Emerging Environmental Contaminants

Analytical Methods, Environmental Monitoring and Human Exposure

by

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Preface

Environmental contamination is no longer defined solely by a limited group of well-known pollutants. Contemporary production, health care, agriculture, urbanization, consumer practices, and waste generation release an exceptionally diverse range of chemicals and materials into environmental systems. Many of these substances have been used for decades, yet only recent advances in analytical science have made their widespread occurrence visible. Others are associated with new products, technologies, or transformation processes whose environmental implications are still being established. Together, they form the changing field of emerging environmental contaminants.

This book was conceived in response to a practical scientific need. Research on emerging contaminants is often divided among analytical chemistry, environmental monitoring, toxicology, exposure science, and regulation. Each discipline contributes essential information, but none can describe the complete problem in isolation. A contaminant must first be recognized and measured reliably; its sources, transport, transformation, and environmental distribution must then be understood; and the resulting evidence must be interpreted in relation to ecological effects, human exposure, uncertainty, and the decisions that monitoring is intended to support.

Analytical chemistry occupies a central position in this process. Improvements in sampling, extraction, preconcentration, chromatography, spectroscopy, fluorescence, high-resolution mass spectrometry, nanotechnology-assisted sensing, and data processing have expanded the range of substances that can be detected at trace and ultratrace levels. Nevertheless, instrumental sensitivity alone does not guarantee environmental meaning. The quality of a result depends on the representativeness of the sample, control of contamination and matrix effects, calibration, traceability, validation, quality assurance, and transparent communication of uncertainty. For this reason, the book treats the analytical workflow as a connected sequence rather than as an isolated instrumental measurement.

The first part establishes the conceptual and environmental foundation of the subject. It defines emerging contaminants, examines their environmental fate and transport, describes human exposure pathways, considers ecological and human-health implications, and compares regulatory approaches. These chapters emphasize that the word emerging does not necessarily mean newly created. A contaminant may emerge because it has become analytically detectable, because its use or release has increased, because new effects have been recognized, or because scientific and regulatory priorities have changed.

The second part focuses on analytical chemistry. It addresses representative sample collection, preservation, preparation, extraction, cleanup, and preconcentration; the principles and applications of spectroscopic and chromatographic methods; solid-surface fluorimetry; and the growing contribution of nanomaterials and nanostructured platforms. Method validation and quality assurance are treated as integral components of environmental analysis. Particular attention is given to fitness for purpose, measurement uncertainty, matrix effects, quality control, and the need to balance analytical performance with accessibility, cost, safety, and environmental sustainability.

The final chapters translate these principles into environmental monitoring. Water, soil, and sediment are considered not as isolated matrices but as connected compartments within source-to-exposure systems. Surface water can reveal current discharges and watershed processes; groundwater records mobility and subsurface persistence; wastewater reflects community and industrial inputs; soils integrate land-use pressures; and sediments preserve both recent and historical contamination while acting as potential secondary sources. Monitoring design must therefore connect the analytical measurement to location, time, depth, hydrology, particle characteristics, and the environmental question being addressed.

Throughout the book, emphasis is placed on contaminants and challenges that illustrate the breadth of the field, including pharmaceuticals, personal care products, pesticides, PFAS, micro- and nanoplastics, tobacco- and vaping-related residues, transformation products, and engineered nanomaterials. These examples differ in structure, environmental behavior, and biological activity, but they share a common requirement: reliable evidence must connect chemical occurrence with environmental processes and realistic exposure.

The intended readership includes researchers, graduate and advanced undergraduate students, analytical chemists, environmental scientists, toxicologists, professionals involved in water and soil quality, and decision-makers who need to interpret analytical information. Readers may use the book sequentially or consult individual chapters according to their interests. The learning objectives, comparative tables, practical considerations, and key messages are designed to support both teaching and professional reference.

This book does not attempt to provide a permanent catalogue of every contaminant of emerging concern. Such a list would quickly become incomplete. Its aim is instead to develop transferable concepts and analytical criteria that remain useful as new substances, matrices, and technologies appear. The essential questions are enduring: What should be measured? Where and when should samples be collected? Which analytical fraction is relevant? How reliable is the result? What does the measurement reveal about exposure or environmental change? And how can the evidence guide prevention, monitoring, remediation, and regulation?

