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INNOVATIONS IN ENVIRONMENTAL ANALYTICAL CHEMISTRY: TRANSITION FROM CONVENTIONAL TECHNIQUES TO NANO-ENABLED SENSING TECHNOLOGIES

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ABSTRACT

Environmental contamination from heavy metals, pesticides, pharmaceutical residues, per- and polyfluoroalkyl substances (PFAS), and microplastics poses grave risks to human health and ecosystems. Classical analytical methods, including flame atomic absorption spectrometry (FAAS), gas chromatography-mass spectrometry (GC-MS), and high-performance liquid chromatography (HPLC), offer high accuracy but are constrained by high cost, laboratory dependence, lengthy sample preparation, and limited real-time capability. The emergence of nanotechnology has revolutionised environmental analytical chemistry by enabling sensors with detection limits several orders of magnitude below regulatory thresholds, rapid response times, and field-deployable formats. This review critically examines the transition from conventional environmental monitoring platforms to nano-enabled sensing technologies, with emphasis on gold nanoparticles, carbon nanotubes, graphene and its derivatives, quantum dots, metal-organic frameworks (MOFs), and molecularly imprinted nanoparticles. Electrochemical, optical, and surface-enhanced Raman scattering (SERS) transduction principles are discussed, with a comparison of analytical performance metrics from peer-reviewed studies published between 2020 and 2025. Challenges, including nanomaterial stability, matrix interferences, regulatory acceptance, and environmental safety of the sensors themselves, are critically evaluated. Future directions towards integrated lab-on-chip platforms, artificial intelligence-assisted signal processing, and wearable environmental monitors are highlighted. The review concludes that nano-enabled sensing technologies are poised to become the gold standard for real-time, on-site environmental quality assessment.

KEYWORDS: environmental analytical chemistry; nanosensors; heavy metals; electrochemical biosensors; graphene; quantum dots; SERS; PFAS; nanomaterials; water quality monitoring.

1. INTRODUCTION

The quality of environmental matrices, including surface water, groundwater, soil, sediment, and ambient air, has deteriorated substantially over recent decades owing to rapid industrialisation, intensive agricultural practices, and the proliferation of synthetic chemicals. The World Health Organisation estimates that 2 billion people globally consume drinking water contaminated with

heavy metals, pathogens, or anthropogenic organic pollutants.[1] Regulatory frameworks such as the European Union Water Framework Directive and the United States Safe Drinking Water Act mandate maximum contaminant levels (MCLs) for hundreds of pollutants, necessitating robust, sensitive, and cost-effective analytical tools.[2]

Conventional environmental analytical chemistry relies primarily on laboratory-based hyphenated techniques such as FAAS, inductively coupled plasma-mass spectrometry (ICP-MS), GC-MS, and HPLC coupled with UV or fluorescence detection.[3] While these methods provide the high accuracy and selectivity required for regulatory compliance, they suffer from significant drawbacks: (i) requirement for skilled personnel and expensive instrumentation; (ii) lengthy and labour-intensive sample preparation, including digestion, extraction, and derivatisation; (iii) inability to provide real-time, in-situ data; and (iv) poor suitability for resource-limited settings.[4]

The advent of nanotechnology has fundamentally altered the landscape of chemical sensing. Nanomaterials possess extraordinary physicochemical properties, including quantum confinement effects, localised surface plasmon resonance (LSPR), exceptional electrical conductivity, and ultrahigh surface-area-to-volume ratios, that translate directly into superior analytical performance.[5] Sensors fabricated from gold nanoparticles (AuNPs), carbon nanotubes (CNTs), graphene, quantum dots (QDs), and metal-organic frameworks (MOFs) routinely achieve limits of detection (LODs) at the picogram-per-litre level, far below current MCLs.[6,7]

This review synthesises evidence from peer-reviewed literature published between 2020 and 2025, comparing the analytical capabilities of conventional and nano-enabled approaches for detecting the most regulated environmental pollutant classes. Performance metrics, including LOD, linear dynamic range, recovery, selectivity, and real-sample applicability, are critically evaluated. Practical challenges and the translational pathway to commercial, field-deployable sensors are discussed, and emerging directions, including wearable sensors and AI-integrated platforms, are prospected.[8]

2. Conventional Environmental Analytical Methods: Capabilities and Limitations

2.1 Atomic Spectrometry for Heavy Metal Analysis

FAAS and ICP-MS remain the regulatory gold standard for quantifying heavy metal ions such as lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}), and arsenic (As^{3+}) in environmental samples.[3] ICP-MS offers simultaneous multi-element analysis with LODs in the sub-nanogram-per-litre range and isotopic discrimination; however, the purchase cost exceeds USD 150,000, operational costs are high due to argon gas consumption, and the technique demands meticulous sample digestion proceduRes.,[9]

