63].

The interpretation of AI data has improved spectral and chromatographic resolution, circumventing the challenges associated with overlapping peaks and low signal-to-noise ratios. ML-assisted deconvolution algorithms are also useful for distinguishing chemically similar compounds, thereby improving quantification. Deep learning models are widely used to interpret the more subtle Raman shifts that can occur in SERS based detection of pollutants, allowing for the detection of trace-level contaminants, such as bisphenol A, arsenates, or remnants of pharmaceuticals. Furthermore, it is increasingly common to apply Deep Belief Networks (DBNs) and Recurrent Neural Networks (RNNs) in the automation of chromatographic peak identification and the correction of retention times to reduce the variations that can occur from human intervention. Environmental monitoring frequently relies on integrating data collected from multiple analytical sources that differ in their spectral, spatial, and temporal dimensions. The fusion of multimodal data supports pollutant detection accuracy when ML is used to leverage the information sets imparted by various data modalities. An example of this application is the combination of the outputs of gas chromatography and mass spectrometry (GC–MS) with Fourier transform infrared spectroscopy (FTIR) data when analyzed using ML algorithms, which allows for complete characterization of the extracted volatile organic compounds (VOCs) in environmental matrices. In addition, the

advanced use of ensemble learning and Bayesian fusion methods can add to the robustness of a pollutant detection system and allow for the consideration of uncertainty quantification and probabilistic reasoning [64].

Predictive modelling for environmental monitoring

Predictive modeling is one of the most innovative uses of ML and AI for environmental pollutant detection. AI systems can predict concentrations, forecast pollution events, and help build monitoring programs using historical datasets for training. ML models used for air, water, and soil pollution forecasting include long short-term memory (LSTM) networks, gradient boosting machines (GBM), and Random Forest regression. Because of their ability to retain memory, LSTM networks can be effectively used to analyze time-series data to forecast the concentrations of pollutants such as PM_{2.5}, NO₂, and SO₂. Forecasting and making predictions are critical to the success of early warning systems in urban and/or industrial settings. AI-assisted source apportionment methods assist in identifying the sources and contributions of various pollutants. For instance, positive matrix factorization (PMF) coupled with ML models has been utilized to estimate the contributions of transportation, industry, and agricultural runoff to the observed pollutant levels. These hybrid models provide useful analyses for policymakers that address targeted mitigation efforts [65].

AI-based quantitative structure-activity relationship (QSAR) models are useful tools for predicting the environmental fate and toxicity of new contaminants. By relating molecular descriptors to physicochemical properties, ML algorithms can model a variety of parameters, including biodegradation potential, bioaccumulation, and ecotoxicity. Deep learning models have also enhanced the accuracy of QSAR models in predicting the toxicological potential of pharmaceuticals, microplastics, and compounds

that disrupt the endocrine system. For example, deep neural networks can be trained on molecular datasets to quickly predict lethal concentration (LC₅₀) values for aquatic organisms exposed to new chemicals, thus eliminating the need for large-scale animal testing. This supports both ethical environmental assessments and sustainability analyses. AI facilitates the assimilation of spatiotemporal data to create pollution maps with a high spatial resolution. The integration of data (including air quality data) has addressed gaps and has been applied using Geographically Weighted Regression (GWR), Deep Spatiotemporal Networks, and hybrid models, such as CNN-RNN models, to track the dynamics of pollutants over space and time. Some applications are focused on predicting the plume dynamics of airborne particulate matter, heavy metal contamination in soil, and water quality related to fluoroalkyl substances in surface water [66].

The advancement of remote sensing and satellite imagery, when combined with AI-based classification algorithms (such as Random Forests and Support Vector Machines), has vastly improved the feasibility of large-scale monitoring. For example, Sentinel-2 and Landsat imagery combined with an AI model can be used to quantify chlorophyll concentrations, turbidity, and the occurrence of algal blooms as proxies for pollution in aquatic systems. An important aspect of AI-based predictive modeling is the continuous optimization of the model, which involves cross-validation, hyperparameter tuning, and the use of ensemble learning to ensure consistency in prediction. The reliability of the models can be further enhanced through quantification of uncertainty and frameworks that support interpretability of predictions, such as Shapley Additive Explanations (SHAP) and Local Interpretable Model-agnostic Explanations (LIME). The use of these methodologies allows environmental scientists to assess the relative influence of variables associated with pollutant

behavior and spatial distribution, while simultaneously providing reliability to predictions and enhancing transparency [67].

Integration with sensor networks and iot devices

The rapid advancement of the IoT and smart sensor technologies has further increased the impact of AI and ML on environmental monitoring in real time. The limitations of traditional analytical procedures are periodic sampling and laboratory-based measurements, which may not capture significant temporal environmental variability. The implementation of AI algorithms within a network of distributed sensors provides a continuous, automated, and adaptive monitoring system for detecting pollutants even at very low concentrations. Sensor networks deployed under extreme environmental conditions suffer from signal drift, noise, and sensor aging. ML algorithms are essential for dynamically calibrating sensors and adjusting error signals. For example, Gaussian Process Regression (GPR) and Adaptive Neural Networks can be used to model the non-linear responses of a sensor while correcting drift from electrochemical sensors or optical sensors that are used to measure air and water quality. Transfer learning provides a mechanism for sharing knowledge between sensors deployed in different environments while ensuring that calibration is maintained [68].

The idea of Edge AI, which deploys AI models directly to IoT devices or local processing units, has transformed pollutant monitoring in the field. Edge computing reduces the latency for data transmission, making real-time decision-making and anomaly detection possible. For example, AI-based microcontrollers in portable water-quality sensors can instantaneously warn of abnormal pH, turbidity, or heavy metal concentrations. Similar air quality drones using CNN models can autonomously detect pollution plumes in industrial areas, circling back to send alerts to

environmental agencies. AI-enabled autonomous underwater vehicles (AUVs) and aerial drone systems have been helpful for large spatial range environmental monitoring. These AUVs and aerial systems have ML algorithms built into their functions for navigation, data collection, and pollutant detection. For example, underwater robots employing optical techniques (*e.g.*, fluorescence and Raman sensors) embedded with AI models can be used to detect oil spills, microplastics, and nutrient imbalances in aquatic ecosystems. Aerial drones equipped with hyperspectral imaging and deep learning classifiers can identify and map pollution gradients in agricultural or urban settings with a high level of spatial resolution. Environmental monitoring infrastructure includes many sensor networks that are often connected. For example, AI-enabled predictive maintenance models can monitor the health metrics of sensors (*i.e.*, battery health, connectivity of sensors, and signal integrity) to predict near-miss sensor failures and provide seamless monitoring. In addition, AI technology in cloud applications collects sensor data distributed across a range of geographical locations, allowing the analytics and retraining of models at scale. The combination of Big Data analytics and blockchain to authenticate data, as well as the AI-fueled autonomous monitoring of data, facilitates transparency, scalability, and reliability in global environmental monitoring networks [69].

Green and sustainable analytical approaches

Concern regarding environmental pollution has not only increased the need for rigorous and rapid analytical detection methods, but has also created a demand for these methods to be more sustainable. While conventional analytical methods are effective, they utilize large volumes of hazardous solvents, create toxic waste, and require excessive amounts of energy, which contradicts the essential objective of protecting

the environment. Thus, green chemistry principles are properly incorporated into analytical protocols, a subdiscipline of analytical methods collectively referred to as GAC. The idea of GAC focuses on the development and use of analytical procedures that minimize their negative environmental impact and maximize efficiency and sustainability while still

demonstrating analytical excellence. In this context, green and sustainable analytical approaches for the detection of environmental pollutants are quickly becoming transformative approaches for environmental monitoring, risk assessment, and environmental compliance (Table 2)[70].

