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REVIEW

From Bench to Field: Evolving Analytical Techniques in Environmental Testing

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ABSTRACT

The field of environmental testing is rapidly changing from laboratory-based measurements to field-deployable, real-time, and data-integrated monitoring systems. Conventional methods such as chromatography, mass spectrometry, atomic spectroscopy, and molecular spectroscopy remain essential due to their high sensitivity, selectivity, reproducibility, and regulatory confidence. They are, however, limited in their usefulness due to the need for lab facilities, complicated preparation, and reporting lag times under changing environmental conditions. This review's distinctive contribution is the development of a hybrid bench-to-field monitoring framework that conceptualizes environmental testing as an integrated system rather than a collection of separate analytical techniques. In this framework, laboratory-based methods provide reference accuracy, confirmatory power, and regulatory defensibility, while field-deployable sensors, portable instruments, remote platforms, and IoT-enabled networks provide rapid screening, spatial coverage, real-time warning, and adaptive decision support. By linking analytical performance, field applicability, data analytics, validation, uncertainty assessment, and regulatory translation, the review provides a conceptual pathway for transforming emerging technologies into reliable environmental monitoring systems. There is a key lesson here: future environmental testing will not be based on the elimination of lab testing practices, but on the ability to marry lab accuracy and field responsiveness. The use of hybrid monitoring frameworks and chemometrics, artificial intelligence tools, validation protocols, and uncertainty assessment will be key to producing reliable, actionable, and scientifically defensible environmental data.

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1. Introduction

Environmental testing now plays a key role in scientific and regulatory analyses of the quality of water, soil, air, sediments, food chains, and ecosystems that are subjected to natural and anthropogenic stressors [1]. The complexity of environmental contamination, resulting from industrialization, urbanization, intensive agriculture, mining activities, use of pharmaceuticals, electronic waste management, and climate-induced redistribution of contaminants, has led to a rising need for analytical approaches that are sensitive, selective, and fast, and can be portable, sustainable, and used for real-time decision-making. Traditional environmental analysis has been limited to a centralized laboratory process of sample collection, preservation, transportation, pretreatment, instrumental determination, and post-analysis interpretation. Due to their high accuracy, low detection limits, broad analyte coverage, and broad regulatory acceptance, these approaches remain essential, particularly those that use gas chromatography, liquid chromatography, mass spectrometry, atomic spectrometry, and molecular spectroscopy. Recent problems with sample degradation during transport, the need for trained personnel, the cost of sophisticated instrumentation, and the time lag between sampling and reporting, however, have brought the drawbacks of laboratory-based testing models to new prominence [2,3].

Today, the analytical ecosystem of environmental testing is dramatically shifting from traditional bench- and lab-based approaches to field-based, miniaturized, automated, and intelligent monitoring [4]. This shift does not mean a paradigm change in the use of traditional laboratory methods; however, it points to the development of an analytical system in which high-performance laboratory instruments, portable detection methods, sensor networks, remote sensing methods, and data-driven interpretation systems are integrated. In this evolving framework, laboratory-based methods are used for reference-level accuracy and confirmatory capability, and field-based methods for rapid screening, spatially resolved measurements, early warning, and continuous monitoring. In particular, it is significant for contaminants that exist at trace or ultra-trace levels, exhibit short-term variability in concentration, or can exist in multiple chemical forms, such as heavy metals, pesticides, pharmaceuticals and personal care products, endocrine-disrupting compounds, microplastics, PPCS, VOCs, pathogenic microorganisms, nutrients, and emerging transformation products [5,6].

The conceptual contribution of this review is the proposal of a hybrid bench-to-field monitoring framework for environmental testing. Rather than treating laboratory analysis, sample preparation, portable instrumentation, sensor networks, remote monitoring, and artificial intelligence as separate technical developments, this review organizes them as interdependent components of a single environmental decision-support system. In this framework, conventional laboratory methods remain essential for accuracy, trace-level quantification, confirmatory analysis, and regulatory confidence, whereas field-deployable and real-time technologies provide rapid screening, spatially resolved information, early warning, and adaptive monitoring. The novelty of the review therefore lies not simply in summarizing available techniques, but in clarifying how these approaches can be strategically combined, validated, and translated into practical monitoring programs [7–9].

Simultaneously, instrumental technologies have also advanced quickly. Contaminants can now be identified and quantified at very low levels using high-resolution mass spectrometry, tandem mass spectrometry, hyphenated chromatographic systems, inductively coupled plasma mass spectrometry, and advanced spectroscopic platforms. The scope of environmental testing has shifted from known-pollutant testing to suspect screening and non-target analysis of unknown compounds and their transformation products. However, they are typically costly, require infrastructure, and are not suitable for continuous deployment in the field. As a result, portable and miniaturized alternatives are becoming increasingly attractive. Portable gas chromatographs, portable mass spectrometers, handheld X-ray fluorescence analyzers, Raman and surface-enhanced Raman spectroscopy devices, portable infrared spectrometers, fluorescence probes, colorimetric kits, electrochemical sensors, biosensors, paper-based analytical devices, and microfluidic lab-on-a-chip systems are changing the ways environmental measurements are made. These technologies have the potential to reduce time to measurement from the time a sample is taken to the time it is analyzed, and to increase the spatial and temporal resolution of environmental data, thus significantly increasing the value of the data [10,11].

The emergence of sensor networks, Internet of Things (IoT)-based monitoring systems, unmanned aerial vehicles, autonomous sampling platforms, and remote sensing technologies is closely coupled to the transition from the laboratory bench to environmental testing in the field. Environmental pollution is not static; pollutant levels vary with rainfall, temperature, industrial discharge patterns, land use, hydrology, atmospheric transport, and seasonal biological activity. Traditional grab sampling may thus fail to detect short-term pollution events or spatial heterogeneity. These limitations can be overcome by field-deployable and real-time monitoring technologies, which provide continuous or near-continuous data sets. These can be complemented by wireless communication systems, cloud-based storage, geospatial mapping, and machine learning algorithms to aid early-warning systems, identification of pollution sources, assessment of exposure, and adaptive environmental management. These are important applications for emergency response, industrial accident monitoring, drinking water safety, agricultural runoff control, and urban air quality surveillance [12].

Despite these developments, it is difficult to translate some of the new analytical methods from research prototypes into routine environmental use. In addition to sensitivity in controlled laboratory conditions, a number of field-deployable sensors and portable devices have shown potential to perform in the field but are not as sensitive in real environmental matrices because of fouling, temperature changes, humidity, salinity, matrix interference, sensor drift, limited selectivity, and calibration instability. Also, results from field-based devices do not always translate easily to the results from standard laboratory methods. Method validation, detection limits, method reproducibility, uncertainty estimation, data comparability, quality assurance, and regulatory acceptance are still important challenges. The success of environmental testing in the future will rely not just on the creation of new analytical instruments but also on the development of robust validation protocols, standardized performance criteria, data-processing frameworks, and decision-making models that effectively link real-time in-field measurements to legally sound laboratory-based ones [13–15].

The uniqueness of this review lies in its integration of analytical technologies into a hybrid monitoring framework that connects bench-based accuracy with field-based responsiveness. Unlike reviews that focus on a single contaminant class, platform, or sensing technology, this review examines how sample preparation, laboratory reference methods, portable instruments, sensor networks, remote monitoring, chemometrics, artificial intelligence, validation protocols, and regulatory requirements interact across the full environmental testing workflow. This framework emphasizes complementarity rather than replacement: laboratory methods anchor data quality and regulatory defensibility, while field technologies expand temporal resolution, spatial coverage, and early-warning capacity.

A unique aspect of this review is the emphasis on the practical pathway from research innovation to field application and regulatory use. Sensitivity, selectivity, and detection limit are used to assess analytical technologies in environmental analysis. These parameters are necessary, but do not provide a definitive answer to whether a method can be implemented in a real monitoring program. The following, therefore, examines other factors such as portability, cost, simplicity of operation, robustness, tolerance to matrices, calibration needs, maintenance, data reliability, and compatibility with existing regulatory frameworks. The review will consider the analytical and practical aspects of both bench-based and field-based approaches to compare and contrast the advantages and disadvantages of each method and how new technologies can be incorporated. In light of this, the review details the developments in the analytical toolbox for environmental testing [16]. The overall conceptual transition from centralized bench-based analysis to field-responsive environmental monitoring is illustrated in **Figure 1**.

It first reviews known laboratory techniques and their ongoing use as reference techniques. It then discusses developments in sample preparation and preconcentration to improve sensitivity, minimize solvent use, and miniaturize the workflow. Later sections focus on new instrumental and sensor technologies, such as portable spectroscopic, electrochemical, biosensing, nanomaterial-based, and microfluidic platforms. Field-deployable and real-time monitoring systems are then reviewed, with a focus on in situ analysis, remote sensing, UAS, and connected sensor networks. Lastly, it addresses data analysis, method validation, method standardization, and regulatory translation as key enablers for the successful transfer of technologies into sound environmental use. In this structure, the article aims to explain the evolution of environmental analytical techniques and how they could be integrated strategically to meet future needs for faster, greener, more intelligent, and more actionable environmental testing [17].