Emerging contaminants demonstrate that scientific visibility carries responsibility. Detecting a substance does not automatically prove risk, but failing to investigate persistent, biologically active, or widely distributed contaminants can delay protective action. The most constructive path lies between alarm and complacency: rigorous measurement, proportionate interpretation, transparent uncertainty, and sustained collaboration across disciplines. It is hoped that this book contributes to that path and helps transform analytical information into knowledge capable of protecting ecosystems and human health.

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About the Author

María Carolina Talio holds a PhD in Biochemistry and is a researcher and faculty member at the Universidad Nacional de San Luis, Argentina. She is affiliated with the Instituto de Química de San Luis (INQUISAL), a research institute of the National Scientific and Technical Research Council of Argentina (CONICET) and the Universidad Nacional de San Luis. Her teaching and research activities are centered on analytical chemistry, general and inorganic chemistry, environmental monitoring, and the development of sensitive and sustainable methodologies for trace analysis. Her work includes fluorescence and solid-surface fluorimetry, chromatographic methods, micellar media, metallic nanoparticles, metal-organic frameworks, and other nanomaterial-assisted analytical platforms. These approaches have been applied to contaminants and trace elements in natural waters, foods, plant materials, biological samples, soils, sediments, and aquatic organisms. Her current scientific interests integrate analytical method development, Green Analytical Chemistry, human exposure, ecotoxicology, and the monitoring of emerging contaminants, including pesticides, pharmaceuticals, tobacco-related residues, and potentially toxic elements. She also supervises students and early-career researchers and participates in scientific publishing and academic evaluation activities.

Chapter 1
Emerging Environmental Contaminants: Concepts, Scope, and Significance

Introduction

Environmental pollution has traditionally been described through a relatively limited set of well-characterized hazards: toxic metals, persistent organic pollutants, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, chlorinated pesticides, and other substances for which occurrence, persistence, and toxicity had already been demonstrated. This framework was essential for the development of environmental legislation and remains indispensable today. Nevertheless, it is no longer sufficient to represent the chemical complexity created by contemporary patterns of production, consumption, health care, agriculture, and waste generation.

During the last three decades, improvements in analytical chemistry have revealed thousands of substances in water, soil, sediment, air, food, wildlife, and human samples at concentrations that were previously inaccessible to routine measurement. Some of these compounds have been used for many years but were not included in conventional monitoring programs; others result from new technologies, changing consumption patterns, or environmental transformation of known chemicals. Their detection has changed the scientific understanding of pollution by showing that low environmental concentration, absence from a priority list, or limited persistence does not necessarily imply negligible relevance [1-4].

The terms *emerging environmental contaminants* (EECs) and *contaminants of emerging concern* (CECs) are used to describe this broad and evolving universe. The adjective *emerging* does not mean exclusively "newly manufactured." A contaminant may become emergent because it has only recently become analytically detectable, because its use or environmental release has increased, because a previously unknown effect has been identified, or because new evidence has changed its regulatory priority. Emergence is therefore a relationship among chemical occurrence, analytical capability, scientific knowledge, societal concern, and regulatory attention [2-5].

This distinction is important. The category includes well-established chemicals such as pharmaceuticals, personal care product ingredients, pesticides, plastic additives, per- and polyfluoroalkyl substances (PFAS), tobacco-related compounds, and industrial chemicals. It may also include transformation products, engineered nanomaterials, micro- and nanoplastics, disinfection by-products, artificial sweeteners, illicit drugs, and naturally occurring toxins whose distribution has been altered by human activity. These substances differ substantially in molecular structure, polarity, persistence, bioavailability, and biological activity. Consequently, they cannot be treated as a single toxicological or analytical class.

The challenge is amplified by continuous release. Many EECs enter the environment every day through municipal wastewater, hospital effluents, agricultural runoff, industrial discharge, atmospheric deposition, landfill leachate, consumer-product use, and improper disposal. Even when an individual compound degrades relatively rapidly, repeated input may maintain measurable environmental concentrations. Moreover, environmental exposure rarely involves one substance at a time. Organisms and human populations encounter dynamic mixtures containing parent compounds, metabolites, transformation products, and co-occurring conventional pollutants.