Table 2. Green and sustainable analytical approaches

Approach	Principle/technique	Green chemistry features	Advantages	Limitations	Ref.
Miniaturized sample preparation	Microextraction techniques (spme, lpme, dllme, and μ -spe)	Low solvent use, reduced sample volume, and minimal waste generation	High sensitivity, rapid extraction, and portable and field-use potential	Limited extraction capacity, method and optimization required	[71]
Solvent-free and alternative solvent methods	Supercritical fluid extraction (sfe), pressurized hot water extraction (phwe), ionic liquids, and deep eutectic solvents	Replaces toxic solvents, uses water or CO_2 , and improves biodegradability	Eco-friendly, high selectivity, and improved analyte recovery	High instrumentation cost (sfe) and viscosity issues (des/ils)	[72]
Green chromatographic techniques	Uhplc, hilic, capillary electrophoresis, and eco-friendly mobile phases	Reduced solvent consumption, and energy-efficient systems	Faster analysis, high resolution, and suitable for complex samples	Requires advanced detectors and careful method development	[73]
Sensor-based and biosensing approaches	Electrochemical sensors, bioassays, and optical/fluorescent sensing	Low reagent use, real-time monitoring, and reusable components	On-site detection, low-cost, minimal waste	Limited multi-analyte detection, and sensitivity to environmental conditions	[74]
Paper-based and microfluidic devices	μ pads, lab-on-chip systems	Biodegradable substrates, ultra-low reagent volume	Portable, affordable, suitable for field applications	Lower precision compared to lab instruments; short shelf-life	[59]
Green spectroscopic methods	Ftir, raman, nir, and fluorescence spectroscopy	No chemicals/solvents, direct analysis with	Rapid, non-destructive, and versatile	Matrix interference	[64]

		minimal sample prep		may reduce accuracy	
Automation & AI-assisted approaches	Robotics, ML-based data interpretation	reduces Experimental error, minimizes reanalysis cycles	Enhanced accuracy, lower overall resource consumption	Requires computational resources & training data	
Waste-minimized analytical platforms	Reusable columns, closed-loop solvent recycling, miniaturized lab setups	Reduced hazardous waste, lower environmental footprint	Cost-effective, regulatory compliance-friendly	Initial setup cost may be high	[75]

Miniaturized and solvent-free sample preparation techniques

The preparation of analytical samples is a pivotal step in any analytical itinerary, frequently signifying over 70 % of the total time, expense, and environmental footprint of an analytical workflow. Conventional sampling methods, such as liquid-liquid extraction (LLE) and Soxhlet extraction, are both solvent-intensive, require high energy consumption, and produce significant waste byproducts. To mitigate these limitations, several miniaturized and solvent-free methods have been developed that align with the principles of GAC by minimizing solvent use, sample volume, and energy consumption. SPME is a primary example of a miniaturized sample preparation method that incorporates sampling, extraction, concentration, and introduction of a sample for analysis in a single step without the use of solvents. A fiber pre-coated with a selective sorbent (*e.g.*, polydimethylsiloxane, polyacrylate, or carboxyl) is used to extract target analytes directly from the sample matrix and/or the sample headspace. This method has been successfully employed to detect volatile and semi-volatile organic pollutants such as PAHs, pesticides, and volatile organic compounds (VOCs). It has been shown to be solvent-free with minimal sample manipulation and is highly

compatible with gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) systems, making SPME a sustainable and versatile choice for environmental analysis. Stir bar sorptive extraction (SBSE) is another miniaturized sample preparation method that employs a stir bar coated in a polymeric film, allowing for the adsorption of analytes while the sample is agitated compared to SPME. This technique offers a superior extraction capacity and improved sensitivity for hydrophobic contaminants. FPSE is a relatively new variation of this idea, which utilizes a sorbent created from a sol-gel on a flexible substrate, such as polyester fabric. FPSE offers direct immersion of flexible substrates into aqueous or biological matrices, while also providing good extraction efficiency, reusability, and green solvent compatibility. Both techniques significantly reduce the amount of solvent used and the generation of waste in analytical applications. DLLME has become widely utilized as an analysis method that is fast, simple, and has a low impact on the environment that extracts analytes from liquid samples. It employs a very small number of extraction solvent microliters, which disperse very quickly throughout the aqueous sample to achieve very high enrichment factors. Variations in ionic liquid-based DLLME (IL-DLLME) and deep eutectic

solvent-based DLLME (DES-DLLME) have further enhanced its green credentials [76]. These solutions substitute toxic organic solvents with biodegradable, non-volatile, and recyclable solvents, providing selective extraction of heavy metals, pesticides, and pharmaceuticals from environmental waters. Energy-efficient extraction principles, such as MAE and ultrasound-assisted extraction (UAE), have significantly shortened the extraction time, amount of solvent used, and thermal degradation of analytes. MAE utilizes microwave energy to induce rapid heating of solvents and their matrices, which accelerates mass transfer processes. UAE employs ultrasonic energy waves to effectively disrupt sample matrices and enhance the diffusion of analytes. Both MAE and UAE are particularly useful methods for extracting pollutants from solid matrices, including sediments, soils, and plant tissues, while achieving very high recoveries with relatively low environmental impact. Supercritical fluids, particularly carbon dioxide (CO₂), have been recognized as green solvents in the field of analytical extraction because of their adjustable solvent properties, low toxicity, and ease of recovery. Supercritical combination methods, such as supercritical fluid extraction (SFE), provide a green alternative to organic solvent extraction when working with nonpolar or moderately polar compounds. With supercritical fluid extraction (SFE), the mild operating conditions of supercritical fluids minimize the degradation of samples and permit the extraction of hydrophobic pollutants, including, but not limited to, hydrocarbons and PCBs. When combined with a chromatographic system, SFE provides an entirely green analytical process in which the environmental monitoring of hydrophobic pollutants is achievable [77].

Green chromatography and eco-friendly detection methods

Chromatography continues to be the basis of analytical science for the detection of environmental pollutants. However, conventional chromatographic techniques such as high-performance liquid chromatography (HPLC) use substantial amounts of organic solvents, resulting in an abundance of waste. Therefore, the development of green chromatography and eco-friendly detection systems has been a key area of focus for sustainable analytical chemistry. SFC is characterized by the use of supercritical CO₂ as the mobile phase along with a small percentage of co-solvent (usually methanol or ethanol) as the mobile phase. The tunable polarity of supercritical CO₂ enables its use in a wide range of analytes with a relatively low environmental footprint. SFC has demonstrated high efficiency and selectivity in the detection of pesticides, pharmaceuticals, and endocrine-disrupting chemicals. In addition, CO₂ used for SFC can be recycled, leading to substantially lower solvent consumption and waste compared to HPLC. Currently, high-performance liquid chromatography (HPLC) is focused on minimizing the use of hazardous solvents and reducing energy consumption. For example, aqueous normal-phase chromatography (ANP) and hydrophilic interaction liquid chromatography (HILIC) have been implemented as green alternatives using a water-dominant mobile phase or changing toxic solvents such as acetonitrile for ethanol or propanol with lower toxicity. Miniaturized HPLC formats such as capillary HPLC, or ultra-high-performance liquid chromatography (UHPLC), reduce solvent consumption and waste volume. All four methods provided improved separation efficiencies and speeds [78]. While traditional GC methods make use of small amounts (if at all) of a carrier gas (*e.g.*, helium or hydrogen), the trend toward hydrogen as a renewable carrier gas and toward fast GC has