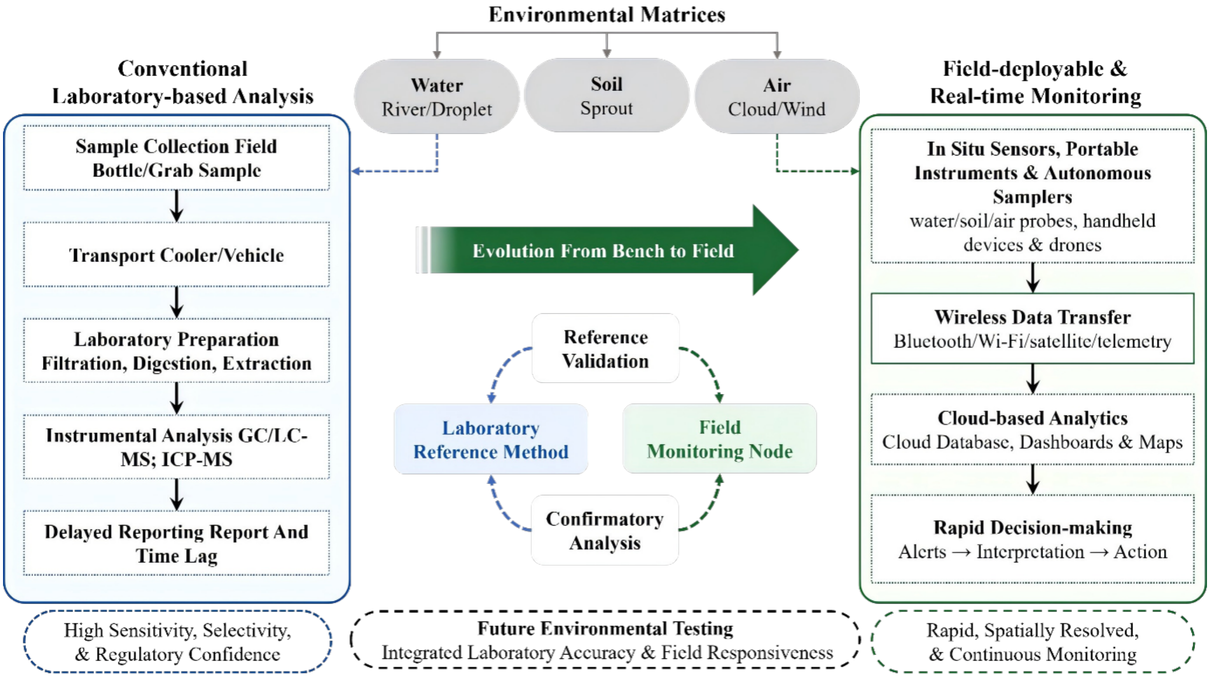

Figure 1. Conceptual framework illustrating the evolution of environmental testing from centralized laboratory-based analysis to field-deployable, real-time, and data-integrated monitoring systems. The framework highlights that emerging field technologies complement rather than replace laboratory reference methods.

2. Conventional Laboratory-Based Analytical Techniques

Traditional laboratory analyses continue to be the backbone of environmental testing, as they offer the accuracy, sensitivity, repeatability, and legal validity necessary for regulatory monitoring and scientific evaluation. While field-deployable sensors and real-time monitoring systems have recently grown in significance, laboratory methods remain important platforms for testing and assessing new sensors and monitoring systems. They are not only instrumentally sophisticated but also have standardized workflows that include sampling, preservation, pretreatment, calibration, quality assurance, and data verification. These controlled conditions are crucial in environmental analysis, where contaminants are frequently present in chemically complex matrices, and levels are usually trace or ultra-trace [18,19].

However, conventional techniques are not without limitations. Most require expensive instrumentation, skilled operators, labor-intensive sample preparation, and centralized laboratory infrastructure. The delay between sample collection and result generation may reduce their usefulness in emergency response or dynamic pollution events. Moreover, transportation and storage can alter sample integrity, particularly for unstable organic compounds, redox-sensitive species, volatile analytes, and biologically active contaminants. Therefore, the role of conventional methods must be understood critically: they offer analytical reliability and regulatory confidence, but they are often less suited to rapid, distributed, or continuous environmental surveillance [20].

2.1. Chromatographic Techniques for Organic Contaminant Analysis

Spectroscopic methods are important for the environmental testing of metals and metalloids, nutrients, and inorganic species. Elemental analysis of water, soil, sediment, atmospheric particles, and biological samples is commonly performed by atomic absorption spectroscopy, inductively coupled plasma optical emission spectroscopy, and inductively coupled plasma mass spectrometry [21]. Of these, ICP–MS is the most sensitive and multi-element capable, and is particularly useful for ultra-trace analysis of toxic elements such as arsenic, cadmium, mercury, lead, chromium, and rare earth elements.

The main benefits of elemental spectroscopy are its large dynamic range, excellent precision and compatibility with current regulatory procedures. The ICP-based methods can be used to analyze several elements in a single sample, which is beneficial for environmental risk assessment, where metal mixtures are often found. However, elemental methods are typically performed after acid digestion or extraction before measurement, which often significantly affects data quality due to the degree of digestion. In solid matrices, analytes may be under- or not completely dissolved or redistributed during the preparation, which can result in under- or poor reproducibility. Moreover, the concentrations of elements do not necessarily correlate with their mobility, bioavailability or toxicity in the environment. For instance, the toxicity of chromium, arsenic, and mercury is species-dependent, and speciation analysis is often more informative than measuring only the total concentration [22,23].

Environmental characterization is also possible by molecular spectroscopic techniques, such as UV–Vis, Fourier-transform infrared, fluorescence, and Raman. These are relatively easy, rapid, and cheap and can be used for the routine determination of nutrients, colorimetric assays, and some organic compounds. FTIR and Raman spectroscopy are increasingly popular methods for polymer identification, especially for microplastic analysis. These methods can, however, have weak sensitivity and spectral overlap in more complex environmental samples. They are dependent on sample preparation, spectral libraries, and data-processing algorithms. Therefore, spectroscopy is fast and, in some instances, non-destructive, but in other situations, complementary techniques may be needed for high selectivity or trace-level quantification [24,25].

2.2. Spectroscopic and Elemental Analysis Techniques

Environmental testing of metals and metalloids, nutrients, and inorganic species is important by spectroscopic methods. Elemental analysis of water, soil, sediment, atmospheric particles and biological samples is typically done using atomic absorption spectroscopy, inductively coupled plasma (ICP) optical emission spectroscopy, and ICP mass spectrometry. Of these, ICP–MS is the most sensitive and multi-element capable, and is particularly useful for the ultra-trace analysis of toxic elements like arsenic, cadmium, mercury, lead, chromium and rare earth elements [26].

The main benefits of elemental spectroscopy are its large dynamic range, excellent precision and compatibility with current regulatory procedures. The ICP-based methods can be used to analyze several elements in a single sample, which is beneficial for environmental risk assessment, where metal mixtures are often found. Elemental methods, however, are usually performed after digestion or extraction of the sample, before measurement, which may significantly affect the result, depending on the extent of digestion or extraction. In solid matrices, analytes can be under- or not fully dissolved or redistributed when preparing the sample, leading to under- or poor reproducibility. Furthermore, the concentration of elements is not always related to their mobility, bioavailability or environmental toxicity. The toxicity of chromium, arsenic, and mercury, for example, is species-specific, and a speciation analysis may be more useful than just measuring the total concentration.

Molecular spectroscopic methods, such as UV–Vis, Fourier-transform infrared (FTIR), fluorescence, and Raman, can also be used for environmental characterization. These are comparatively simple, fast and inexpensive and may be employed in the routine determination of nutrients, colorimetric assays, and some organic compounds. FTIR and Raman spectroscopy are increasingly adopted techniques for polymer identification, particularly for the analysis of microplastics. These methods can, however, have weak sensitivity and spectral overlap in more complex environmental samples. They are dependent on sample preparation, spectral libraries, and data-processing algorithms. Therefore, spectroscopy is fast and, in some instances, non-destructive, but in other situations, complementary techniques may be needed for high selectivity or trace-level quantification [24,27].

2.3. Electrochemical and Classical Analytical Methods

An important class of conventional and semi-conventional methods applied to environmental testing is electrochemical methods. The ions, metals, nutrients, dissolved oxygen, pH, and redox-active pollutants have been detected using potentiometry, voltammetry, amperometry, or conductometry. The methods are appealing due to their low costs, high sensitivity for select analytes, and their promise of miniaturization. Preconcentration at the electrode surface and electrochemical measurement can be combined to detect very low concentrations of trace metals, for example, using anodic stripping voltammetry [28].

Although this is beneficial, electrochemical methods are quite susceptible to interference from interfering species, ionic strength, pH, matrix composition, and electrode fouling. Electrode responses and reproducibility can be affected by dissolved organic matter, suspended particles, surfactants, and competing ions in real environmental samples. In this context, electrochemical methods have proven more successful for targeted measurements under well-controlled conditions than for contaminant screening. Their principles, however, have had a significant influence on the development of modern field sensors and biosensors, and they have thus been a stepping stone towards conventional laboratory analysis and field environmental monitoring.

In some aspects of environmental testing, classical analytical techniques such as titration, gravimetry, colorimetry and turbidity measurement are still applicable. They are simple, cheap and good for routine parameters like alkalinity, hardness, chloride, suspended solids, chemical oxygen demand, and biochemical oxygen demand, although not as sophisticated as chromatographic or mass spectrometric methods. They are still in use and this shows that the value of analytical use goes beyond the complexity of the technology. Simple standardized methods are often useful in many monitoring programs because they are acceptable, easy to implement, and are adequate for regulatory purposes. They are, however, not very sensitive and selective, meaning that they can only be used for certain contaminants and emerging pollutants [28].

2.4. Quality Assurance, Calibration, and Method Validation

Besides instrumental performance, the credibility of laboratory-based environmental testing is dependent on the quality of the laboratory procedures (quality assurance) and also on the validation of the method used. Analytical data may be influenced by a host of factors related to the sampling design, preservation, extraction efficiency, contamination, matrix effects, calibration strategy, and the analyst's skill. Environmental samples are subject to natural variation. As a result, the following criteria must be met to demonstrate the acceptability of a validated method: accuracy, precision, linearity, selectivity, detection and quantification limits, recovery, robustness, and measurement uncertainty.

Calibration is especially important in trace environmental analysis. Simple matrices can be calibrated from outside, while internal calibration, isotope dilution, standard addition and matrix-matched calibration are almost always required for complex matrices. Using Certified Reference Materials, procedural blanks, spiked recoveries, duplicate samples, and control charts improves data reliability. These practices separate laboratory-based methods from numerous methods emerging from the field, which can yield a rapid response but may not have the same level of validation depth [29].

Method validation can, however, also impede innovation. Standardized methods may lag behind the creation of new contaminants and transformation products. In some cases, regulatory requirements favor existing protocols over newer methods that can detect more or detect more quickly. This puts analytical conservatism in opposition to technological progress. One of the major challenges for environmental science is maintaining the rigor of laboratory validation while enabling the ready use of innovative methods.

2.5. Strengths and Limitations in Contemporary Environmental Testing

The major strength of conventional laboratory techniques is their ability to generate high-confidence data. They provide low detection limits, strong selectivity, structural information, multi-analyte capability, and compatibility with legal and regulatory requirements. For confirmatory analysis, pollutant source identification, risk assessment, and long-term monitoring, laboratory methods remain indispensable. A comparative overview of major conventional laboratory techniques, including their target analytes, strengths, limitations, and best-use scenarios, is provided in **Table 1**. They are especially important when environmental decisions have economic, legal, or public-health consequences [30].