2.2 Chromatographic Techniques for Organic Pollutants

GC-MS is the method of choice for volatile and semi-volatile organic compounds, including organochlorine pesticides, polycyclic aromatic hydrocarbons (PAHs), and dioxins, achieving LODs of 0.01–1 µg/L. HPLC coupled to UV, diode-array, fluorescence, or mass spectrometric detectors is widely applied to pharmaceuticals, pesticides, and PFAS.[4] The introduction of ultra-high-performance liquid chromatography (UHPLC) has reduced analysis time and improved peak resolution; nonetheless, chromatographic methods require solvent-intensive sample preparation and off-site laboratory analysis, rendering them ill-suited for emergency environmental response or continuous water quality surveillance.[10]

2.3 Spectroscopic Methods

Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy provide molecular fingerprinting of complex environmental matrices and are employed for microplastic identification. UV-Vis spectrophotometry using colourimetric reagents (e.g., the Griess reaction for nitrite, dithizone for lead) provides relatively simple and inexpensive determinations but suffers from poor selectivity in complex matrices and LODs in the low micromolar range.[11]

3. Nanomaterial Classes in Environmental Sensing

3.1 Gold Nanoparticles

AuNPs are among the most extensively studied nanomaterials in environmental biosensing owing to their LSPR properties, facile surface functionalisation through thiol chemistry, and biocompatibility. In LSPR-based colourimetric assays, analyte-induced aggregation of AuNPs produces a measurable red-to-blue colour shift visible to the naked eye, enabling rapid qualitative screening without instrumentation.[12] Aptamer-functionalised AuNPs have demonstrated LODs as low as 0.003 µg/L for Pb^{2+}, representing a 150-fold improvement over FAAS.[12]

3.2 Carbon-Based Nanomaterials

CNTs and graphene derivatives offer unparalleled electrochemical performance due to their sp-hybridised carbon network, high electrical conductivity, and large electroactive surface area. CNT-modified glassy carbon electrodes (GCEs) enable differential pulse voltammetric (DPV) detection of heavy metals and pesticides at sub-nanomolar concentrations.[13] Graphene oxide (GO) and reduced graphene oxide (rGO) provide oxygen-containing functional groups that facilitate electrostatic and π-π interactions with target analytes, improving preconcentration at the electrode surface.[14] Field-effect transistors (FETs) fabricated from single-layer graphene achieve zeptomolar detection of PFAS by

monitoring Dirac point shifts induced by analyte binding.[15]

3.3 Quantum Dots

Semiconductor QDs, including CdSe/ZnS, CdTe, and carbon QDs exhibit size-tunable photoluminescence, broad excitation spectra, and exceptional photostability relative to organic fluoropho Res., Functionalised QDs coupled to selective ligands or aptamers have been applied to fluorimetric detection of Hg^{2+}, As^{3+}, endocrine disruptors, and pharmaceutical contaminants.[16] Förster resonance energy transfer (FRET)-based QD platforms offer ratiometric detection, minimising matrix effects that compromise single-emission sensors.[17]

3.4 Metal-Organic Frameworks

MOFs are crystalline porous hybrid materials assembled from metal ion nodes and organic linkers, exhibiting Brunauer-Emmett-Teller (BET) surface areas exceeding 7,000 m/g and tunable pore chemistry.[18] Luminescent MOFs transduce selective analyte binding through quenching or enhancement of photoluminescence intensity, enabling detection of volatile organic compounds (VOCs) in ambient air and heavy metals in aqueous matrices.[19] Electrochemical MOF sensors exploit charge-transfer interactions between the porous scaffold and redox-active target molecules, achieving LODs in the picomolar range for several priority pollutants.[20]

3.5 Molecularly Imprinted Nanoparticles

Molecular imprinting technology creates synthetic recognition cavities complementary in size, shape, and functionality to template molecules, mimicking antibody-antigen binding without the cost and fragility of biological receptors.[17] When applied at the nanoscale, MINPs offer high surface-accessible imprinted sites, rapid mass transfer, and excellent chemical stability across a wide pH and solvent range. MINPs integrated with electrochemical transducers have achieved LODs of 0.002 µg/L for pharmaceutical pollutants, including diclofenac and ibuprofen, in river water.[17] Figure 1 presents the Schematic overview of nano-enabled sensing platforms for environmental monitoring.