resulted in some improvements to the environmental profile of gas-phase separations. Methods, including micro-GC and thermal desorption techniques, have allowed traditional detectors, such as UV-Vis or flame ionization, to introduce solvent-free samples, which is beneficial for the analysis of volatile pollutants. Furthermore, detector technology is increasingly being developed to minimize the use of energy and reagents. Examples include electrochemical detectors, fluorescence-based sensors, and photoacoustic spectroscopy. Electrochemical detectors are a particularly attractive option for green analysis because of their low power consumption, high sensitivity, and ability to be analyzed in aqueous systems without reagents. Likewise, both surface plasmon resonance (SPR) and fiber-optic biosensors are powerful platforms for label-free detection with low environmental footprint, making them ideally suited for use in green chemical initiatives. Sustainable solvents, such as ionic liquids (ILs) and deep eutectic solvents (DESSs), have attracted interest as alternatives to traditional organic solvents because they have negligible vapor pressure, are biodegradable, and their solvation properties can be tailored. These types of solvents are used more frequently in chromatographic and spectroscopic instrumentation for pollutant analysis. Moreover, the utilization of biobased stationary phases in the form of renewable polymers derived from cellulose or chitosan reduces continued reliance on petrochemical sources, fostering sustainability in chromatographic separations [79].

Bioanalytical and enzyme-based systems for environmental assessment

The rise of bioanalytical systems, including enzyme-based assays, whole-cell biosensors, and biomimetic recognition elements, represents a shift in the rationale toward sustainable pollutant detection. They offer a level of biological recognition and catalysis that potentially allows

for high selectivity, low toxicity, and minimal reagent use. These approaches provide skeptical promise as complementary methods to traditional instrumental analysis as they can be rapid, on-site, and cheaper whole monitoring systems. Enzyme-based biosensors utilize biological catalysts (*e.g.*, oxidases, reductases, and hydrolases) to selectively detect environmental pollutants. A well-established example of enzyme-based biosensors is the use of acetylcholinesterase as a recognition element to detect organophosphate and carbamate pesticides through enzyme inhibition. Other examples of enzyme-based biosensors include the use of laccases and peroxidases for detecting of phenolic compounds. These systems frequently involve the application of nanomaterials, including graphene, gold nanoparticles, and carbon nanotubes, to increase the rate of electron transfer and provide analytical sensitivity. In all scenarios, enzyme-based biosensors utilize aqueous solutions as the pure phase, avoiding the need for organic solvents or cell-deadening reagent applications, as in other methodologies. Whole-cell biosensors utilize living microbial or algal cells that have been genetically engineered to produce measurable signals (luminescence, fluorescence, or color change) in response to pollutants. For example, bioluminescent bacteria have been engineered to express lux genes and are being increasingly used to assess the toxicity of heavy metals and organic pollutants. Such biosensors offer a comprehensive evaluation of both bioavailability and toxicity, rather than just the concentration levels. They are environmentally friendly because they use renewable biological materials and can be used with limited or no instrumentation [80]. Aptamers, synthetic single-stranded DNA, and RNA oligonucleotides are increasingly popular recognition elements for green analytical systems. Aptamers exhibit high affinity and specificity toward a wide range of pollutants including heavy metals, antibiotics, and pesticides. Aptamer-based

sensors (aptasensors) eliminate the need to use antibodies, which are frequently expensive and a burden on the environment through their production. In addition, aptasensors coupled with electrochemical or fluorescence readout systems provide reusable, inexpensive, and solvent-free analytical systems that can be used to monitor pollutants in the environment. Enzyme-mimicking nanomaterials (nanozymes) demonstrate a combination of enzyme-like catalytic efficiency and the stability and sustainability of nanomaterials. Fe₃O₄, CeO₂, and MnO₂ nanoparticles, for example, have peroxidase- or oxidase-like activity for detecting pollutants via colorimetric or electrochemical responses. Nanozymes are viable, stable, and economical options for ecological detection

compared to natural enzymes while fully adhering to green analytical principles. The co-location of bioanalytical systems with microfluidic chips and lab-on-a-chip approaches has revolutionized the field of sustainable monitoring of pollutants. These instruments operate using very small sample volumes (in the microliter range), consume negligible amounts of reagents, and can produce on-site real-time analyses. For example, paper-based microfluidic devices functionalized with either enzymes or aptamers can be low-cost, disposable, and biodegradable alternatives for environmental monitoring, particularly in restrictive resource contexts [81] Bioanalytical and enzyme-based systems are tabulated in Table 3.

Table 3. Bioanalytical and enzyme-based systems for environmental assessment

Category	Technique	Biological component	Target pollutants	Analytical advantages	Challenges / limitations	Ref.
Enzyme-based biosensors	Electrochemical enzyme biosensors	Laccase, peroxidase, tyrosinase, and urease	Phenols, pesticides, heavy metals, and ammonia	High selectivity, rapid response, low detection limits, and minimal sample prep	Enzyme instability, temperature/pH sensitivity, and limited operational lifetime	[82]
Whole-cell biosensors	Microbial bioreporters	Genetically engineered bacteria/yeast	heavy metals (hg, cd, pb), organics, and toxins	Affordable, scalable, detect bioavailable fractions, and suitable for field monitoring	Requires biological containment, and slower response time	[83]
DNA- and Aptamer-based systems	Aptasensors, and biosensors	Ssdna, aptamers, and riboswitches	Heavy metals, pesticides, and endocrine disruptors	Ultra-high specificity, regenerable sensing surfaces, and stable under harsh conditions	Complex design, requires advanced synthesis	

Bioelectrochemical monitoring systems	Enzyme-linked nanomaterial systems	Bio-optical analytical platforms	Immunoassay-based bioanalytical systems	Enzyme inhibition assays
Microbial fuel cell biosensors	Nano-enzyme conjugates and nanozymes	Fluorescent/bioluminescent biosensors	Elisa and lateral flow immunoassays	Enzyme activity inhibition tests
Electroactive bacteria	Metal nanoparticles, carbon nanostructures	Luciferase, GFP-tagged proteins	Antibodies (monoclonal/polyclonal)	Acetylcholinesterase, alkaline phosphatase, β -galactosidase
Organic load (bod/cod), and wastewater pollutants	Phenols, dyes, and metal species	Organic pollutants, metals, and toxicity assessment	Pesticides, hormones, pharmaceuticals, and pathogens	Organophosphates, carbamates, metal ions
Self-powered sensing, and long-term operability	Enhanced catalytic activity, high stability, and robust environmental sensing	Non-destructive, real-time detection, and suitable for continuous	High sensitivity, quantitative/qualitative detection, and portable formats	Simple, cost-effective, and sensitive to toxic compounds
Slow response, affected by temperature and nutrient availability	Nanotoxicity concerns, cost of nanomaterial synthesis	Light-based interference, requires optical equipment	Antibody degradation, cross-reactivity, and complex sample pretreatment	Lack of pollutant specificity; and interference from sample matrices

[84]

[85]

[86]

[87]