This chapter establishes the conceptual foundation for the book. It examines how the idea of an emerging contaminant developed, clarifies the terminology used throughout the text, summarizes the major contaminant groups and release pathways, and explains why analytical chemistry is central to identifying and interpreting these substances. Detailed discussions of sampling, sample preparation, instrumental methods, nanomaterial-assisted sensing, environmental monitoring, and human biomonitoring are reserved for subsequent chapters.

From priority pollutants to contaminants of emerging concern

The twentieth-century regulatory model was built largely around compounds that were persistent, bioaccumulative, toxic, produced at high volumes, or associated with obvious contamination events. Priority lists enabled governments and laboratories to standardize sampling, analytical methods, quality criteria, and emission limits. This target-oriented model remains necessary because it creates comparability and legal enforceability. Its limitation is that the number of chemicals in commerce and in environmental mixtures is far greater than the number routinely monitored.

The development of gas and liquid chromatography, tandem mass spectrometry, high-resolution mass spectrometry, sensitive spectroscopic techniques, and improved sample-preparation methods progressively reduced detection limits and expanded the range of analytes that could be investigated. Groundwater and wastewater studies demonstrated that polar, mobile, and biologically active chemicals could pass through treatment systems and occur far from their points of use [6,7]. At the same time, bibliometric and historical analyses showed rapid growth in research on pharmaceuticals and other previously overlooked contaminants [8].

Pharmaceuticals provide a representative example. Their environmental presence was not a consequence of a single discovery or spill. It emerged gradually from advances in analytical capability, rising consumption, continuous excretion, incomplete removal during wastewater treatment, and increasing awareness of chronic ecological effects. Daughton and Ruhoy used the concept of "pseudo-persistence" to describe substances that may not be intrinsically persistent but remain continuously present because their environmental input exceeds their removal [9]. This concept broadened concern beyond the classical emphasis on long-lived organic pollutants.

The analytical expansion also changed the questions being asked. Target analysis determines known compounds selected before measurement and remains essential for routine monitoring and regulatory compliance. Suspect screening searches for compounds anticipated from databases, use patterns, or transformation pathways, even when authentic standards are not initially available. Non-target analysis attempts to characterize previously unanticipated signals. Together, these approaches have shown that conventional priority lists capture only a fraction of environmental chemical space [10].

Scientific networks subsequently developed frameworks to prioritize substances on the basis of occurrence, analytical feasibility, persistence, toxicity, and knowledge gaps. The NORMAN Network has played an important role in coordinating European information on emerging substances and in connecting research laboratories with environmental policy [11,12]. More broadly, the planetary-boundary discussion on novel entities has emphasized that the production and release of chemicals and materials may exceed society's capacity to evaluate and manage them [13]. Although such global frameworks do not replace compound-specific risk assessment, they demonstrate why emerging contaminants are not a temporary list but a continuing feature of environmental science.

Terminology and defining attributes

No single definition of an emerging environmental contaminant has been universally adopted. The terms *emerging pollutant*, *emerging contaminant*, and *contaminant of emerging concern* overlap, but they carry slightly different implications. A contaminant is a substance present where it would not normally occur, or at a concentration above its expected background. The word *pollutant* generally implies evidence of harmful effects. Because harm is often uncertain when a substance first attracts attention, *contaminant of emerging concern* is frequently the more scientifically cautious term [2,11].

In this book, EEC is used as an inclusive term for chemical substances, particles, or biologically active agents that meet one or more of the following conditions:

- they are not routinely included in established environmental monitoring programs;
- they are unregulated or only partially regulated in one or more relevant jurisdictions;
- evidence of their occurrence, persistence, mobility, bioaccumulation, toxicity, or exposure significance is recent or incomplete;
- improvements in analytical methods have newly enabled their reliable detection;
- changes in production, use, disposal, or environmental conditions have increased their release;

- transformation products or mixture effects create concerns not represented by assessment of the parent compound alone.

These criteria intentionally avoid defining EECs only by concentration. Many substances occur at nanogram-per-liter or microgram-per-liter levels, but concentration alone does not establish risk. Biological potency, exposure duration, toxicokinetics, species sensitivity, mixture interactions, and the timing of exposure are also important. Endocrine-active chemicals, for example, may require assessment approaches that account for sensitive developmental windows and nontraditional dose-response behavior. Conversely, analytical detection does not by itself demonstrate an unacceptable health risk. Reliable interpretation requires an explicit distinction among detection, exposure, hazard, and risk.