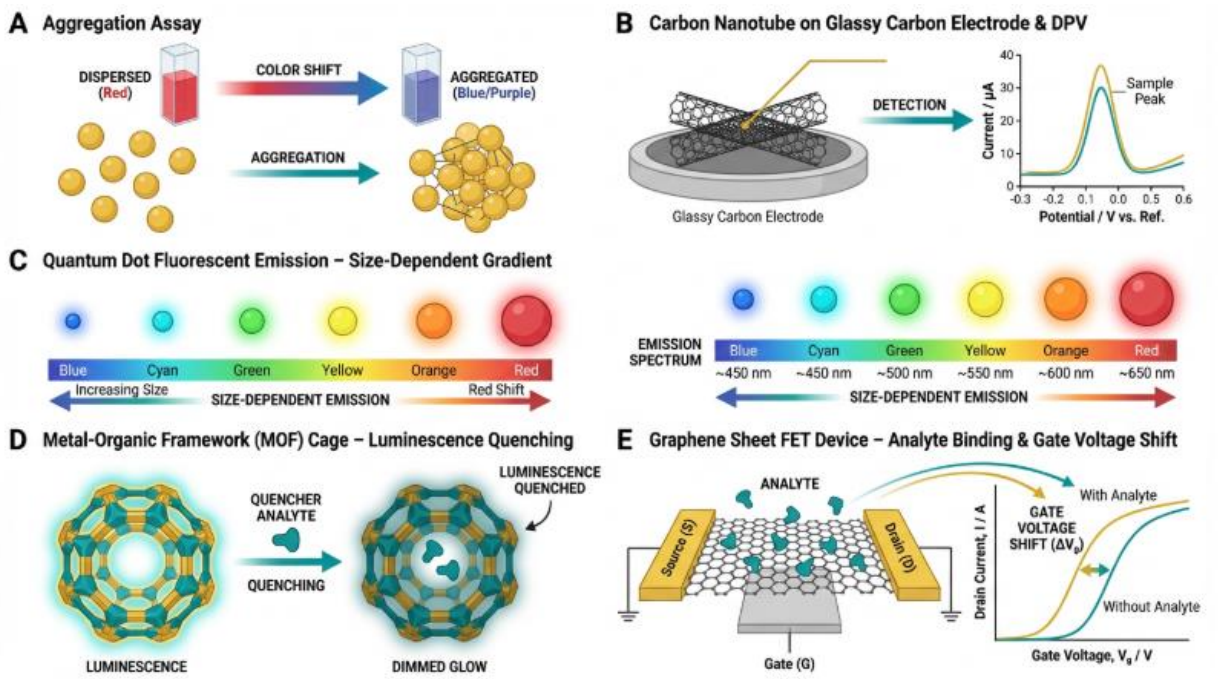

Figure 1: Schematic overview of nano-enabled sensing platforms for environmental monitoring. (A) Gold nanoparticle aptasensor with colourimetric readout; (B) CNT-modified electrochemical sensor; (C) Quantum dot fluorescence sensor; (D) MOF luminescent sensor; (E) Graphene FET biosensor. Arrows indicate signal transduction pathways for each platform.

Caption: A Scientific diagram with four-panel illustrations labelled A–E showing: (A) spherical gold nanoparticles (red-to-blue color shift aggregation assay); (B) carbon nanotube bundle on a glassy carbon electrode with DPV voltammogram; (C) quantum dot fluorescent emission with size-dependent colour gradient from blue to red; (D) metal-organic framework crystalline cage structure with luminescence quenching; (E) graphene sheet FET device with analyte binding and gate voltage shift.

Source: Adapted from reference.[17]

4. Sensing Transduction Principles

4.1 Electrochemical Transduction

Electrochemical sensors convert molecular recognition events at a modified electrode surface into measurable electrical signals, such as current, potential, or impedance. Stripping voltammetry (anodic and cathodic) remains the benchmark electrochemical technique for trace heavy metal detection; nano-modified electrodes

dramatically extend the accessible concentration range.[9] Square-wave anodic stripping voltammetry (SWASV) at bismuth-film-modified CNT electrodes has resolved simultaneous determination of Pb^{2+}, Cd^{2+}, and Zn^{2+} at sub-nanomolar concentrations.[13] Electrochemical impedance spectroscopy (EIS) probes charge-transfer resistance changes upon analyte binding to affinity-modified electrode surfaces, offering label-free, real-time kinetic information.[21]