Challenges, Limitations, and Future Perspectives

Analytical and instrumental limitations

Although substantial advancements have been made in the field of analytical science, the detection and quantification of environmental pollutants are still severely limited by the problems associated with developing analytical methods. One such problem is the complex and heterogeneous chemical makeup of many environmental matrices, such as soil, sediment, and wastewater, which present matrix effects that normally inhibit accurate quantification. Nanomaterial-based sensors, SERS, and LIBS

methods have extremely sensitive detection levels; however, reproducibility and stability of the signal are common issues. Variability in the preparation, modification, or overall use of nanomaterials can lead to variations in the standard response, making the reproducibility of data outcomes difficult. Furthermore, environmental samples are rarely isolated and may contain several different co-occurring contaminants that produce similar signals, leading to possible false positives or negatives in detection. Instrumental limitations also create significant hurdles for trace detection. For example, although mass spectrometric (MS) techniques, such as gas chromatography-mass

spectrometry (GC-MS) or liquid chromatography-tandem mass spectrometry (LC-MS/MS), are selectively sensitive to environmental pollutants, they are not simple instruments requiring custom modifications, lengthy methods, careful calibration, and experienced personnel, all of which may constitute extensive maintenance. These high capital and operational costs, combined with the demanding operating conditions of laboratories, confine their use in environmental systems. Portable instruments and other devices, usually have lower analytical resolution and at least concerning analyte detection limits, these portable instruments often compromise on sensitivity relative to a benchtop system. Another significant limitation is the sample preparation step; despite advances in miniaturized and solvent-free sample preparation techniques, the pre-treatment of samples remains labor-intensive and time-consuming. Solid-phase extraction (SPE), SPME, and microfluidic devices have made it possible to increase the analytical throughput; however, problems of clogging, sample loss, and variability in different matrices remain challenges. Real-time monitoring technologies (*e.g.*, biosensors, lab-on-a-chip systems) can be further hindered by long-term stability and selectivity issues when faced with varying environmental conditions (*e.g.*, temperature, humidity, and pH) throughout the duration of monitoring. The detection of ECCs, such as pharmaceuticals, personal care products, and micro/nanoplastics, is particularly problematic when these pollutants are in ultra-trace (<ng/L) concentrations and requires advanced analytical techniques that can detect analytes at extremely low limits of quantification (LOQs). Techniques such as nano-sensors, fluorescence-based probes, and electrochemical devices have all contributed to the sensitive detecting these contaminants, but these methodologies still struggle to detect multiple analytes simultaneously, further complicating quantification in real environmental samples.

Natural organic matter, salts, and particulate matter can interfere with the detection of target analytes, creating uncertainty in the quantification. Finally, some of these contaminants degrade or transform, creating byproducts that go undetected using traditional sample preparation and analytical configurations that may underrepresent the overall contamination.

Standardization and regulatory issues

The rapid evolution of analytical methods has surpassed the creation of standardized methods and regulations for environmental monitoring. The lack of an internationally accepted method for validation, data interpretation, and performance assessment inhibits the ability to compare the results on a global scale. There are numerous new analytical methods, especially nanosensors, SERS, and microfluidic devices, which do not have standardized methods for calibration or certified reference materials. This gap reduces the reproducibility between laboratories and makes it difficult to obtain regulatory approvals. Regulatory agencies such as the U.S. environmental protection agency (EPA), european chemicals agency (ECHA), and national pollution control boards have developed methods for traditional pollutants; however, methods are still being developed for the new generation of contaminants such as pharmaceuticals, endocrine disruptors, and microplastics. Disagreements regarding threshold concentration limits, toxicity, and environmental half-life complicate the formation of guidelines for detection methods complex. In addition, the lack of agreement on analytical performance parameters (*e.g.*, limit of detection (LOD), limit of quantification (LOQ), and signal-to-noise ratio) makes it difficult to compare different methods. Data management and reporting remain as regulatory challenges. In addition to the model approaches for pollutant detection and prediction using AI and ML, data

integrity and traceability are critical considerations. Many AI-driven models suffer from a lack of transparency concerning algorithmic rationales or decision-making - the "black box" issue - which hampers the traceability of predictive results in regulatory terms. Additionally, the variability of analytical results can be caused by differences in the frequency of data collection, calibration of sensors and analytical methodologies, and variable environmental conditions for longitudinal trend assessment. Nor is there a global harmonization on the certification of analytical devices, which presents an additional concern regarding data confidence as portable or *in situ* monitoring systems developed in the context of specific regional conditions may not meet international validation standards. For example, biosensors that electrochemically detect heavy metals in rivers and were constructed for use in Europe were shown not to detect the same heavy metals under modified conditions in tropical climates (humidity and temperature). Thus, limitations of scalability and commercialization of analytical systems will continue to exist with no global collaboration undertaken to harmonize regulations. Ethical and environmental considerations associated with the use of nanomaterials in sensors and detection platforms also require attention. Even with nanomaterials, the disposal of these devices after environmental monitoring could lead to a secondary pollution impacts if not rendered inert. Therefore, regulatory policies need to include a life-cycle approach to risk concerning the ongoing use of analytical materials by promoting eco-design, recyclability, and waste minimization. Regulatory agencies must collaborate with research institutions to establish validation protocols that ensure that analytical techniques are reliable, environmentally safe, and data traceable and reproducible in meeting global sustainability objectives.

Integration of smart sensing systems

The future of detecting environmental pollutants lies in smart sensing systems where analytical chemistry and digital technologies, IoT and artificial intelligence converge, leading to complex technical as well as management and analysis the data to obtain results to share. Smart sensors with wireless communication modules handle large amounts of real-time data that require proper data analytics frameworks for processing, interpretation, and storage functions. There are many areas where the current infrastructure, especially in developing regions, is not suitable for handling the required data, resulting in significant monitoring shortfalls. Sensor networks from different monitoring devices also need to have compatibility for signal acquisition, processing, and transmission protocols. Unfortunately, many analyzers operate on different platforms and communication standards, resulting in poor interoperability across platforms. This highlights the need for common protocols to be adopted along with similar metadata formats to facilitate data sharing throughout global-based monitoring systems. The supply of power and energy efficiency are also two hurdles facing IF: an autonomous sensor must be deployed for continuous remote monitoring of the environment. Even though some energy-harvesting and/or low-power electronic systems are employed, challenges remain in maintaining continuous environmental monitoring, especially in remote and/or water-based-based settings. Environmental changes, such as temperature and salinity fluctuations, can also negatively impact sensor performance, leading to drift in calibration parameters and potentially compromising data certainty. Self-healing materials and adaptive algorithms are being tested to overcome these challenges, but the development of these applications is still in the early stages. Cybersecurity and data privacy can present new threats to smart environmental monitoring

networks. Connecting IoT-based pollutant detection devices to cloud-based data repositories opens new possibilities for data breaches and data manipulation. Resources will need to be allocated to ensure the integrity, authenticity, and confidentiality of data using the strategic use of blockchain or encryption technologies to navigate a new complex vision for smart sensing systems. Another important issue is the high cost and scalability of smart sensing networks. While nanotechnology and microfabrication have helped lower the overall cost of sensors, building distributed real-time monitoring infrastructures over broad geographical areas remains expensive. Technology and institutional support to maintain and calibrate large sensor arrays are essential for practical use, and this support is not consistently available in low-resource contexts. Thus, the creation of cost-effective, self-calibrating, and straightforward sensors is crucial for achieving global equity in monitoring environmental pollutants. From a technological perspective, harnessing the capability of AI-based predictive model systems within sensor network structures has potential, but is challenging. This requires the training of accurate AI models that depend on high-quality, large-scale data. Unfortunately, high-quality datasets are often inconsistent or unavailable. Low-quality datasets will result in biased predictions or generalizations when AI-based predictive models are applied to new environmental conditions. Additionally, in terms of maintenance, when pollutant profiles, seasonal variations, and human activity require continued model retraining, this becomes more complicated. Data sharing between academic institutions, the government, and industry may mitigate these weaknesses and encourage the development of more resilient environmental monitoring frameworks.