Table 1. Comparative overview of conventional laboratory-based analytical techniques used in environmental testing.

Analytical Technique	Main Target Analytes	Typical Matrices	Major Strengths	Limitations	Best Use in Environmental Testing
GC and GC-MS	Volatile and semi-volatile organic compounds, PAHs, VOCs, pesticides, petroleum hydrocarbons	Air, water, soil, sediment	High separation efficiency, strong compound identification, regulatory acceptance	Limited suitability for polar or thermally unstable analytes; derivatization may be required	Confirmatory analysis of volatile and semi-volatile pollutants
HPLC, UHPLC, LC-MS/MS	Pharmaceuticals, hormones, pesticides, PFAS, endocrine disruptors, transformation products	Water, wastewater, sludge, biota	Suitable for polar and thermally labile compounds; excellent sensitivity and selectivity	Matrix effects, ion suppression, high cost, skilled operation	Trace analysis of emerging organic contaminants
ICP-OES and ICP-MS	Metals, metalloids, rare earth elements	Water, soil, sediment, particulate matter, biological samples	Multi-element detection, wide dynamic range, very low detection limits with ICP–MS	Requires digestion; total concentration may not indicate toxicity or bioavailability	Elemental monitoring and regulatory compliance
AAS	Selected metals and metalloids	Water, soil extracts, biological samples	Robust, established, relatively accessible	Single-element analysis, lower throughput than ICP methods	Routine metal analysis in standard monitoring laboratories
UV-Vis and fluorescence spectroscopy	Nutrients, dyes, organic matter, selected pollutants	Water, wastewater, extracts	Rapid, simple, low-cost	Limited selectivity, matrix interference, lower sensitivity for many trace pollutants	Screening and routine parameter measurement
FTIR and Raman spectroscopy	Microplastics, functional groups, selected organic materials	Particles, sediments, soils, polymers	Non-destructive molecular fingerprinting	Spectral overlap, matrix complexity, detection limit constraints	Polymer identification and qualitative characterization
Classical methods	Alkalinity, hardness, COD, BOD, suspended solids, chloride	Water and wastewater	Inexpensive, standardized, simple	Limited sensitivity and specificity	Routine environmental quality assessment

Meanwhile, their shortcomings are becoming more apparent in the face of contemporary environmental issues. Pollution events can be episodic, geographically variable, and very dynamic. Laboratory work that uses discrete sampling can either fail to detect short-term concentration spikes or not reflect spatial heterogeneity. Furthermore, central analyses are expensive and require significant resources, which can hinder monitoring activities in resource-poor areas. These are not weaknesses in the conventional methods themselves, but are a reminder of the need for complementary field-based methods.

So the future of laboratory methods is mainly about supporting environmental monitoring programs, which are now integrated systems and are likely to become the analytical backbone of these programs. Portable instruments and sensor networks will enhance monitoring coverage and responsiveness, while conventional methods remain as reference measurements, confirmatory evidence, and validation standards. The best environmental testing strategies will not be a choice between bench and field approaches, but rather the synergy of their strengths to achieve enhanced accuracy, speed, spatial resolution, and regulatory confidence [31].

3. Advances in Sample Preparation and Preconcentration

Sample preparation is one of the most critical steps of environmental testing as it affects the reliability, sensitivity, selectivity, and applicability of an analytical method. Direct instrumental analysis of environmental samples is seldom suitable. Suspended solids, dissolved organic matter, salts, humic substances, lipids, proteins, and other interfering components are common in water, soil, sediments, air particulate matter, sludge, and biological matrices; these can affect instrumental signals, contaminate analytical systems, and distort quantitative results. When the contaminant level is extremely low (trace and ultra-trace), the problem is even more difficult, as analytes may be present at levels below the instrumental detection limit or be strongly bound to matrix components. Thus, sample preparation is not only a precursor to the analytical process but also a significant analytical process in its own right that determines if environmental data are accurate, repeatable, and meaningful [9].

Conventionally, sample preparation involves steps to isolate target compounds, eliminate interfering compounds and enhance the concentration of analytes prior to measurement. But current environmental testing has a greater demand. Nowadays, preparation techniques should be faster, "greener," more selective, less solvent-based, easy to automate, and field-friendly. This represents a significant change in analytical science, as the benefit of a method is no longer solely determined by its instrumental sensitivity, but extends to its sustainability, ease of use, speed of analysis and applicability to practical monitoring. The advancement of analytical instruments toward greater sophistication and portability has made sample preparation a limiting step and a key area for innovation [32].

3.1. Traditional Sample Preparation Workflows

Traditional sample preparation techniques, such as liquid–liquid extraction, Soxhlet extraction, ultrasonic extraction, filtration, centrifugation, acid digestion, evaporation, and column chromatography, have long supported environmental analysis. The methodologies are well-proven and can be efficient at removing a wide spectrum of contaminants. Liquid–liquid extraction is still a valuable method for extracting hydrophobic organic compounds from aqueous samples, and both Soxhlet and ultrasonic extraction are commonly used for soils and sediments. Acid digestion is a common method for elemental analysis because it dissolves solids into solution, which can then be analyzed spectroscopically.

Many traditional methods are labor-intensive, time-consuming, and resource-intensive, yet reliable. They are not well-suited to the modern requirements of green, high-throughput analysis because of the large amounts of solvent used, the time required for extraction, and the number of handling steps involved. They are incompatible with the modern need for green, high-throughput analysis due to large solvent volumes, extended extraction times, multi-step handling, and high energy consumption. Additionally, the risk of contamination or loss of analyte increases with repeated transfer of samples, especially for volatile, unstable or strongly adsorptive compounds. This is particularly an issue for processing a large number of samples and for making rapid decisions in the event of a contamination incident. Hence, although traditional techniques remain relevant as well-established reference methods, they have increasingly been replaced by miniaturized, more efficient methods [33].

One of the most important issues is that traditional workflows may involve sampling and analysis occurring long after one another and across long distances. A range of controlled storage conditions is used to transport samples to the laboratory; however, these are not always sufficient to prevent degradation, transformation, volatilization, adsorption, or microbial alteration. The problem is especially important for redox-sensitive metals, volatile organic compounds, pharmaceuticals, pesticides, and biologically active compounds. As a result, the development of sample preparation also parallels the trend towards field-based and real-time environmental monitoring [34].

3.2. Solid-Phase Extraction and Microextraction Approaches

Solid-phase extraction is one of the most important sample preparation techniques in environmental testing, due to its high enrichment, cleanup and solvent reduction capabilities versus liquid–liquid extraction. Selective retention of analytes on a sorbent and elution with an appropriate solvent are the principles behind which SPE operates.

It can be adapted to a variety of sorbent chemistries and applies to pesticides, pharmaceuticals, phenols, endocrine disruptors, per- and polyfluoroalkyl substances, and other trace contaminants. The combination of chromatographic and mass spectrometric techniques, such as SPE, can enhance detection limits and minimize matrix effects [35].

But there are some drawbacks to SPE. The choice of sorbent is very critical to recovery and there is no single sorbent that will work well for compounds of a variety of polarities, charges, and molecular sizes. Samples with high suspended solids or organic matter content can cause cartridge clogging, and when the sample volume or flow rate is not optimized, breakthrough can result in analyte loss. Furthermore, while the use of solvents is lower than with older extraction methods, SPE generally requires laboratory facilities and several operational steps. Hence, its performance is strongly reliant on methodology optimization and quality control.

Microextraction techniques have arisen in response to these limitations. Solid-phase microextraction, stir-bar sorptive extraction, dispersive liquid–liquid microextraction, hollow-fiber liquid-phase microextraction, and related methods minimize solvent use and combine extraction and preconcentration steps. Such methods are well-suited to green analytical chemistry, as they require less sample and less solvent and may streamline the workflow. An important aspect of SPME is its ability to combine sampling, extraction, and preconcentration into a single step, and its ease of integration with chromatographic systems.

Reproducibility under difficult-to-control environmental conditions is the critical challenge for microextraction. The small extraction phases are highly dependent on extraction time, agitation, ionic strength, pH, and extraction matrix. Good detection limits can be achieved under controlled experimental conditions, but real-world matrices can affect precision and robustness. The laboratory optimization/field reliability challenge is continuous. To make microextraction useful for routine monitoring, it is necessary to further develop standardization and interlaboratory validation, while continuing to innovate materials [34,36].

3.3. Quenchers and High-Throughput Environmental Analysis

The Quenchers approach, originally developed for pesticide residues in food, has increasingly been adapted for environmental samples such as soil, sediment, water, sludge, and biota. Its appeal lies in its operational simplicity, relatively low solvent consumption, and compatibility with multi-residue analysis. By combining extraction, salt-assisted partitioning, and dispersive cleanup, Quenchers provide a flexible platform for processing complex samples with moderate cost and good throughput.

In environmental testing, Quenchers are particularly useful when multiple contaminants must be measured simultaneously. It has been applied to pesticides, pharmaceuticals, personal care products, flame retardants, and persistent organic pollutants. Compared with more exhaustive extraction techniques, it can reduce preparation time while maintaining acceptable recovery for many analytes. This makes it valuable for monitoring programs that require analysis of large sample sets [37].

Nevertheless, the method has limitations that must be critically considered. Quenchers were not originally designed for all environmental matrices, and their performance can vary substantially depending on organic matter content, moisture, particle size, and contaminant properties. Highly hydrophobic compounds may bind strongly to soil or sediment, reducing extraction efficiency, while very polar compounds may not partition effectively into the organic phase. Cleanup sorbents can remove matrix interferences but may also retain target analytes, leading to biased recoveries. Thus, Quenchers should not be treated as a universal extraction method. Its strength lies in pragmatic, high-throughput screening, but careful validation is required when it is applied beyond its original scope.

3.4. Sorbent Innovations and Functional Materials

The advent of innovative sorbent materials has greatly affected the recent advances in sample preparation. Selectivity and capacity of extraction systems have been enhanced using functionalized silica, polymeric sorbents, molecularly imprinted polymers, carbon nanotubes, graphene-based materials, magnetic nanoparticles, metal–organic frameworks (MOFs), covalent organic frameworks (COFs), biochar, and modified clays. These materials may be designed to interact with analytes via one of the following mechanisms: hydrophobic interactions, ion exchange, hydrogen bonding, π–π interactions, electrostatic interactions, molecular recognition, or size exclusion.