Several attributes recur across the category. Continuous discharge can produce pseudo-persistence; polarity and ionization can favor mobility in water; hydrophobicity can promote association with sediments, organic matter, or biota; and resistance to degradation can support long-range transport. Some substances are deliberately bioactive, as in the case of medicines and pesticides. Others become hazardous through additives, impurities, particle properties, or transformation reactions. The category is therefore best understood as a problem-oriented framework rather than a rigid chemical taxonomy.

Major classes of emerging environmental contaminants

Classification helps organize monitoring priorities, but no single scheme is adequate for all purposes. Compounds may be grouped by use, source, physicochemical behavior, biological effect, regulatory status, or analytical requirements. Table 1.1 presents a practical classification based primarily on use and origin.

Table 1.1. Principal groups of emerging environmental contaminants

Group	Representative examples	Major release pathways	Principal concerns
Human and veterinary pharmaceuticals	Antibiotics, analgesics, anti-inflammatory drugs, antidepressants, antiepileptics, beta-blockers, hormones, cytotoxic drugs	Excretion, hospitals, manufacturing, animal production, improper disposal	Chronic biological activity, antimicrobial resistance, effects on aquatic organisms
Personal care and household products	Parabens, UV filters, synthetic musks, triclosan, fragrances, surfactants	Domestic wastewater, bathing, cleaning, direct wash-off	Continuous discharge, endocrine activity, incomplete removal
Pesticides and transformation products	Neonicotinoids, phenoxy herbicides, sulfonylureas, glyphosate-related compounds, fungicides	Agricultural runoff, spray drift, leaching, soil erosion	Non-target toxicity, mixture exposure, mobile or persistent transformation products
PFAS and industrial additives	PFOA, PFOS, short-chain and precursor PFAS, flame retardants, plasticizers, bisphenols	Industrial emissions, products, firefighting foams, landfills, wastewater	Extreme persistence, mobility, bioaccumulation, broad human exposure

Group	Representative examples	Major release pathways	Principal concerns
Micro- and nanoplastics	Fibers, fragments, beads, tire-wear particles, cigarette-filter fibers	Textile washing, plastic degradation, urban runoff, waste, tobacco litter	Particle effects, transport of additives and sorbed chemicals, analytical uncertainty
Tobacco- and vaping-related contaminants	Nicotine, cotinine, PAHs, metals, flavoring compounds, cellulose acetate fibers, battery and cartridge residues	Cigarette butts, smoke and aerosol deposition, e-liquid spills, electronic waste	Aquatic toxicity, chemical leaching, plastic pollution, human exposure
Engineered nanomaterials	Metallic and metal-oxide nanoparticles, quantum dots, carbon nanomaterials, advanced porous materials	Manufacturing, consumer products, medical applications, disposal	Size-dependent behavior, transformation, aggregation, bioavailability
Transformation and disinfection by-products	Metabolites, photoproducts, oxidation products, chlorination and ozonation by-products	Environmental degradation and water treatment	Unknown identity, altered mobility, toxicity different from parent compounds

Pharmaceuticals and personal care products

Pharmaceuticals are continuously introduced into wastewater after human and veterinary use, and conventional treatment does not remove all compounds equally. Global surveys have documented pharmaceutical occurrence in rivers across diverse socioeconomic and climatic settings [14,15]. The environmental relevance of pharmaceuticals arises not only from their frequency of detection but also from their design: active ingredients interact with biological targets at therapeutic doses, and some targets are conserved across species. Antibiotics raise an additional concern because environmental residues may contribute to selective pressure associated with antimicrobial resistance [16,17].

Personal care and household products enter wastewater mainly through routine use. Preservatives, UV filters, fragrances, surfactants, disinfectants, and antimicrobial agents may be discharged daily by large populations. Reviews of personal care products have identified substantial variation in occurrence, persistence, and ecotoxicity [18]. Triclosan illustrates how a widely used ingredient can become an environmental concern after evidence accumulates regarding persistence, transformation, biological effects, and the limitations of product-level regulation [19].