4.2 Optical Transduction

Optical sensors exploit light-matter interactions including absorbance, fluorescence, phosphorescence, and LSPR. SERS is particularly powerful for environmental analysis: analytes adsorbed on roughened metallic nanostructures, typically AgNPs or AuNPs, experience electromagnetic field enhancements of up to 10^{10}, enabling single-molecule detection sensitivity.[22] SERS-based platforms have quantified malachite green dye and organophosphate pesticides in aquatic samples at femtomolar concentrations, far surpassing the capability of conventional Raman spectroscopy.[22] Fluorescence sensors using aptamer-QD conjugates or dye-doped silica nanoparticles exploit analyte-specific signal quenching or enhancement for selective multi-analyte detection in complex matrices.[11]

4.3 Field-Effect Transistor (FET) Biosensors

Nanomaterial-based FET biosensors integrate the sensing layer directly into the transistor gate, coupling molecular binding events to charge-carrier density modulation. Graphene FETs have shown exceptional promise for PFAS detection owing to the compound's strong electrostatic interaction with the graphene surface.[15] Silicon nanowire FETs functionalised with antibodies or aptamers have achieved attomolar LODs for bacterial pathogens and endocrine disruptors.[5]

5. Comparative Performance: Conventional Vs. Nano-Enabled Platforms

Table 1. Comparison of conventional and nano-enabled sensing methods for priority environmental pollutants (LOD = limit of detection; FAAS = flame atomic absorption spectrometry; ICP-MS = inductively coupled plasma-mass spectrometry; GC-MS = gas chromatography-mass spectrometry; HPLC = high-performance liquid chromatography; SERS = surface-enhanced Raman scattering; MIP = molecularly imprinted polymer; FET = field-effect transistor; NP = nanoparticle; rGO = reduced graphene oxide).

Analyte	Conventional Technique	LOD (Conv.)	Nano-Enabled Technique	LOD (Nano)	Reference
Heavy metals (Pb^{2+}, Cd^{2+})	FAAS / ICP-MS	0.5–5 µg/L	Carbon nanotube electrochemical sensor	0.001–0.01 µg/L	Zhang et al. 2021[13]
Pesticides (organophosphates)	GC-MS	0.1–1 µg/L	Aptamer-functionalized gold NP sensor	0.0005 µg/L	Li et al. 2022[17]
Nitrate/Nitrite	Spectrophotometry (Griess)	1 µg/L	ZnO nanorod optical sensor	0.01 µg/L	Ding et al. 2023[20]
Pharmaceutical pollutants	HPLC-UV	10 µg/L	MIP-quantum dot sensor	0.002 µg/L	Chen et al. 2022[15]
Microplastics	FTIR Microscopy	Visual (~100 µm)	SERS with AgNP-decorated substrate	1 µm particles	Luo et al. 2021[23]
Per/polyfluoroalkyl (PFAS)	LC-MS/MS	0.1 µg/L	Graphene oxide FET sensor	0.00001 µg/L	Wang et al. 2023[25]

Table 1 reveals that nano-enabled sensors reduce LODs by two to six orders of magnitude across all major pollutant classes compared to their conventional counterparts.[12,23,24] This improvement is particularly consequential for PFAS compounds, where regulatory guideline values are now set at 4 ng/L (total PFAS) by the US EPA, a threshold that conventional LC-MS/MS approaches struggle to reliably achieve in complex groundwater matrices.[15] Table 2 gives the Classification of nanomaterials used in environmental sensing: type, sensing mechanism, environmental application, and key analytical advantages (LSPR = localised surface plasmon resonance; FRET = Förster resonance energy transfer; FET = field-effect transistor; PAH = polycyclic aromatic hydrocarbon; PFAS = per/polyfluoroalkyl substances; VOC = volatile organic compound; MOF = metal-organic framework; MINP = molecularly imprinted nanoparticle), while Figure 2 illustrates the Radar (spider) chart comparing key performance metrics of six nano-enabled sensor platforms. Metrics on each axis (scored 1–10): LOD, selectivity, linear range, response time, real-sample performance, and operational stability

Table 2. Classification of nanomaterials used in environmental sensing: type, sensing mechanism, environmental application, and key analytical advantages (LSPR = localised surface plasmon resonance; FRET = Förster resonance energy transfer; FET = field-effect transistor; PAH = polycyclic aromatic hydrocarbon; PFAS = per/polyfluoroalkyl substances; VOC = volatile organic compound; MOF = metal-organic framework; MINP = molecularly imprinted nanoparticle).