Molecularly imprinted polymers are especially significant because their recognition sites are complementary to target molecules or molecular classes. This can enhance selectivity when the matrix is complex and minimize interference during trace analysis. Another significant benefit of magnetic sorbents is that they can be separated quickly by an external magnetic field without filtration or centrifugation. MIMs and COFs are highly porous materials with tunable pore structures, suitable for the selective enrichment of organic contaminants/gases.

But material innovation needs to be considered critically. While many advanced sorbents perform well in lab tests, they struggle with issues of repeatability, cost, scale-up, stability, and environmental safety. Synthesis of nanomaterials can be complex, and release or disposal can create secondary environmental concerns, but it can enhance extraction efficiency. Furthermore, highly selective materials can be useful for specific compounds in the unknown pollutants sample pool, but less effective for broad screening. Practical performance of new sorbents, however, is not only dependent on their extraction ability but also on ease of preparation, consistency from batch to batch, regeneration, compatibility with analytical instruments, and performance in real samples [38–40].

3.5. Green and Miniaturized Sample Preparation

Green Analytical Chemistry has emerged as a core concept in sample preparation today. The objective is to minimize the use of hazardous solvents, energy consumption, waste production, and analyst exposure, whilst maintaining analytical performance. New methods, which are cheaper, more environmentally friendly, and do not involve the use of solvents, have been investigated, such as miniaturized extraction, aqueous two-phase systems, ionic liquids, deep eutectic solvents, supercritical fluids, and reusable sorbents, which have been investigated as alternative approaches to traditional methods.

That is why the use of deep eutectic solvents and ionic liquids has been gaining interest, as they have tunable physicochemical properties and the potential to replace volatile organic solvents. They are flexible in both organic and inorganic analyses and may be tailored to specific analytes and extraction conditions. But the word “green” has to be used with caution. The toxicity and biodegradability of some ionic liquids and synthetic solvents are unknown, and the production costs of some are very high. Thus, environmental friendliness must be evaluated from synthesis through disposal, including any potential environmental impacts [7].

The miniaturization also helps the field’s applicability. The smaller extraction devices take up less reagent, are more portable, and can be coupled with portable sensors or microfluidic devices. For decentralized analysis of the sample, paper-based extraction, membrane-based sampling, passive sampling, and in-tip or in-syringe extraction formats are promising. However, miniaturization can also impact the representativeness of the sample, especially in heterogeneous matrices. The problem is how to “trade off” small-scale efficiency for representation of environmental variability.

3.6. Automation and Integration with Analytical Platforms

The automation of sample preparation has reduced operator-dependent variability and manual handling, improving reproducibility and throughput. The consistent performance and automated SPE, online extraction, robotic sample processing, and integrated chromatographic workflows are particularly convenient for routine monitoring laboratories. Coupling of sample preparation and instrumental analysis online can reduce contamination, shorten analysis time, and increase precision.

An important aspect of automation is that it makes sample preparation a truly integral part of the analytical process. This is of critical importance for high-frequency monitoring and for enabling lab-level analysis alongside field-deployed systems. Examples of such microfluidic platforms, lab-on-a-chip (LOC) devices, and portable extraction modules are available. They enable filtration, mixing, reaction, separation, enrichment, and detection within a compact system.

Automated systems, however, are costly, method-specific, and can suffer clogging or fouling when exposed to real environmental samples. They might require maintenance and have limited flexibility, which can make them hard to use in non-controlled laboratory environments. So, automation can help with consistency but not with complexity. Future developments should be based on robust designs that can process variable-field samples with minimal user interaction [41].

The sensitivity, sustainability and applicability of environmental testing have been significantly enhanced by advances in sample preparation. But there is still an inherent conflict in the field between analysis performance and real-world use. Laboratory-based procedures might achieve very high recoveries and detection limits but not be simple enough to be used in the field. On the other hand, simpler methods performed in the field may be less selective, precise, or robust. The main challenge is to find preparation strategies that are efficient in an ideal scenario and robust in a variety of real-world matrices.

More attention needs to be given to the need for standardization, interlaboratory comparison, lifecycle assessment, and integration with portable detection technologies in the future. Sample preparation should be tailored to the application of the test, for instance, confirmatory laboratory testing, rapid screening, continuous monitoring, and emergency response. There is no universal technique that meets all the analytical requirements. Rather, the best environmental testing systems will feature tiered strategies, combining rapid, simple preparation/extraction methods that complement field methods with more robust extraction and cleanup methods that complement confirmatory lab testing.

In this context, sample preparation is not a passive supporting step but an important contributor to the shift from the bench to the field. Its development will help determine the reliability of advanced instruments and sensors in complex environmental conditions. Therefore, novel, robust, and sustainable sample preparation, as well as new detection technologies, will play vital roles in the future of environmental testing. The main sample preparation and preconcentration techniques mentioned in this section are critically compared in **Table 2** about their purpose, advantages, limitations, and applicability [42–44].

Table 2. Advances in sample preparation and preconcentration for environmental analysis.

Sample Preparation Strategy	Analytical Purpose	Main Advantages	Critical Limitations	Field Applicability
Liquid–liquid extraction	Extraction of hydrophobic organic pollutants from water	Established, effective for many non-polar compounds	High solvent use, labor-intensive, emulsion formation	Low
Soxhlet and ultrasonic extraction	Extraction of pollutants from soil, sediment, and sludge	Good extraction efficiency for solid matrices	Long extraction time, high solvent and energy demand	Low
Solid-phase extraction	Enrichment and cleanup of trace organic contaminants	High preconcentration, flexible sorbent chemistry, good compatibility with LC-MS and GC-MS	Sorbent-dependent recovery, clogging, breakthrough risk	Moderate
Solid-phase microextraction	Solvent-minimized extraction and preconcentration	Integrates sampling and enrichment; low solvent use	Sensitive to extraction conditions and matrix variability	Moderate to high
Dispersive liquid-liquid microextraction	Rapid enrichment of organic contaminants	Fast, low solvent volume, high enrichment factors	Reproducibility challenges and solvent selection issues	Moderate
QuEChERS	Multi-residue extraction from complex samples	Simple, high-throughput, adaptable	Matrix-dependent recovery; not universal for all analytes	Moderate
Magnetic sorbent extraction	Rapid separation and enrichment	Eliminates filtration or centrifugation; suitable for miniaturization	Sorbent stability and reproducibility concerns	High
Molecularly imprinted polymers	Selective extraction of target analytes	High selectivity and recognition capability	Template leakage, limited universality, synthesis complexity	Moderate
Nanomaterial-assisted extraction	Enhanced adsorption and preconcentration	High surface area, tunable selectivity	Cost, reproducibility, and potential secondary environmental concerns	Moderate
Green solvents and miniaturized formats	Sustainable sample preparation	Reduced solvent use, lower waste generation, improved portability	Green claims require lifecycle assessment	High

4. Emerging Instrumental and Sensor-Based Technologies

One of the most rapidly evolving changes in environmental testing is the emergence of new technologies, such as instruments and sensors. Traditional lab-based analyses achieve a high level of analytical assurance; however, they are constrained by either centralized infrastructure or temporal and/or spatial coverage and turnaround times. The emerging technologies seek to address these issues by providing faster, smaller, cheaper, and more adaptable analytical systems in the field. They are also important because they can shift the paradigm of environmental monitoring from a confirmatory to a screening, warning, and ongoing assessment approach, resulting in better detection capability [45].

But the new era of portable instruments and sensors does not mean that these are intended to replace laboratory-based platforms. Numerous new technologies give useful pre-lab or semi-quantitative data that need to be confirmed in the laboratory for enforcement or for the identification of complex contaminants. Environmental factors, matrix effects, calibration stability, and long-term reliability can frequently significantly impact their performance. The real concern is not the impact of emerging technologies on the replacement of traditional instruments, but rather the potential to combine them with traditional monitoring tools to produce more effective and comprehensive monitoring systems [46].

4.1. Portable Chromatography and Miniaturized Mass Spectrometry

Because of their ability to bring high-selectivity analysis to the sampling location, portable chromatographic and mass spectrometric systems have received considerable attention. Volatile Organic Compounds, field-deployable GC–MS, and Miniaturized Mass Spectrometers are very beneficial for chemical spills, industrial emissions, emergency response, and petroleum hydrocarbons. The biggest benefit is that they can provide chemically specific information on-site, which reduces time delays caused by sample transport and laboratory scheduling.

Miniaturization, however, has important trade-offs. The high-vacuum stability of laboratory-based chromatographic and mass spectrometric systems, optimized separation columns, precise temperature control, advanced detectors, and a controlled operating environment are beneficial. Portable systems, on the other hand, have to be lightweight, rugged, power-efficient, portable, and easy to operate while maintaining analytical performance. Consequently, they might be less resolving, less sensitive, may lack analyte coverage, or be more sensitive to environmental changes. Field instruments must also be simplified in terms of sample preparation, which can increase matrix interference or reduce quantitative accuracy.

Even with these constraints, portable chromatography and mass spectrometry are playing an important role in rapid screening and confirmatory analysis. They are particularly useful when the chemical identity of the sample is of more critical importance than the ultra-trace level of analysis. They will grow only as their ionization sources improve, as low-power vacuum systems are used, as automated introduction is implemented, as ruggedized designs are developed, and as data-processing software is developed to support the non-specialist user [47].

4.2. Optical Sensors and Spectroscopic Detection Platforms

The application of optical sensing technologies to environmental testing has grown in significance, including fluorescence, colorimetry, chemiluminescence, infrared, Raman, and surface-enhanced Raman. Such techniques are appealing for their ability to give rapid, non-destructive, and even label-free detection. Many types of optical sensors are being investigated for detecting heavy metals, pesticides, explosives, nutrients, pathogens, microplastics, and organic pollutants. They are expected to be useful tools for field-based monitoring due to their compatibility with portable readers, smartphones, fiber optics, and remote platforms.

Fluorescence-based sensors can be developed using organic dyes, quantum dots, carbon dots, metal nanoclusters, and biomolecular probes and are highly sensitive. They can induce a high response to certain analytes by quenching, enhancing, or shifting the wavelength. Colorimetric sensors are even simpler and sometimes require visual or smartphone-based detection, making them suitable for low-resource environments. Raman and surface-enhanced Raman spectroscopy offer molecular fingerprinting capabilities useful for identifying chemical structures with minimal damage.