Pesticides and agricultural contaminants

Pesticides differ from many other EECs because they are intentionally biologically active and deliberately released into the environment. Some are already regulated, yet they may still be considered emerging concerns when new uses, metabolites, mixture patterns, or sensitive endpoints are identified. Transformation can decrease toxicity, but it can also generate products that are more mobile, persistent, or difficult to detect than the parent compound [20]. Surveys of agricultural soils have demonstrated that multiple currently used pesticide residues can coexist long after application [21]. The challenge is therefore not a simple opposition between agricultural benefit and environmental protection, but the development of monitoring and management systems that preserve food production while reducing unnecessary exposure [22].

PFAS and persistent industrial chemicals

PFAS represent a particularly important group because the strength of the carbon-fluorine bond produces exceptional resistance to environmental degradation. Thousands of PFAS have been associated with industrial processes and consumer products, while most historical monitoring focused on a small number of well-known compounds [23]. The combination of persistence, mobility, diverse precursor chemistry, and incomplete toxicological information has complicated both analysis and regulation. Recent assessments have argued that the global distribution of PFAS is incompatible with conventional assumptions about localized contamination [24]. Harmonized terminology is also critical because different structural definitions produce substantially different estimates of the number of substances included in the PFAS universe [25].

Microplastics, nanoplastics, and particle-associated contamination

Microplastics and nanoplastics challenge monitoring systems designed primarily for dissolved chemicals. Their environmental behavior depends on size, shape, polymer composition, aging, surface chemistry, and associated additives. They may also interact with metals and organic contaminants, although the environmental significance of vector effects must be evaluated case by case. Reviews have documented major gaps in sampling comparability, particle identification, reference materials, and dose metrics [26]. Concern about human exposure has grown, but evidence must be interpreted carefully because analytical contamination and incomplete method harmonization remain important limitations [27].

Cigarette filters are a major and often overlooked source of cellulose acetate microfibers. Discarded cigarette butts can release nicotine, metals, organic chemicals, and plastic fibers into water and soil [28,29]. Their effects extend beyond visible litter, and experimental evidence indicates adverse responses in aquatic organisms and ecosystem components [30]. Electronic cigarettes add a different waste stream involving cartridges, residual liquids, plastics, metals, and batteries. These products illustrate how changing consumer behavior can create new combinations of chemical and material contaminants before monitoring and waste-management systems are fully prepared.

Sources and environmental pathways

EECs arise from both point and diffuse sources. Point sources include industrial outfalls, pharmaceutical manufacturing, hospitals, wastewater-treatment facilities, mines, landfills, and waste-processing sites. Diffuse inputs include agricultural runoff, urban stormwater, atmospheric deposition, household product use, transport-related particles, and litter. A single contaminant may have several sources, while a single source may release hundreds of chemicals.

Municipal wastewater-treatment plants are central nodes in this network. They receive complex mixtures from homes, commercial activities, hospitals, and small industries. Conventional treatment was developed primarily to remove suspended solids, biodegradable organic matter, nutrients, and pathogens, not the complete universe of trace organic contaminants. Removal varies according to biodegradability, sorption, volatility, hydraulic retention, treatment configuration, temperature, and operational conditions. Some compounds are efficiently degraded, some partition into sludge, and others pass into receiving water. Treatment may also generate transformation products that require separate analytical attention [7,31,32].

Agricultural systems receive veterinary drugs, pesticides, fertilizers, manure, biosolids, and reclaimed wastewater. These inputs interact with soil mineralogy, organic matter, pH, microbial communities, and hydrological conditions. Rainfall and irrigation can transport dissolved substances and particle-bound residues toward surface water, while mobile compounds may reach groundwater. The use of treated wastewater and biosolids can support circular resource management, but it also requires monitoring strategies that account for contaminants not captured by conventional microbiological or nutrient criteria [20-22,33].

Urban environments combine wastewater, stormwater, traffic emissions, building materials, tire and road wear, consumer-product residues, litter, and atmospheric particles. Landfills and informal waste disposal can release mixed leachates containing pharmaceuticals, plastic additives, PFAS, metals, and transformation products. Climate and hydrology affect all these pathways: intense rainfall can mobilize stored contaminants, drought can reduce dilution, and rising temperature can alter degradation, volatilization, and biological uptake.