Future research directions

Future research should aim to create analytical approaches that are highly sensitive, selective, stable, portable, and suitable for real-time use. The next generation of analytical platforms should focus on detecting multiple analytes, minimizing sample preparation, and reducing the use of toxic materials. Hybrid analytical systems that integrate a combination of spectroscopy, chromatography, and electrochemical sensing into microfluidic or lab-on-chip schemes represent a very promising direction for analysis, as these systems can merge preconcentration, separation, and detection into a single analytical platform that can produce rapid results while consuming minimal time and resources. A key area of research should help improve the reproducibility and longevity of nanomaterial-based sensors and biosensors in the field. Strategies, such as surface passivation, polymer encapsulation, and bio-inspired coatings, may enhance fouling and performance variability related to environmental variations. Furthermore, the use of molecularly imprinted polymers (MIPs), which are recognition elements that include aptamers and peptide receptors, can improve the specificity of target analytes and enhance the detection of trace contaminants. The expansion of AI and ML in the analytical workflow should extend beyond data interpretation. Future applications should encompass to the optimization of instruments, signal correction, and predictive analytics. Adaptive algorithms that can learn from the variability in the environment or analysis process can enhance robustness and lead to fully autonomous field-deployable systems. In addition, the integration of digital twins and environmental modeling may offer virtual simulations to optimize sensor placement, anticipate pollutant transport, and evaluate remediation plans. From a sustainability standpoint, it should be a priority to apply GAC principles; it should be the focus of research to

employ solvent-free extraction, biodegradable materials for sensors, and energy-efficient detection technologies. Conventional methods that require solvents should be replaced by green chromatography methods that leverage aqueous mobile phases, recyclable adsorbents, and minimize waste. Renewable energy applications, using microfluidics leveraged by solar energy as an example, could improve the environmental footprint of environmental principles of environmental monitoring process. The next stage is the evolution of environmental analytical science. Chemists, material scientists, data engineers, and environmental policymakers must coordinate efforts to establish integrated systems that can operate continuously and autonomously. Global pollutant databases and open-access repositories will also improve work transparency and expedite advancements. Data-sharing frameworks can also facilitate the production of global pollution maps to support the identification of hotspots of contamination and remediation efforts. Converting laboratory-scale analytical innovations into commercially viable and field-deployable technologies remains a significant ongoing challenge. Future work should focus on the cost, simplicity of use, and robustness of the device to make its widespread implementation feasible. Pilot-scale field test programs are necessary to scale up analytical performance in real-world situations and bridge the gap between academic research and industrial applications. Furthermore, policy context that those policies should reward the development of sustainable analytical technologies for commercial use, utilizing funding and subsidies as well as international cooperation. The forthcoming trends in environmental analytical science are expected to be based on smart, sustainable, and autonomous systems. This long-term vision should be integrated with smart sensors, AI-powered analytics, and cloud-enabled environmental databases to monitor the global environment continuously in real time. In

addition to overcoming the current issues of standardization of methods, data management, and technical performance, these new analytical platforms have the potential to dramatically increase our ability to screen, determine quality, and measure exposure on a comprehensive scale and mitigate environmental pollution, contributing to a cleaner and more sustainable planet.

Conclusion

The detection and monitoring of environmental pollutants have been transformed by the rapid development of new analytical techniques that allow for the accurate, sensitive, and real-time evaluation of contaminants across a variety of ecosystems. Complex pollutant mixtures can now be quantified at the trace level due to advancements in analytical accuracy, sensitivity, and detection limits brought about by nanomaterial-based sensors, SERS, LIBS, and hybrid mass spectrometry techniques. Data interpretation, predictive modeling, and environmental surveillance capabilities are further strengthened by the combination of artificial intelligence, ML, and IoT-enabled smart sensing systems. Additionally, the use of GAC concepts, such as solvent-free, bioanalytical, and miniature methods, reduces the environmental impact and aligns pollutant detection with sustainability objectives. Despite these developments, there are still obstacles to achieving cost-effectiveness, field-deployable dependability, global standardization, and regulatory compliance. Future research should emphasize AI-driven autonomous sensing systems capable of self-calibration and real-time decision-making; the development of hybrid multimodal platforms integrating spectroscopic, chromatographic, electrochemical, and nanosensor-based methods; the expansion of IoT-enabled smart sensor networks for continuous monitoring; and globally harmonized standards

for method validation and data interoperability to ensure reliability and regulatory acceptance of next-generation analytical technologies.

Disclosure Statement

No potential conflict of interest was reported by the authors.