Optical sensors have the key drawback of selectivity in complicated environmental matrices. Signal distortion and false positives or false negatives can be caused by natural organic matter, turbidity, suspended particles, pH changes, and background fluorescence. As sensitive as it is, surface-enhanced Raman spectroscopy requires a high degree of uniformity in the substrates, hot-spot distribution, and analyte adsorption. Reproducibility is difficult when transitioning from laboratory-controlled samples to systems with varying environmental conditions. Thus, the application of optical technologies is greatest when used in conjunction with proper sample preparation, calibration, internal calibration, spectral correction, and chemometric analysis [48].

4.3. Electrochemical Sensors and Biosensors

Electrochemical sensors are among the most promising tools for portable environmental testing because they are compact, inexpensive, and sensitive, and can be miniaturized and integrated with miniaturized electronics. They can be used to detect metals, nutrients, phenolic compounds, pesticides, pharmaceuticals, dissolved gases, and other electroactive species. Various techniques, such as voltammetry, amperometry, potentiometry, and impedance spectroscopy, enable flexible detection strategies tailored to the target analyte and electrode design.

The performance of electrochemical sensors has been greatly enhanced by the recent development of nanomaterial-modified electrodes. Surface area, electron transfer, and catalytic activity can be improved by using graphene, carbon nanotubes, metal nanoparticles, metal oxides, conductive polymers, and hybrid nanocomposites. The selectivity of biosensors can be extended with the use of enzymes, antibodies, aptamers, microorganisms or nucleic acids as recognition elements. These systems can be highly effective at detecting pesticides, pathogens, toxins, endocrine disruptors, and biologically active contaminants.

However, there are ongoing challenges to the widespread adoption of electrochemical sensors in environmental use. Fouling of the electrodes, drift, short lifetime, and interference from coexisting ions or organic matter can affect reliability. The activity of biological recognition elements can be disrupted by changes in temperature, pH, salinity, or storage conditions. Many sensors are also designed using spiked laboratory matrices rather than real matrices, which leads to an overly pessimistic perception of their actual performance. Electrochemical sensors should be more rigorously validated under realistic field conditions, subject to standard calibration, and designed to be antifouled, regenerated, and stable over long periods [49,50].

4.4. Microfluidic and Lab-on-a-Chip Platforms

Microfluidic and lab-on-a-chip technologies are integrated solutions for environmental analysis, involving handling, reaction, separation, preconcentration and detection in small volumes within a small device. These can be used to minimize reagent use, decrease analysis time, and provide automation. Due to their small size, they are very appealing for field monitoring, particularly in conjunction with optical, electrochemical or mass-sensitive detection systems.

The key advantage of microfluidics is the ability to integrate processes. Microfluidic devices can provide a controlled environment for microscale filtering, mixing, derivatization, enrichment, and measurement, rather than performing these processes separately. This is especially valuable for quick, easy testing of nutrient, pathogen, metal, organic pollutant, and toxicity indicators. Other benefits of paper-based microfluidic devices include low cost, ease of disposal, and minimal equipment requirements; they are useful for decentralized or resource-limited applications [51].

Microfluidic platforms, however, are also limited in practice. Particles, biofilms, organic matter, and changing ionic strength are common in environmental samples that can plug channels and/or disrupt surface reactions. Certain materials or manufacturing processes are needed to make the device, which can be difficult to scale up. Some of them work with clean or pretreated samples, but not with field samples. Thus, the future success of the lab-on-a-chip environmental analysis will rely on good sample introduction, anti-fouling channel design, robust fluid control, and compatibility with real-world matrices.

4.5. Nanomaterial-Enabled Detection Systems

The surface area, tunable optical and electrical properties, catalytic activity, and selective interaction with the target analytes of nanomaterials have had a profound influence on modern environmental sensing. Optical, electrochemical, and magnetic detection platforms have been enhanced by the use of gold and silver nanoparticles, quantum dots, carbon dots, graphene derivatives, carbon nanotubes, magnetic nanoparticles, metal oxides, metal-organic frameworks, and hybrid nanocomposites. They have nanoscale properties that enable signal amplification, and their limits of detection are lower, which is crucial for detecting trace environmental contaminants.

Nanotechnology has also enabled the design of multifunctional sensors. One nanostructured platform can integrate all functionalities, such as analyte recognition, signal generation, preconcentration, and separation. Magnetic nanoparticles can concentrate pollutants and facilitate separation, for instance, and plasmonic nanoparticles can boost the optical signal. High porosity and selective adsorption can be achieved using metal–organic frameworks and carbon-based nanomaterials to improve electron transfer in electrochemical sensing.

There are still benefits to be considered; however, with the use of nanomaterial-enabled technologies, a cautious approach is necessary. Laboratory demonstrations frequently focus on sensitivity and sometimes underrepresent the challenges of synthesis reproducibility, material stability, selectivity, and environmental safety. The sensor's response can vary from batch to batch, and aggregation or surface oxidation can reduce performance during storage or in the field. It is also important to ask whether engineered nanomaterials pose secondary environmental risks during use and disposal. Therefore, nanomaterials should be evaluated as materials, including their lifecycle and regulatory aspects, rather than solely as a performance add-on [52].

4.6. Performance Comparison with Conventional Laboratory Techniques

A key comparison between new technologies and traditional lab methods demonstrates both interdependence and conflict. Laboratory instruments such as LC–MS/MS, GC–MS, ICP–MS, and high-resolution spectrometers are typically more sensitive, more selective, and more structurally confirmable, and are more likely to be accepted by regulators. New sensors and portable devices, on the other hand, offer superior advantages in field applications, temporal resolution, access, cost, and speed. These distinctions indicate the different analytical roles that these approaches fulfill.

Emerging technologies are particularly valuable for screening, mapping contamination gradients, identifying contamination hotspots, sample collection, and emergency response. They can provide a quick assessment of the information needed to identify the appropriate location and time for further laboratory testing. Laboratory techniques still play an important role in confirmatory analyses, characterization of complex mixtures, legal requirements, and long-term reference databases, however. Monitoring strategies, therefore, will best leverage emerging technologies as front-line tools and use traditional methods as validation anchors [10].

Many emerging technologies suffer from a lack of bridging between research and the operational stage. A high sensitivity for buffer solutions or spiked samples does not imply a reliable result in wastewater, soil leachates, sediment extracts or atmospheric aerosols. Future studies should be conducted to examine sensors under variable temperatures, humidities, salinities, pH, fouling and matrix interference, instead of idealized testing conditions. Comparative studies using standardized laboratory methods are necessary to define practical detection limits, false-response rates, calibration stability, and uncertainty.

The new instrumental and sensor technologies are changing the way environmental testing is conducted by bringing analytical power out of the centralized laboratory. Their biggest impact goes beyond rapid detection, however, and includes the development of new monitoring opportunities, including real-time monitoring, decentralized testing, high-density spatial mapping, and early-warning systems. The capabilities are becoming increasingly significant due to the growing dynamics, diffusiveness, and complexity of environmental pollution [10].

But, enthusiasm for technology needs to be tempered with analytical realism. Several newly developed platforms still need enhancements in robustness, reproducibility, selectivity, validation, and standardization. An under-controlled laboratory-condition sample to a sensor system is not necessarily successful when transferred to a field environment if sample preparation, calibration, anti-fouling protection, and data correction are not properly addressed. Similarly, the usability, maintenance, operational costs, and data quality of portable instruments need to be considered when assessing their detection limits.

A hybrid analytical system is likely to become the future of environmental testing, rather than a single technology dominating the field. A critical comparison of emerging instrumental and sensor-based technologies is presented in **Table 3**, which emphasizes their target applications, benefits, analytical challenges, and roles in the bench-to-field transition.

Table 3. Emerging instrumental and sensor-based technologies for environmental testing.

Technology	Target Applications	Main Benefits	Major Analytical Challenges	Role in Bench-to-Field Transition
Portable GC and GC-MS	VOCs, petroleum hydrocarbons, chemical spills, industrial emissions	Field-based chemical identification, reduced turnaround time	Lower sensitivity and resolving power than laboratory systems; simplified sample preparation	Bridges laboratory confirmation and field screening
Miniaturized mass spectrometry	On-site identification of organic contaminants and hazardous chemicals	Molecular specificity, rapid response	Power, vacuum, calibration, and ruggedness constraints	Supports emergency response and mobile analysis
Optical sensors	Metals, pesticides, nutrients, organic pollutants, pathogens	Rapid, portable, compatible with visual or smartphone detection	Turbidity, background fluorescence, and matrix interference	Enables low-cost screening and decentralized testing
SERS platforms	Trace organic pollutants, dyes, pesticides, explosives	High sensitivity and molecular fingerprinting	Substrate reproducibility and signal variability	Promising for selective field detection
Electrochemical sensors	Metals, nutrients, phenols, pesticides, pharmaceuticals	Compact, low cost, sensitive, easily miniaturized	Fouling, drift, cross-sensitivity, electrode stability	Strong potential for portable and real-time monitoring
Biosensors	Pathogens, toxins, pesticides, endocrine disruptors	Biological selectivity, low detection limits	Limited stability of enzymes, antibodies, or aptamers	Useful for targeted biological and chemical monitoring
Microfluidic lab-on-a-chip systems	Nutrients, metals, pathogens, organic contaminants	Integrated sample handling and detection, low reagent use	Clogging, fabrication cost, real-sample compatibility	Supports automated and miniaturized analysis
Nanomaterial-enabled sensors	Trace pollutants and emerging contaminants	Signal amplification, tunable surface chemistry	Material reproducibility, stability, and environmental safety	Enhances sensitivity of portable platforms
Paper-based analytical devices	Nutrients, metals, pathogens, simple chemical assays	Low cost, disposable, easy to use	Limited quantification and sensitivity	Valuable for low-resource and rapid screening applications

Portable instruments, optical sensors, electrochemical devices, microfluidic platforms, nanomaterial-based probes, and laboratory reference methods will each play distinct but interconnected roles. The most important advances will arise from integration: sensors linked with sample preparation modules, portable devices connected to cloud databases, field measurements validated by laboratory analysis, and data interpreted through chemometric or machine-learning tools. In this integrated framework, emerging technologies will strengthen environmental decision-making by providing rapid and actionable information while remaining grounded in the reliability of established analytical science [53,54].