Environmental compartments are therefore connected rather than isolated. A compound discharged in wastewater may sorb to sediment, enter benthic organisms, move into floodplain soil, be taken up by crops irrigated with contaminated water, or reach groundwater.

Atmospheric transport can redistribute volatile and particle-associated substances across regional or global scales. This connectivity supports a source-to-exposure approach in which monitoring is designed around pathways and processes rather than around a single sample type [1,6,34].

Environmental fate, transformation, and mixture complexity

The environmental fate of an EEC is governed by its intrinsic properties and by the characteristics of the receiving environment. Molecular size, aqueous solubility, acid dissociation constants, vapor pressure, and distribution coefficients influence partitioning among water, particles, sediments, air, and biota. For ionizable compounds, pH-dependent speciation can substantially change sorption, membrane transport, and analytical recovery. Temperature, light, redox conditions, dissolved organic matter, and microbial activity further affect transformation.

Degradation should not automatically be equated with detoxification. Hydrolysis, photolysis, biodegradation, oxidation, and water-treatment processes can generate products with different polarity, persistence, and biological effects. Some transformation products are transient; others are more mobile or more stable than their parent compounds. Analytical methods targeting only the original substance may therefore underestimate total exposure or misinterpret removal efficiency [20]. A decrease in the parent-compound signal is evidence of transformation, not necessarily complete mineralization.

Mixtures add another level of complexity. Environmental samples contain chemicals at different concentrations and with different modes of action. Additive effects are plausible when compounds act through similar pathways, while synergistic or antagonistic interactions may occur in particular systems. Even when individual chemicals are below effect thresholds, the combined biological activity of a mixture may be relevant. Effect-based methods and bioassays can complement chemical analysis by measuring integrated biological responses, but they generally cannot identify all causative substances. Conversely, high-resolution chemical screening can characterize many features without directly establishing their biological significance. A robust assessment therefore combines targeted measurement, broader chemical screening, effect-based evidence, and exposure modeling [35].

The mixture perspective also exposes a limitation of compound-by-compound regulation. Chemical production and diversity are expanding faster than complete hazard and exposure assessments can be performed. Planetary-boundary analyses have used this imbalance to argue for preventive approaches, greater transparency, safer chemical design, and group-based management where scientifically justified [13,36]. For analytical science, the practical consequence is a need to prioritize intelligently while retaining the capacity to detect unexpected contaminants.

Ecological and human health significance

The ecological significance of EECs depends on exposure, bioavailability, sensitivity, and biological effect. Acute mortality is only one possible endpoint. Chronic exposure may alter growth, reproduction, development, behavior, immune responses, endocrine signaling, or community structure. Pharmaceuticals and pesticides may affect nontarget organisms through conserved receptors or physiological pathways. Antibiotics can influence microbial communities and resistance selection. Particle-associated contaminants can produce physical and chemical effects that differ from those of dissolved substances.

Endocrine-disrupting chemicals illustrate why traditional assumptions may be insufficient for some contaminant classes. Timing of exposure, developmental stage, and receptor-mediated mechanisms can be as important as the administered dose. The scientific literature has connected endocrine-active environmental chemicals with reproductive, developmental, metabolic, and neuroendocrine outcomes, while also emphasizing the need for rigorous exposure characterization [37]. These complexities do not justify treating every detection as evidence of harm, but they do require methods capable of measuring biologically relevant compounds at appropriate temporal and spatial scales.

Human exposure may occur through drinking water, food, inhalation, dermal contact, consumer products, occupational settings, and tobacco-related sources. The contribution of each pathway varies among contaminants and populations. Vulnerability is also unequal: children, pregnant individuals, workers, communities near emission sources, and populations with limited access to safe water or waste management may experience different exposure profiles.

The exposome was proposed to complement genomic information by considering the totality of environmental exposures across the life course [38]. Later definitions integrated external exposures, internal chemical processes, and biological responses [39,40]. Human biomonitoring contributes to this framework by measuring contaminants, metabolites, or effect markers in biological matrices such as blood, urine, hair, nails, saliva, and breast milk [41]. It integrates multiple exposure routes but also introduces interpretive challenges related to toxicokinetics, sampling time, biological variability, and the distinction between exposure biomarkers and effect biomarkers.