ORCID

Phanindra Erukulla

<https://orcid.org/0009-0001-2900-2881>

Pericharla Venkata Narasimha Raju

<https://orcid.org/0009-0003-2259-6693>

Konatham Teja Kumar Reddy

<https://orcid.org/0000-0003-0227-2248>

Venkata Ramana Singamaneni

<https://orcid.org/0009-0006-4328-8253>

Ashutosh Pathak

<https://orcid.org/0009-0000-9158-9356>

Sunil Kumar Yadav

<https://orcid.org/0000-0003-1670-1859>

M. Sandeep Kumar

<https://orcid.org/0009-0006-5920-3402>

Abdul Ajeed Mohathasim Billah

<https://orcid.org/0000-0003-0552-0948>

References

- [1] Zhou, Y., Gu, B. **The impacts of human activities on earth critical zone.** *Earth Critical Zone*, **2024**, 1(1), 100004.
- [2] Li, Y., Chen, B., Yang, S., Jiao, Z., Zhang, M., Yang, Y., Gao, Y. **Advances in environmental pollutant detection techniques: Enhancing public health monitoring and risk assessment.** *Environment International*, **2025**, 109365.
- [3] Center for drug evaluation and research. **definitions.** 2024.
- [4] Kumar, M., Chaudhary, V., Kumar, R., Srivastav, A. **Microplastics, their effects on ecosystems, and general strategies for mitigation of microplastics: A review of recent developments, challenges, and future prospects.** *Environmental Pollution and Management*, **2025**, 2, 87-105.
- [5] Nizzetto, L., Macleod, M., Borgå, K., Cabrerizo, A., Dachs, J., Guardo, A.D., Ghirardello, D., Hansen, K.M., Jarvis, A., Lindroth, A. **Past, present, and future controls on levels of persistent organic pollutants in the global environment.** *Environmental Science and Technology*, **2010**, 44(17), 6526-6531.
- [6] Nishmitha, P., Akhilghosh, K.A., Aiswriya, V.P., Ramesh, A., Muthuchamy, M., Muthukumar, A. **Understanding emerging contaminants in water and wastewater: A comprehensive review on detection, impacts, and solutions.** *Journal of Hazardous Materials Advances*, **2025**, 18, 100755.
- [7] Caracci, E., Vega-Herrera, A., Dachs, J., Berrojalbiz, N., Buonanno, G., Abad, E., Llorca, M., Moreno, T., Farré, M., **Micro (nano) plastics in the atmosphere of the atlantic ocean.** *Journal of Hazardous Materials*, **2023**, 450, 131036.
- [8] Li, X., Shen, X., Jiang, W., Xi, Y., Li, S. **Comprehensive review of emerging contaminants: Detection technologies, environmental impact, and management strategies.** *Ecotoxicology and Environmental Safety*, **2024**, 278, 116420.
- [9] Rawat, S., Phogat, P., Chand, B. **Advances in nanomaterial-based biosensors: Innovations, challenges, and emerging applications.** *Materials Today Communications*, **2025**, 113334.
- [10] Alanazi, S. **Recent advances in liquid chromatography–mass spectrometry (LC–MS) applications in biological and applied sciences.** *Analytical Science Advances*, **2025**, 6(1), e70024.
- [11] Dakal, T.C., Xu, C., Kumar, A. **Advanced computational tools, artificial intelligence and machine-learning approaches in gut microbiota and biomarker identification.** *Frontiers in Medical Technology*, **2025**, 6, 1434799.
- [12] Umeh, O.R., Ibo, E.M., Eke, C.I., Afeku-Amenyo, H.C., Ophori, D.U. **A review of the sidelined pollutant: Reviving the fight against heavy metal contamination in an era of emerging contaminants.** *Toxicology Reports*, **2025**, 102073.
- [13] Chen, Z., Daka, Z., Yao, L., Dong, J., Zhang, Y., Li, P., Zhang, K., Ji, S. **Recent progress in the application of chromatography-coupled mass-spectrometry in the analysis of contaminants in food products.** *Food Chemistry: X*, **2025**, 102397.
- [14] Abdelhamid, M.A., Ki, M.R., Yoon, H.J., Pack, S.P. **Microfluidic sensors for micropollutant detection in environmental matrices: Recent advances and prospects.** *Biosensors*, **2025**, 15(8), 474.
- [15] Mehta, M., Mehta, D., Mashru, R. **Recent application of green analytical chemistry: Eco-friendly approaches for pharmaceutical analysis.** *Future Journal of Pharmaceutical Sciences*, **2024**, 10(1), 83.
- [16] Saroj, S., Shah, P., Jairaj, V., Rathod, R. **Green analytical chemistry and quality by design: A combined approach towards robust and sustainable modern analysis.** *Current Analytical Chemistry*, **2018**, 14(4), 367-381.

- [17] Fritea, L., Banica, F., Costea, T.O., Moldovan, L., Dobjanschi, L., Muresan, M., Cavalu, S. [Metal nanoparticles and carbon-based nanomaterials for improved performances of electrochemical \(bio\) sensors with biomedical applications.](#) *Materials*, **2021**, 14(21), 6319.
- [18] Patel, K.N., Patel, J.K., Patel, M.P., Rajput, G.C., Patel, H.A. [Introduction to hyphenated techniques and their applications in pharmacy.](#) *Pharmaceutical methods*, **2010**, 1(1), 2-13.
- [19] Liu, D., Wang, Y., Li, X., Li, M., Wu, Q., Song, Y., Zhu, Z., Yang, C. [Integrated microfluidic devices for in vitro diagnostics at point of care.](#) *Aggregate*, **2022**, 3(5), e184.
- [20] Popescu, S.M., Mansoor, S., Wani, O.A., Kumar, S.S., Sharma, V., Sharma, A., Arya, V.M., Kirkham, M., Hou, D., Bolan, N. [Artificial intelligence and iot driven technologies for environmental pollution monitoring and management.](#) *Frontiers in Environmental Science*, **2024**, 12, 1336088.
- [21] Huang, L., Duan, Q., Liu, Y., Wu, Y., Li, Z., Guo, Z., Liu, M., Lu, X., Wang, P., Liu, F. [Artificial intelligence: A key fulcrum for addressing complex environmental health issues.](#) *Environment International*, **2025**, 109389.
- [22] Koley, B.L., Ray, S., Biswas, A.K., Dutta, S., Roy, S., Bhattacharjee, K., Kotal, A. [A predictive ai framework for proactive pollution control and environmental protection.](#) *International Journal of Environmental Sciences*, **2025**, 11(10s), 190-200.
- [23] Thakar I, Patel K, Goswami J, Bhavsar A, Patel C.N. [GAC: A Critical Review of Eco-friendly Techniques.](#) *International Journal of Pharmacy and Pharmaceutical Research*, **2025**, 31(4), 445-454.
- [24] Alvarado-Ramírez, L., Rostro-Alanis, M., Rodríguez-Rodríguez, J., Sosa-Hernández, J.E., Melchor-Martínez, E.M., Iqbal, H.M., Parra-Saldívar, R. [Enzyme \(single and multiple\) and nanozyme biosensors: Recent developments and their novel applications in the water-food-health nexus.](#) *Biosensors*, **2021**, 11(11), 410.
- [25] Miladinović, S.M., [Green analytical chemistry: Integrating sustainability into undergraduate education.](#) *Analytical and Bioanalytical Chemistry*, **2025**, 417(4), 665-673.
- [26] Münzel, T., Hahad, O., Daiber, A., Landrigan, P.J. [Soil and water pollution and human health: What should cardiologists worry about?](#) *Cardiovascular Research*, **2023**, 119(2), 440-449.
- [27] Sadiq, F.K., Sadiq, A.A., Matsika, T.A., Momoh, B.A. [Sustainable remediation of persistent organic pollutants: A review on recent innovative technologies.](#) *Current Research in Biotechnology*, **2025**, 100293.
- [28] Kazapoe, R.W., Amuah, E.E.Y., Dankwa, P., Fynn, O.F., Addai, M.O., Berdie, B.S., Douli, N.B. [Fluoride in groundwater sources in ghana: A multifaceted and country-wide review.](#) *Heliyon*, **2024**, 10(13).
- [29] Yee, M.S.L., Hii, L.W., Looi, C.K., Lim, W.M., Wong, S.F., Kok, Y.Y., Tan, B.K., Wong, C.Y., Leong, C.O. [Impact of microplastics and nanoplastics on human health.](#) *Nanomaterials*, **2021**, 11(2), 496.
- [30] Wang, F., Xiang, L., Leung, K.S.Y., Elsner, M., Zhang, Y., Guo, Y., Pan, B., Sun, H., An, T., Ying, G. [Emerging contaminants: A one health perspective.](#) *The Innovation*, **2024**, 5(4).
- [31] Arora S. [Review Article: Ecotoxicological Impacts of Pollution on Biodiversity and Ecosystem Health in the Anthropocene.](#) *Journal for Research in Applied Sciences and Biotechnology*. **2025**, 4(3), 136-42.
- [32] Meher, A.K., Zarouri, A. [Environmental applications of mass spectrometry for emerging contaminants.](#) *Molecules*, **2025**, 30(2), 364.
- [33] Srogi, K. [Monitoring of environmental exposure to polycyclic aromatic hydrocarbons: A review.](#) *Environmental Chemistry Letters*, **2007**, 5(4), 169-195.
- [34] López-Benítez, A., Guevara-Lara, A., Domínguez-Crespo, M.A., Andraca-Adame, J.A., Torres-Huerta, A.M. [Concentrations of organochlorine, organophosphorus, and pyrethroid pesticides in rivers worldwide \(2014–2024\): A review.](#) *Sustainability*, **2024**, 16(18), 8066.
- [35] Samal, K., Mahapatra, S., Ali, M.H. [Pharmaceutical wastewater as emerging contaminants \(ec\): Treatment technologies, impact on environment and human health.](#) *Energy Nexus*, **2022**, 6, 100076.
- [36] Horvat, T., Pehnc, G., Jakovljević, I. [Volatile organic compounds in indoor air: Sampling, determination, sources, health risk, and regulatory insights.](#) *Toxics*, **2025**, 13(5), 344.
- [37] Briffa, J., Sinagra, E., Blundell, R. [Heavy metal pollution in the environment and their toxicological effects on humans.](#) *Heliyon*, **2020**, 6(9).
- [38] Singh, S., Anil, A.G., Kumar, V., Kapoor, D., Subramanian, S., Singh, J., Ramamurthy, P.C. [Nitrates in the environment: A critical review of their distribution, sensing techniques, ecological effects and remediation.](#) *Chemosphere*, **2022**, 287, 131996.
- [39] Amobonye, A., Bhagwat, P., Raveendran, S., Singh, S., Pillai, S. [Environmental impacts of microplastics and nanoplastics: A current overview.](#) *Frontiers in Microbiology*, **2021**, 12, 768297.
- [40] Rafa, N., Ahmed, B., Zohora, F., Bakya, J., Ahmed, S., Ahmed, S.F., Mofijur, M., Chowdhury, A.A., Almomani, F. [Microplastics as carriers of toxic pollutants: Source, transport, and toxicological effects.](#) *Environmental Pollution*, **2024**, 343, 123190.
- [41] Zhang, J., Peng, M., Lian, E., Xia, L., Asimakopoulos, A.G., Luo, S., Wang, L. [Identification of poly](#)