5. Field-Deployable and Real-Time Environmental Monitoring

Field-deployable, real-time environmental monitoring is a radical transformation of analytical science from laboratory-based retrospective confirmation to real-time, location-specific, and continuous assessment. Traditional environmental testing relied on sample collection, transport, lab preparation, instrumental analysis, and delayed reporting. This approach guarantees a high level of analytical confidence but is not always adequate for recording rapidly changing environmental conditions. Most pollution events are episodic and spatially variable, and can be affected by precipitation, industrial effluents, flow, wind direction, temperature, and biological activity. In this instance, laboratory findings may be obtained after the event, by which time the condition may have changed [55].

This trend towards field monitoring thus follows the demand for quicker environmental intelligence. New technologies such as portable instruments, in situ sensors, autonomous samplers, wireless sensor networks, drones, satellite observations, and Internet of Things (IoT) platforms are transforming the collection and utilization of environmental information. These systems can be used for early warning, tracking pollution sources, assessing exposure, response actions, and adaptive management [56].

5.1. In Situ Detection in Water, Soil, and Air

In situ detection allows measurements to be made at or near the sampling site, minimizing sample transport and storage time and associated uncertainty. Aquatic: Field Deployable Probes/Sensors for pH, DO, conductivity, turbidity, temp, nutrients, chlorophyll, organic, and selected metals. Pesticides, pharmaceuticals, pathogens, microplastics, and emerging organic contaminants are currently being developed with more advanced systems. The advantage of these technologies is that they are especially useful in rivers, lakes, wastewater treatment facilities, coastal areas, groundwater wells, and drinking water networks where the level of contamination can change on short time scales.

Field deployment is more complex in soil and sediment because of various factors such as matrix heterogeneity, moisture content, particle size distribution, organic matter and high binding of the analytes. Portable X-ray fluorescence has proven useful for screening metals in contaminated soils, mining operations and industrial facilities. Other applications of portable IR, Raman, and LIDB have been studied for soil characterization and pollutant detection. But soil measurements can be quite challenging to make and need careful calibration due to matrix effects, which affect the signal intensity. A field reading could identify contamination trends or hotspots, but it is often necessary to verify in a laboratory to get a good idea of the extent of contamination and to make regulatory decisions [57,58].

Portable and real-time air monitoring systems have significantly contributed to the field of air monitoring. High-resolution spatio-temporal information can be obtained from low-cost gas sensors, particulate matter sensors, mobile chromatographs, optical particle counters and mobile air-quality platforms. They can be used to monitor air pollution in the city, industrial pollution, wildfire smoke, traffic pollution, and indoor air quality. Low-cost air sensors, however, tend to be sensitive to humidity, temperature, cross-sensitivity, sensor ageing, and calibration drift. They offer value in terms of the high density of monitoring, detecting trends but the results should be carefully interpreted when used for compliance or health risk assessment purposes [59].

5.2. Remote Sensing and Unmanned Monitoring Platforms

The increasing capabilities of remote sensing have allowed environmental testing to move beyond a point-based approach and to monitor the status of land, water and atmosphere at a broad scale. Examples of satellite-based sensors include those that monitor algal blooms, suspended sediments, vegetation stress, land-use change, thermal pollution, oil spills, aerosols and atmospheric gases. The high value of these observations is that they provide multiple coverage over extensive areas which are hard or impractical to cover with ground sampling.

The UAV has also cemented the relationship between remote sensing and field testing. High-resolution data will be gathered over contaminated sites, agricultural landscapes, water bodies, industrial areas and inaccessible areas using drones with optical, multispectral, hyperspectral, thermal, or gas-sensing payloads. They have particular applications in the case of chemical spills, flooding, fire and mining accidents where a quick assessment is required. Other autonomous platforms, such as underwater and surface-based vehicles, are also becoming common tools for water-quality monitoring, bathymetric mapping, and tracking pollutants [60–62].

While they have benefits, remote and unmanned platforms generally yield indirect measurements. To translate spectral signals into environmental parameters, models, calibration datasets and ground-truth observations are needed. The accuracy may be affected by cloud cover, atmospheric conditions, sensor resolution, surface reflectance, water depth, vegetation cover, or the number of mixed pixels. Besides the limitations of flight time, payload weight, regulation, weather, and data processing, drones have a few more restrictions. Hence, remote platforms must be considered as a powerful tool for spatial evaluation and prioritization rather than a replacement for chemical analysis. The most useful value that they add is when used in conjunction with targeted field sampling and laboratory validation.

5.3. Internet of Things-Enabled Sensor Networks

The emergence of Internet of Things (IoT)-based architectures has opened up possibilities for continuous and distributed monitoring through the integration of environmental sensors. IoT systems integrate sensors, microprocessors, wireless connectivity, cloud storage, and data visualization tools to deliver real-time environmental data. These networks can be used in urban air quality, smart water, agricultural runoff, climate-sensitive ecosystem assessment, and industrial discharge monitoring, and flood monitoring, among others.

The biggest benefit of IoT monitoring is its scalability. Dense spatial coverage can be achieved by using a network of lower-cost sensors instead of a handful of high-cost stations. This enables the identification of local pollution hot spots, short-term concentration peaks and spatial pollutant gradients that are not identified by traditional monitoring. When integrated with automated alerts, IoT platforms can aid in a quick response; for example, when the plant detects a water treatment failure, triggers the alarm system, or sends a warning to the community in case of air quality deterioration [63].

Yet there are new data-quality challenges in terms of scalability. Most of the time, low-cost sensors are less stable and less selective than laboratory instruments. Sensor calibration, power supply, communication reliability, data security, maintenance, and environmental durability are all essential factors for network performance. If not managed, missing data, sensor drift, biofouling, and inconsistent calibration can lead to misinterpretations. Thus, the deployment of IoT devices is not enough; data governance, data quality control algorithms, data metadata monitoring, and periodic validation with reference methods are also required for IoT monitoring.

5.4. Real-Time Data Acquisition and Interpretation

Real-time monitoring generates vast amounts of data that have to be understood quickly. This is a chance and a challenge. Continuous datasets can provide information on the dynamics of this pollution that discrete sampling cannot capture, such as diurnal variation, pollution pulses during storms, industrial activity patterns, seasonal fluctuations, and sudden pollution events. The patterns are key to understanding exposure, ecological risk, and the effectiveness of management interventions [64].

Meanwhile, data collected in real time is susceptible to noise, drift, outliers and sensor malfunction. If not processed correctly, continuous monitoring could give the false impression of accuracy. Therefore, statistical filtering, baseline, anomaly detection, calibration transfer and uncertainty estimation are essential. High-quality training data and clear validation are essential for the success of chemometric and machine-learning tools in pattern recognition and predictive modeling. Modelling may be incorrect, may be overfitting local conditions, or may not perform when the environment changes.

This difference between the analytical signal and its environmental meaning also needs to be taken into account when interpreting real-time data. The sensor response could be a measure of conductivity, fluorescence, turbidity or electrochemical current, but a specific contaminant concentration may need to be determined in addition. This is especially crucial when using surrogate measurements, where a sensor measures a surrogate rather than the pollutant. Therefore, it is important to have real-time monitoring in conjunction with periodic laboratory analyses to ensure analyte identification and calibration, and to maintain confidence in long-term data [65].

5.5. Calibration, Robustness, and Field Reliability

Calibration is a very common issue in field-deployable environmental monitoring. Laboratory instruments are typically calibrated under controlled conditions, while field sensors are exposed to variable temperature, humidity, pH, salinity, pressure, light, flow rate, and biological activity. All of these variables may affect sensor responses and lead to drift over time. Biofouling and sedimentation can affect the sensitivity of water sensors and/or cover their surfaces. Humidity and reactive gases can cause false readings on air sensors. Moisture and mineral content have been shown to significantly influence measurement signals from soil sensors.

Therefore, it is necessary to have robust field monitoring strategies that go beyond initial laboratory calibration. The reliability may be enhanced through in situ calibration, reference-site comparisons, automatic baseline correction, internal standards, sensor redundancy, and periodic co-location with reference instruments. Maintenance is also important. To maintain data quality, cleaning, recalibration, battery replacement, firmware updates and physical inspection are required. These operational requirements are sometimes overlooked in research demonstrations, where sensors are tested only for short periods under controlled or semi-controlled conditions.

The difference between deployability and reliability needs to be made very clear. Maybe a portable and inexpensive device that is easy to install, but that does not mean that it can provide stable and defensible data in weeks or months in the real environment. To decide if the field systems will meet the requirements of scientific or regulatory decisions, their long-term performance testing, intercomparisons and uncertainty reporting need to be considered [66].

5.6. Regulatory and Practical Implications

New monitoring technologies, which are both field-deployable and real-time, will become increasingly relevant to environmental governance, but their role in regulation is complex. Traditionally, regulatory frameworks have been developed using standard laboratory procedures, sampling procedures and analytical methods used in the laboratory. Real-time sensors and portable systems may produce data faster and more often, but might not be subject to the same validation requirements as traditional systems. This raises questions about the use of this data in compliance monitoring and enforcement, as well as for public communication.

A practical solution is using field systems with a tiered monitoring system. In addition to providing confirmatory evidence, real-time sensors can also be used for early warning systems, screening platforms and decision support systems. This approach is based on recognizing the strengths in both systems. Data obtained in the field can help to pinpoint areas and times of potential contamination and focus lab resources. Laboratory results can then be used to support observations made in the field and to give legally acceptable measurements [67].

Real-time environmental data that is publicly communicated also needs attention. Continuous monitoring can lead to greater transparency and/or community involvement, but unclear or inadequately understood data can create confusion or unnecessary anxiety. Therefore, data platforms should contain an uncertainty estimate, a calibration status, quality flags and explanations of what is being measured. Real-time monitoring is only credible if the interpretation and communication are responsible as well as the performance of the sensor.

Field-deployable and real-time monitoring technologies are changing environmental testing by enabling real-time measurement and environmental intelligence across space. Their best legacy is enhanced responsiveness. They enable pollution events to be detected as they happen, closer to the source, shifting the focus to proactive environmental management rather than reactive. However, these technologies need to be analyzed carefully. If not underpinned by calibration, portability, and connectivity, they would be of little value, as would long-term stability and clear data validation. A large proportion of field systems are better suited to screening, trend analysis, and early warning than to definitive quantification. They are no less significant, but they help to determine their conditions of use.