The One Health framework further emphasizes that human, animal, plant, and ecosystem health are interdependent [42,43]. For EECs, this is more than a conceptual slogan. Antimicrobial resistance, contaminated food chains, wildlife effects, wastewater reuse, and occupational exposure all cross disciplinary and institutional boundaries. An integrated approach can connect environmental monitoring with ecotoxicology, veterinary science, public health, and risk management.

Analytical chemistry as an enabling science

Emerging-contaminant research is inseparable from analytical capability. A substance may be environmentally present yet remain scientifically invisible if available methods lack adequate sensitivity, selectivity, recovery, or identification confidence. Conversely, an instrumental signal becomes useful environmental evidence only when sampling, calibration, quality assurance, data processing, and uncertainty are adequately controlled.

Targeted chromatography coupled to tandem mass spectrometry remains central for reliable quantification of known organic contaminants. High-resolution mass spectrometry has expanded suspect and non-target screening by providing accurate-mass data, isotope patterns, fragmentation information, and retrospective analysis [44]. However, tentative identification must be communicated transparently. The confidence-level framework proposed by Schymanski and co-workers distinguishes confirmed structures from probable structures, tentative candidates, formulas, and exact-mass features [45]. This distinction prevents an unconfirmed signal from being reported as a fully identified contaminant.

Spectroscopic, luminescent, electrochemical, immunochemical, and biosensing approaches provide complementary advantages. Many can reduce cost, analysis time, or instrument complexity and can support screening or field deployment. Nanomaterials, molecular recognition elements, solid supports, and microfluidic systems may improve sensitivity and selectivity. Their performance must nevertheless be evaluated in real matrices and compared against appropriate reference methods. Very low detection limits alone do not demonstrate fitness for environmental monitoring.

The analytical process begins before the instrument. Sampling design must represent spatial and temporal variability; containers and preservation conditions must minimize analyte loss or contamination; and sample preparation must address matrix effects without compromising recovery. Method validation should include selectivity, calibration, detection and quantification limits, precision, trueness or recovery, robustness, and measurement uncertainty. Quality-control samples, blanks, reference materials, and confirmatory analysis are particularly important when concentrations approach the limits of detection.

Sustainability is increasingly part of analytical quality. Green Analytical Chemistry evaluates reagent hazard, solvent consumption, energy use, waste generation, miniaturization, and operator safety. Tools such as the Analytical Eco-Scale and more recent greenness metrics provide structured ways to compare procedures [46,47]. These assessments should complement, rather than replace, conventional validation. An environmentally benign method that produces unreliable data is not sustainable, while a highly accurate method with excessive resource use may still require redesign.

Recent reviews describe a rapid convergence of high-resolution instrumentation, portable sensing, data science, and advanced treatment-monitoring technologies [48]. The objective is not to select a single universally superior technique. It is to construct a defensible analytical strategy aligned with the contaminant, matrix, concentration range, decision context, available resources, and required degree of identification certainty.

Regulatory and monitoring landscape

Regulation of EECs is necessarily dynamic. The European Water Framework Directive established a broad framework for protecting surface water and groundwater, while subsequent priority-substance and watch-list mechanisms created pathways for collecting occurrence data on substances that may require future regulation [49]. The European Union's 2025 watch list illustrates the continuing revision of Union-wide monitoring priorities as evidence and analytical capability evolve [50].

In the United States, the Drinking Water Contaminant Candidate List identifies substances that are not subject to national primary drinking-water regulations but may require future action. The final CCL 5 included individual chemicals, chemical groups such as PFAS, cyanotoxins, and disinfection by-products, and microbial contaminants [51]. The Fifth Unregulated Contaminant Monitoring Rule required monitoring for 29 PFAS and lithium during the 2023-2025 sampling period, generating national occurrence data to inform regulatory decisions [52]. These programs demonstrate how analytical feasibility and occurrence data precede many regulatory determinations.

International initiatives provide additional coordination. NORMAN databases and prioritization tools organize occurrence, ecotoxicity, and screening information for emerging substances [11,12]. The United Nations Environment Programme has emphasized the global growth of chemical production and the unequal capacity of countries to monitor and manage chemical risks [53]. The One Health Joint Plan