- (ethylene terephthalate) nanoplastics in commercially bottled drinking water using surface-enhanced raman spectroscopy. *Environmental Science & Technology*, **2023**, 57(22), 8365-8372.
- [42] Feng, W., Deng, Y., Yang, F., Miao, Q., Ngien, S.K. Systematic review of contaminants of emerging concern (CECS): Distribution, risks, and implications for water quality and health. *Water*, **2023**, 15(22), 3922.
- [43] Diamanti-Kandarakis, E., Bourguignon, J.-P., Giudice, L.C., Hauser, R., Prins, G.S., Soto, A.M., Zoeller, R.T., Gore, A.C., Endocrine-disrupting chemicals: An endocrine society scientific statement. *Endocrine Reviews*, **2009**, 30(4), 293-342.
- [44] Rocco, L. Engineered nanomaterials for environmental and health applications. *Nanomaterials*, **2025**, 15(7), 516.
- [45] Piscopo, M., Marinaro, C., Lettieri, G. The multifaceted impact of environmental pollutants on health and ecosystems. *Biomolecules*, **2024**, 14(8), 1021.
- [46] Hong, Y., Boiti, A., Vallone, D., Foulkes, N.S. Reactive oxygen species signaling and oxidative stress: Transcriptional regulation and evolution. *Antioxidants*, **2024**, 13(3), 312.
- [47] Kurniawan, S.B., Roziqin, A., Ahmad, A., Ahmad, M.M., Alfanda, B.D., Pambudi, D.S.A., Said, N.S.M., Abdul, P.M., Imron, M.F. Tackling marine pollution in the blue economy: Synergies between wastewater treatment technologies and governmental policies. *Marine Pollution Bulletin*, **2026**, 222, 118627.
- [48] Singh, N., Gupta, V.K., Kumar, A., Sharma, B. Synergistic effects of heavy metals and pesticides in living systems. *Frontiers in Chemistry*, **2017**, 5, 70.
- [49] Sharma, M., Mahajan, P., Alsubaie, A.S., Khanna, V., Chahal, S., Thakur, A., Yadav, A., Arya, A., Singh, A., Singh, G. Next-generation nanomaterials-based biosensors: Real-time biosensing devices for detecting emerging environmental pollutants. *Materials Today Sustainability*, **2025**, 29, 101068.
- [50] Malik, S., Singh, J., Goyat, R., Saharan, Y., Chaudhry, V., Umar, A., Ibrahim, A.A., Akbar, S., Ameen, S., Baskoutas, S. Nanomaterials-based biosensor and their applications: A review. *Heliyon*, **2023**, 9(9).
- [51] Mark D, Haerberle S, Roth G, Stetten F Von, Zengerle R. Microfluidic lab-on-a-chip platforms: Requirements, characteristics and applications. *Chemical Society Reviews*, **2010**, 39(3):1153-1182.
- [52] Han, Y., Wen, R., Liu, J., Wei, J., Yin, Q., Wu, L. Advances and innovations in surface-enhanced raman scattering detection of microcystins: Towards sensitive, rapid, and high-throughput analysis. *Food Chemistry*, **2025**, 146824.
- [53] Cialla-May, D., Bonifacio, A., Markin, A., Markina, N., Fornasaro, S., Dwivedi, A., Dib, T., Farnesi, E., Liu, C., Ghosh, A. Recent advances of surface enhanced raman spectroscopy (sers) in optical biosensing. *TrAC Trends in Analytical Chemistry*, **2024**, 181, 117990.
- [54] Shah, S.K.H., Iqbal, J., Ahmad, P., Khandaker, M.U., Haq, S., Naeem, M. Laser induced breakdown spectroscopy methods and applications: A comprehensive review. *Radiation Physics and Chemistry*, **2020**, 170, 108666.
- [55] Gao, Z., Zhong, W. Recent (2018–2020) development in capillary electrophoresis. *Analytical and Bioanalytical Chemistry*, **2022**, 414(1), 115-130.
- [56] Zhu, H., Fohlerová, Z., Pekárek, J., Basova, E., Neužil, P. Recent advances in lab-on-a-chip technologies for viral diagnosis. *Biosensors and Bioelectronics*, **2020**, 153, 112041.
- [57] Kaddah, M.M., El Demellawy, M.A., Talaat, W. Comprehensive analytical approaches: The use of lc-MS and IC-MS in modern pharmaceutical and biomedical sciences. *Microchemical Journal*, **2025**, 114780.
- [58] Sun, Q., Dong, Y., Wen, X., Zhang, X., Hou, S., Zhao, W., Yin, D. A review on recent advances in mass spectrometry analysis of harmful contaminants in food. *Frontiers in Nutrition*, **2023**, 10, 1244459.
- [59] Li, W., Ma, X., Yong, Y.C., Liu, G., Yang, Z. Review of paper-based microfluidic analytical devices for in-field testing of pathogens. *Analytica Chimica Acta*, **2023**, 1278, 341614.
- [60] Lenzi, E., Jimenez de Aberasturi, D., Liz-Marzán, L.M. Surface-enhanced raman scattering tags for three-dimensional bioimaging and biomarker detection. *ACS Sensors*, **2019**, 4(5), 1126-1137.
- [61] Subramaniam, S., Raju, N., Ganesan, A., Rajavel, N., Chenniappan, M., Prakash, C., Pramanik, A., Basak, A.K., Dixit, S. Artificial intelligence technologies for forecasting air pollution and human health: A narrative review. *Sustainability*, **2022**, 14(16), 9951.
- [62] Lin, J.T., Chung, Y.P., Lee, Y.Y., Wu, T.L., Huynh, T.T.T., Nguyen, P.T., Lu, M.J., Huang, B.W., Sriram, B., Wang, S.F. Emerging analytical frontiers in microplastic detection: From spectroscopy to smart sensor technologies. *Talanta Open*, **2025**, 12, 100514.
- [63] Nasir, N., Kansal, A., Alshaltone, O., Barneih, F., Sameer, M., Shanableh, A., Al-Shamma'a, A. Water quality classification using machine learning algorithms. *Journal of Water Process Engineering*, **2022**, 48, 102920.
- [64] Ziani, I., Bouakline, H., El Guerraf, A., El Bachiri, A., Fauconnier, M.L., Sher, F. Integrating ai and advanced spectroscopic techniques for precision