Integrated systems, involving powerful sensors, automated sample handling, wireless communication, data analysis and periodic laboratory verification, will be critical to the future of field monitoring. Field-deployable technologies will complement, not supplant, traditional analysis. The best environmental testing regimes will be based on real-time monitoring that identifies change, which will inform the sampling regime and drive speedy decision-making, and laboratory testing will validate the results and assure the regulatory community. Thus, the move from lab to field is not necessarily a step away from the analytical approach but rather a step toward more dynamic, decision-based environments [68].

6. Data Analytics, Validation, and Regulatory Translation

Environmental testing has been transformed from lab-based analysis to field-deployable or real-time monitoring, leading to an explosion in the quantity, variety, and complexity of analytical data. The traditional approaches to lab work tend to yield discrete, well-controlled data, while the new approaches to monitoring can produce continuous signals, high-resolution spatial maps, spectral fingerprints, sensor-network data products, and multi-instrument data products. This transition has led to increased emphasis on data analytics, method validation, and regulatory translation for environmental testing. The ability to analyse is no longer evaluated solely based on detection limits or instrumental sensitivity, but also based on the reliability of the data, its interpretability, comparability, uncertainty and usefulness in the context of environmental decision-making [69].

Data processing in this context does not mean analysing data and then processing it. It has become a part of the analytical flow. Converting raw signals into valuable environmental information is increasingly influenced by chemometric approaches, machine-learning models, calibration algorithms and quality-control systems. But there are new risks with the increasing reliance on computational interpretation. Insufficient validation of models, biased training sets, opaque algorithms, and lack of uncertainty reporting can result in misguided results. As a result, the future acceptance and credibility of new environmental testing technologies rely on the combination of strong analytics and comprehensive validation and regulatory approval [5].

6.1. Chemometrics and Multivariate Data Interpretation

Many modern techniques yield complex, multi-dimensional data, so chemometrics has become an indispensable tool in environmental analysis. The signals obtained, for example, from spectroscopic platforms, chromatographic fingerprints, high-resolution mass spectrometry, sensor arrays, and remote sensing systems cannot be correctly interpreted using a simple univariate calibration. Multivariate techniques like principal component analysis, partial least squares regression, cluster analysis, discriminant analysis, and pattern recognition help to determine associations between samples, pollutants, sources, and environmental conditions [70].

The power of chemometrics lies in its ability to exploit these overlapping and complex signals to extract useful information. The spectral data of natural waters, soils, or atmospheric particles can, for example, consist of several chemical and physical influences. Chemometric modeling enables the differentiation of signals related to the presence of the analyte from background variability, which can enhance the ability to classify contamination sources and assist quantitative prediction when direct measurement is difficult. Multivariate techniques can be used to detect unusual chemical characteristics, prioritize unknown compounds, and differentiate anthropogenic contamination from natural variation in non-target analysis.

However, the chemometric interpretation should be taken with a pinch of salt. Multivariate models can show statistical patterns that may not reflect causal environmental processes. The performance of a model trained in one matrix, season, geographic region, or sensor platform could be suboptimal in other contexts. There will be a special concern about overfitting, especially if the number of variables is large, but the number of representative samples is limited. This means that chemometric models need to be validated independently, their data preprocessing should be transparent, and the model limitations should be reported. They are important not only in terms of mathematical competence but also for their environmental plausibility and analytical traceability [71].

6.2. Artificial Intelligence and Machine Learning in Environmental Testing

In the field of environmental testing, AI and Machine Learning technologies are getting increasingly used to identify which contaminants to test, to predict concentration levels, to detect anomalies, to identify the source of the pollution, to calibrate the sensors and to provide early-warning systems. These techniques can be particularly effective for real-time monitoring networks, remote sensing data, and sensor arrays, where massive amounts of data must be analyzed quickly. Machine-learning techniques have the ability to identify patterns that might be hard to spot by hand, such as short-term pollution events and non-linear sensor responses or complex relationships between environmental variables.

Machine learning can enhance sensor performance in field monitoring by mitigating temperature, humidity, pH, salinity, drift, and cross-sensitivity issues. It can also facilitate predictive environmental management by forecasting pollutant transport, identifying potential contamination sources, or estimating exposure risk.

But there are significant issues to consider with the use of AI. Many models are "black boxes," and it is hard to explain how a prediction was produced. This lack of interpretability can restrict regulatory acceptance and scientific trust, particularly in situations where decisions relate to public health, legal enforcement or industrial compliance. The accuracy and diversity of the training data also heavily influence the accuracy of machine-learning models. The model may not perform well in actual field conditions if the training set is not representative of the full range of environmental variability. The reduced predictive reliability can be caused by bias, data gaps, sensor faults, or unbalanced datasets [72].

Thus, AI should not be used as a replacement for analytical validation. It should be applied as an auxiliary instrument in a scientifically controlled system. The models must be trained on representative data, tested on independent data, evaluated in varying environments, and supplemented by uncertainty estimates. To enhance trust in computational environmental testing, explainable AI approaches, hybrid mechanistic-data models, and standardized performance reporting will be crucial.

6.3. Method Validation and Measurement Uncertainty

Validation of the method is crucial to valid environmental testing. Whether a technique is laboratory, portable, sensor or remote, it will have to show that the technique can yield reliable results for the purpose it was developed to achieve. The most important validation parameters are accuracy, precision, selectivity, sensitivity, linearity, limit of detection, limit of quantification, recovery, robustness, reproducibility and measurement uncertainty. These parameters are clearly known and easily applied to normal laboratory procedures, but are less well known and less easily applied in emerging technologies that provide continuous, indirect or semi-quantitative data [73].

Validation of field-deployable sensors should account for environmental variability. The sensor can function satisfactorily in the standard solution, but not in wastewater, soil extracts, seawater, atmospheric aerosols, or organic-rich surface waters. Over time, the performance can be affected by matrix effects, fouling, drift, temperature changes, and interference. Thus, testing of real samples, long-term tests, intercomparisons with reference methods, and tests under realistic operating conditions should be part of the validation. Technologies used in the field should be lab-validated for an extended period.

A significant challenge is measurement uncertainty, as environmental decisions are often based on whether pollutant concentrations exceed regulatory thresholds. Reporting only a single concentration measurement without uncertainty creates a false sense of certainty. This is particularly important for sensor networks and real-time systems, where data can change due to environmental changes as well as analytical errors. Transparent uncertainty estimation enables users to distinguish genuine environmental change from measurement noise. It also enables regulators, scientists and stakeholders to assess the level of confidence in monitoring outcomes [74].

6.4. Harmonization between Bench and Field Measurements

One of the greatest challenges in current environmental testing is the ability to correlate information from traditional laboratory testing methods and the field-based technologies deployed. Laboratory techniques generally give high selectivity and confirmation measurements, and field systems give immediate and frequent observations. These two types of data have different spatial resolutions, sampling frequencies, uncertainties, and analytical specificities, and are not in the same state of validation. If not harmonized, they can create datasets that are not easily comparable or harmonizable. It is important to have clear definitions of the method's purpose for harmonization. The complementary aspects of bench-based laboratory analysis, field-deployable testing, and online monitoring systems are summarized in **Table 4**. A field sensor used for early warning does not have to have the same performance as a confirmatory LC–MS/MS or ICP–MS method, but must be reliable in the context of the decision(s). Likewise, portable instruments used for contamination hotspot screening should be judged on their ability to accurately classify samples, rather than on absolute quantification accuracy. Using this application-based validation is crucial for integrating bench and field approaches [75,76].

Table 4. Critical comparison of bench-based, field-deployable, and real-time environmental testing approaches.

Evaluation Criterion	Bench-Based Laboratory Analysis	Field-Deployable Testing	Real-Time Monitoring Systems
Analytical accuracy	Very high when validated methods are used	Moderate to high, depending on device and matrix	Variable; depends strongly on calibration and drift correction
Sensitivity	Excellent for trace and ultra-trace analysis	Often lower than laboratory methods, but improving	Suitable for trends and events; may be limited for ultra-trace quantification
Selectivity	High, especially with MS-based and spectroscopic confirmation	Moderate to high for targeted systems	Often limited by low-cost sensors and surrogate measurements
Turnaround time	Slow to moderate due to sampling, transport, and preparation	Rapid, often near-site results	Immediate or near-real-time
Spatial coverage	Limited by sampling design and laboratory capacity	Improved through mobile deployment	High when sensor networks or remote platforms are used
Temporal resolution	Low, usually based on discrete sampling	Moderate, depending on deployment frequency	High, continuous or near-continuous
Cost structure	High capital and operational cost	Moderate; device cost varies widely	Variable; low-cost sensors reduce deployment cost but increase maintenance and data-management needs
Data reliability	Strong when QA/QC protocols are followed	Requires regular calibration and validation	Requires automated quality control, uncertainty estimation, and reference checks
Regulatory acceptance	High	Moderate; often accepted for screening rather than compliance	Limited to moderate; usually requires confirmatory laboratory support
Best application	Confirmatory analysis, compliance monitoring, reference datasets	Screening, hotspot identification, emergency response	Early warning, trend detection, spatial-temporal surveillance
Main limitation	Delayed results and limited monitoring frequency	Matrix effects, robustness, and calibration stability	Drift, data overload, false alarms, and interpretation complexity
Ideal role in integrated monitoring	Provides reference accuracy and legal defensibility	Guides sampling and rapid decisions	Detects change and supports continuous environmental intelligence

Calibration transfer is another critical issue. Field measurements should be periodically checked against laboratory reference methods to correct drift, refine calibration, and identify systematic bias. Co-located measurements, split-sample analysis, reference materials, and interlaboratory comparisons can improve comparability. Harmonization also requires standardized metadata, including sampling time, location, matrix characteristics, calibration status, detection limits, environmental conditions, and quality-control flags. Without such contextual information, high-frequency field data may be difficult to interpret or defend.

6.5. Regulatory Acceptance and Standardization

One of the most important challenges to the widespread adoption of new analytical technologies is regulatory acceptance. Use of standardized procedures, which are subject to extensive testing and validation, is often required by environmental regulations. Such approaches ensure uniformity, legal enforceability and cross-regional and institutional comparability [77]. New technologies can be rapidly developed and cutting-edge, but do not necessarily have the documentation and performance that are required for compliance monitoring. This poses a clash between innovation and standardization. Regulatory solutions need to safeguard data quality, but overreliance on tried-and-tested approaches can also delay the uptake of potentially beneficial new technologies. There is a need for a balance, as new techniques are initially adopted for screening, surveillance, and decision-support functions before they are applied to formal compliance applications. Standardized protocols can incorporate technologies that are robust, reproducible, and comparable over time [78,79].

The standardization should not only apply to instrumental procedures. It should also contain data handling, data processing, quality assurance/quality control, uncertainty reporting, maintenance schedules, and acceptance/

rejection criteria for data. In the case of systems powered by artificial intelligence, standards are also mandatory for system training, documentation, model validation, algorithmic transparency, and performance monitoring. Otherwise, identical data can yield different results depending on the algorithm or preprocessing employed.

6.6. Ethical, Economic, and Practical Considerations

Ethical, economic, and practical considerations are associated with the expansion of real-time and field-deployable environmental testing. The timely information provided by continuous monitoring can help enhance public transparency and environmental protection by alerting the public to pollution episodes. Communities impacted by industrial emissions, contaminated water, or hazardous waste might receive more readily available environmental information. But there needs to be responsible communication of data. The lack of validation and/or poor explanation of sensor outputs can lead to unnecessary alarms, misinterpretation, and/or mistrust.

However, technology adoption is also affected by economic considerations. The advanced laboratory instruments are expensive because they provide high-quality data and broad analytical capabilities. Low-cost sensors lower the entry barriers and facilitate the establishment of dense monitoring networks, but their operation comes at the price of frequent calibration, maintenance, replacement, and data correction. Hence, the actual cost of a monitoring system involves the cost of the hardware, plus training, QC, data management, technical support and confirmatory analysis. Cost-effectiveness must be considered based on the objective of the monitoring, and not on instrument cost [80].

User experience also affects the practical implementation. Field technologies are sometimes described as easy and accessible, but they still require people to understand calibration, sample matrix effects, maintenance, and data interpretation. If not designed and operated correctly, even good instruments can produce inaccurate results. Therefore, the deployment of these is essential and requires capacity building, standard operating procedures and user-friendly data platforms.

Connecting technological innovation to environmental protection is critical to data analytics, validation, and regulatory translation. Although the ability to collect more data is a benefit of emerging analytical systems, it does not always make the data more useful for decision-making simply because of its quantity. The value of environmental testing lies in its accuracy, interpretability, comparability, and suitability for its purpose.

Future progress needs to focus on integrated validation frameworks that account for the variety of modern analytical tools. The assessment of laboratory methods, portable instruments, real-time sensors, remote sensing platforms, and AI-driven models should not be based on the same criteria, but on clear criteria tailored to their use. Screening tools are valued for their ability to detect events and classify risk; confirmatory tools must be held to higher standards of accuracy and legal defensibility. Such a multi-level process can push for innovation without sacrificing data quality [80].

Finally, the process of moving from bench to field will only be successful if this is balanced with equally robust progress in data science, quality assurance and regulatory trust. The future of environmental testing is largely a hybrid system where field technologies deliver real-time data, laboratory techniques validate results, and data analytics convert data into knowledge that can guide action. The proposed integrated framework for future environmental monitoring and decision support is summarized in **Figure 2**. In this framework, validation and standardization are not barriers to innovation; they are the mechanisms that allow innovation to become scientifically credible and socially useful.

7. Conclusion

The development of environmental testing from laboratory-based analysis to field-deployable and real-time analysis is not an isolated advancement in environmental science but an evolution in analytical science. Environmental contamination is growing in complexity, in dynamics, and in spatial variability, not just because of the presence of traditional pollutants such as metals, nutrients, VOCs, pesticides, and pharmaceuticals, and the presence of endocrine disruptors and microplastics, but also because of the presence of transformation products and persistent synthetic compounds. Analytical techniques need not only to provide accurate concentration values but also to enable rapid detection, spatial mapping, temporal tracking, early warning, and evidence-based decision-making in this context.

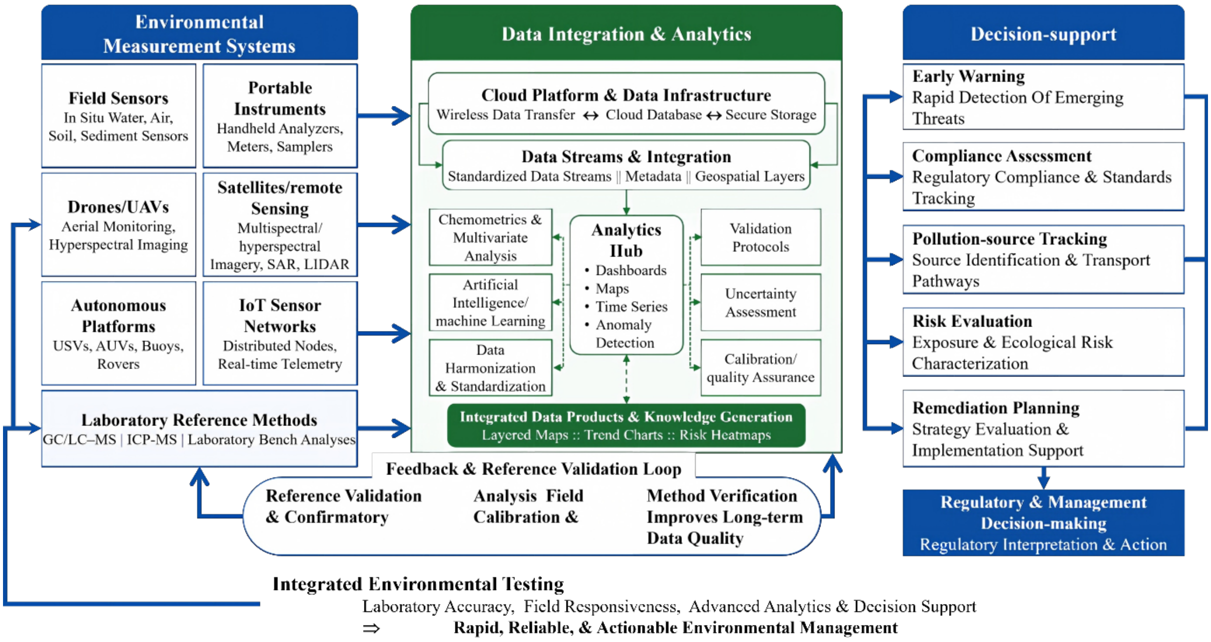

Figure 2. Integrated environmental monitoring and decision-support framework combining field-deployable technologies, laboratory reference methods, real-time data systems, chemometrics, artificial intelligence, validation protocols, uncertainty assessment, and regulatory interpretation. The framework supports rapid, reliable, and actionable environmental decision-making.

The analytical core of environmental testing continues to be conventional laboratory methods. The sensitivity, selectivity, structural confirmation, and reproducibility required for regulatory monitoring and scientific assessment are achieved using chromatographic, mass spectrometric, spectroscopic, and elemental analysis platforms. They are effective when they have control over their workflows, validated protocols, and robust quality assurance systems. But their shortcomings are equally apparent. Time-consuming transportation to a centralized laboratory, complicated sample preparation, high laboratory operational costs, and delayed reporting are often associated with centralized laboratory analysis. These limitations impoverish its usefulness in episodic pollution incidents, emergency response and continuous environmental monitoring.

The key to the development of many of the advances that have helped to bring the precision of the lab closer to the field is in the sample preparation. New extraction and preconcentration techniques, such as solid-phase extraction, microextraction, Quenchers, magnetic sorbents, molecularly imprinted polymers, nanomaterials and green solvents, have enhanced the sensitivity and selectivity of these methods and made them more environmentally friendly. However, one of the most critical points hindering environmental testing is sample preparation. Procedures that are successful in laboratory settings with standard matrices may not be successful in real matrices with organic matter, suspended particles, salts, and competing interferences. Thus, further advancements will need to be made in materials and miniaturized formats, as well as in providing comprehensive validation under representative environmental conditions.

New technologies, including instruments and sensors, are emerging to make environmental analysis more accessible outside the laboratory. New developments, such as portable chromatographs, miniaturized mass spectrometers, optical sensors, electrochemical sensors, biosensors, microfluidic devices and platforms based on nanomaterials, open the door for rapid decentralized and low-cost monitoring. These tools are particularly useful for screening, hotspot identification, source tracking, and initial risk assessment. However, they need to be adopted more widely, and many ongoing issues remain to be addressed regarding selectivity, calibration stability, fouling, reproducibility, and long-term performance. While sensitivity is an important factor, environmental technologies must also be rugged, interpretable, maintainable, and suitable for real-world matrices.

Another significant benefit of field-deployable and real-time monitoring devices is that they can record environmental variability that is not typically captured by grab sampling. Continuous and spatially resolved datasets can be provided by sensor networks, unmanned aerial vehicles, autonomous monitoring platforms, remote sensing technologies, and systems that are connected to the Internet of Things. These are vital attributes for monitoring air- and water-quality trends, detecting short-term pollution pulses, monitoring industrial pollution events, and for emergency response. However, it is important to ensure accurate real-time data interpretation. Sensor drift, environmental interference, missing data, and ambiguous calibration can affect data quality if not addressed by a comprehensive quality control program and periodic laboratory recalibration.

The future of emerging technologies could be as a common working tool or as a research prototype, depending on the results of data analytics, data validation, and regulatory translation. The use of pattern recognition, anomaly detection, calibration correction, and predictive modeling can be enhanced through chemometrics, artificial intelligence, and machine learning. Computational models must, however, be transparent, representational, and independently validated. The criteria for regulatory acceptance will be clear and straightforward: performance, uncertainty estimation, standardized protocols, and harmonization of field measurement methods with reference laboratory methods.

The overall future of environmental testing will not be characterized by the mere replacement of the "bench" with "field" technologies. Rather, it will rely on integrated monitoring frameworks in which laboratory techniques provide confirmatory accuracy, field systems are fast and cover wide areas, and data analytics transform measurements into actionable knowledge. It will be a hybrid, tiered and purpose-driven approach: speedy field tools for screening and early warning; sound laboratory methods for confirmation and compliance; and smart data systems to interpret and support decision-making. With an analytical approach and field responsiveness, environmental testing can be made faster, greener, adaptive, and relevant for the complex environmental challenges of the future.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study. As this is a review, it is based on data and information from previously published sources, which are cited in the reference list.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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