- food safety and quality control. *Trends in Food Science & Technology*, **2025**, 156, 104850.
- [65] Ukoba, K., Onisuru, O.R., Jen, T.C., Madyira, D.M., Olatunji, K.O. Predictive modeling of climate change impacts using artificial intelligence: A review for equitable governance and sustainable outcome. *Environmental Science and Pollution Research*, **2025**, 1-20.
- [66] Heo, S., Safder, U., Yoo, C. Deep learning driven QSAR model for environmental toxicology: Effects of endocrine disrupting chemicals on human health. *Environmental Pollution*, **2019**, 253, 29-38.
- [67] Aziz, G., Minallah, N., Saeed, A., Frnda, J., Khan, W. Remote sensing-based forest cover classification using machine learning. *Scientific Reports*, **2024**, 14(1), 69.
- [68] Rajak, P., Ganguly, A., Adhikary, S., Bhattacharya, S. Internet of things and smart sensors in agriculture: Scopes and challenges. *Journal of Agriculture and Food Research*, **2023**, 14, 100776.
- [69] Ficili, I., Giacobbe, M., Tricomi, G., Puliafito, A. From sensors to data intelligence: Leveraging iot, cloud, and edge computing with ai. *Sensors*, **2025**, 25(6), 1763.
- [70] Imam, M.S., Abdelrahman, M.M. How environmentally friendly is the analytical process? A paradigm overview of ten greenness assessment metric approaches for analytical methods. *Trends in Environmental Analytical Chemistry*, **2023**, 38, e00202.
- [71] Jano, A., De La Fuente Ballesteros, A., Ares Sacristán, A.M., Bernal Yagüe, J.L. Miniaturized solid-phase extraction techniques in sample preparation applied to food matrices: A review. *Microchemical Journal*, **2025**, 213, 113794.
- [72] de OX Machado, T., Portugal, I., de AC Kodol, H., Fathi, A., Fathi, F., Oliveira, M.B.P., Dariva, C., Souto, E.B. Pressurized liquid extraction as an innovative high-yield greener technique for phenolic compounds recovery from grape pomace. *Sustainable Chemistry and Pharmacy*, **2024**, 40, 101635.
- [73] Jankech, T., Gerhardtova, I., Stefanik, O., Chalova, P., Jampilek, J., Majerova, P., Kovac, A., Piestansky, J. Current green capillary electrophoresis and liquid chromatography methods for analysis of pharmaceutical and biomedical samples (2019–2023)—a review. *Analytica Chimica Acta*, **2024**, 1323, 342889.
- [74] Shanbhag, M.M., Manasa, G., Mascarenhas, R.J., Mondal, K., Shetti, N.P. Fundamentals of bio-electrochemical sensing. *Chemical Engineering Journal Advances*, **2023**, 16, 100516.
- [75] Fuente-Ballesteros, A., Ares, A.M., Bernal, J. Paving the way towards green contaminant analysis: Strategies and considerations for sustainable analytical chemistry. *Green Analytical Chemistry*, **2025**, 100221.
- [76] Câmara, J.S., Perestrelo, R., Berenguer, C.V., Andrade, C.F., Gomes, T.M., Olayanju, B., Kabir, A., MR Rocha, C., Teixeira, J.A., Pereira, J.A. Green extraction techniques as advanced sample preparation approaches in biological, food, and environmental matrices: A review. *Molecules*, **2022**, 27(9), 2953.
- [77] Meher, A.K., Zarouri, A. Green analytical chemistry—recent innovations. *Analytica*, **2025**, 6(1), 10.
- [78] El Deeb, S. Enhancing sustainable analytical chemistry in liquid chromatography: Guideline for transferring classical high-performance liquid chromatography and ultra-high-pressure liquid chromatography methods into greener, bluer, and whiter methods. *Molecules*, **2024**, 29(13), 3205.
- [79] Margolin Eren, K.J., Prest, H.F., Amirav, A., Nitrogen and hydrogen as carrier and make-up gases for gc-ms with cold ei. *Journal of Mass Spectrometry*, **2022**, 57(5), e4830.
- [80] Oliveira, S., Sharifuzzaman, M., Moro, G., Sinibaldi, A., Altintas, Z., Kumar, S., Chiavaioli, F., Marques, C. Advances in optical devices for the detection of contaminants in food and water. *TrAC Trends in Analytical Chemistry*, **2025**, 118139.
- [81] Ettayri, K., Gu, Z., Yang, H., Chen, Y., Ma, M., Wang, C., Long, L., Wang, K., Qian, J. Recent advances in DNA aptamer-based fluorescence biosensors for design strategies to diverse applications and future challenges: A review. *International Journal of Biological Macromolecules*, **2025**, 147398.
- [82] Kaur, J., Choudhary, S., Chaudhari, R., Jayant, R.D., Joshi, A. Enzyme-based biosensors. *Bioelectronics and Medical Devices*, **2019**, 211-240.
- [83] Zhu, Y., Elcin, E., Jiang, M., Li, B., Wang, H., Zhang, X., Wang, Z. Use of whole-cell bioreporters to assess bioavailability of contaminants in aquatic systems. *Frontiers in Chemistry*, **2022**, 10, 1018124.
- [84] Esimbekova, E.N., Kalyabina, V.P., Kopylova, K.V., Lonshakova-Mukina, V.I., Antashkevich, A.A., Torgashina, I.G., Lukyanenko, K.A., Nemtseva, E.V., Kratasyuk, V.A. Enzyme inhibition-based assay to estimate the contribution of formulants to the effect of commercial pesticide formulations. *International Journal of Molecular Sciences*, **2023**, 24(3), 2268.
- [85] Li, G., Li, Q., Wang, X., Liu, X., Zhang, Y., Li, R., Guo, J., Zhang, G. Lateral flow immunoassays for antigens, antibodies and haptens detection. *International Journal of Biological Macromolecules*, **2023**, 242, 125186.
- [86] Buonasera, K., Galletta, M., Calvo, M.R., Escobar, G.P., Leonardi, A.A., Irrera, A. Organic fluorescent sensors for environmental analysis: A critical

review and insights into inorganic alternatives.
Nanomaterials, **2025**, 15(19), 1512.

[87] Bindu, A., Bhadra, S., Nayak, S., Khan, R., Prabhu, A.A., Sevda, S. [Bioelectrochemical biosensors for](#)

[water quality assessment and wastewater monitoring.](#) *Open Life Sciences*, **2024**, 19(1), 20220933.

HOW TO CITE THIS ARTICLE

P. Erukulla, P.V. Narasimha Raju, K.T. Kumar Reddy, V.R. Singamaneni, A. Pathak, S. Kumar Yadav, M. Sandeep Kumar, A.A. Mohathasim Billah. Emerging Analytical Techniques for Detection of Environmental Pollutants: A Review. *Adv. J. Chem. A*, 2026, 9(6), 962-996.

DOI: [10.48309/AJCA.2026.561017.1973](https://doi.org/10.48309/AJCA.2026.561017.1973)

URL: https://www.ajchem-a.com/article_238268.html