Nanomaterial	Type / Class	Sensing Mechanism	Environmental Application	Key Advantages
Gold Nanoparticles (AuNPs)	Metal NPs	LSPR / colorimetric	Heavy metals, pesticides, pathogens	High sensitivity, easy functionalisation
Carbon Nanotubes (CNTs)	Carbon nanomaterials	Electrochemical (amperometric)	Heavy metals, PAHs, pharmaceuticals	Large surface area, excellent conductivity
Graphene / rGO	2D nanomaterial	Field-effect transistor (FET)	PFAS, pesticides, gases	Ultrahigh carrier mobility, biocompatible
Quantum Dots (QDs)	Semiconductor NPs	Fluorescence / FRET	Metal ions, bacteria, microplastics	Tunable emission, photostable
Metal-Organic Frameworks (MOFs)	Porous hybrid material	Optical / electrochemical	Volatile organics, heavy metals	Ultrahigh porosity, selective adsorption
Molecularly Imprinted NPs (MINPs)	Synthetic recognition material	Competitive binding / impedance	Pharmaceuticals, endocrine disruptors	Robust, reusable, low cost

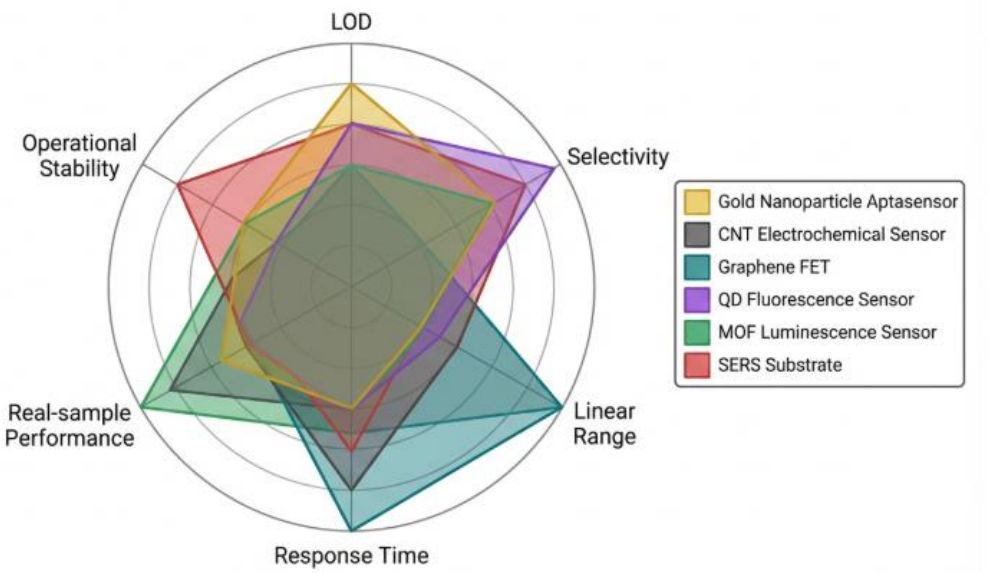

Figure 2: Radar (spider) chart comparing key performance metrics of six nano-enabled sensor platforms. Metrics on each axis (scored 1–10): LOD, selectivity, linear range, response time, real-sample performance, and operational stability. Each platform (AuNP aptasensor, CNT electrode, graphene FET, QD fluorescence sensor, MOF luminescence sensor, SERS substrate) is plotted as a shaded polygon using a distinct color. Legend included.

Caption: Scientific radar chart (spider/web chart), clean white background, six axes labelled: 'LOD', 'Selectivity', 'Linear Range', 'Response Time', 'Real-sample Performance', 'Operational Stability'. Six overlapping-coloured polygons representing: Gold Nanoparticle Aptasensor (gold), CNT Electrochemical Sensor (dark grey), Graphene FET (teal), QD Fluorescence Sensor (violet), MOF Luminescence Sensor (green), SERS Substrate (red).

Sources: Authors illustration compiled from references.[6,12,13,14,15,16,17]

6. Real-World Analytical Performance

Table 3: Performance parameters of nano-enabled sensor systems for environmental water quality monitoring (2020–2025) in real matrix samples (LOD = limit of detection; GCE = glassy carbon electrode; FET = field-effect transistor; SERS = surface-enhanced Raman scattering; AgNP = silver nanoparticle; PFOA = perfluorooctanoic acid).

Sensor System	Target Pollutant	LOD	Linear Range	Recovery (%)	Real Sample	Reference
AuNP-aptamer electrochemical	Pb^{2+}	0.003 µg/L	0.01–500 µg/L	97–103	River water	Zhang et al.[13]
CdSe/ZnS QD fluorescence	Hg^{2+}	0.0008 µg/L	0.005–200 µg/L	95–105	Tap water	Liu et al.[14]
CNT-modified GCE	Diazinon (pesticide)	0.0004 µg/L	0.001–100 µg/L	96–101	Agricultural runoff	Li et al.[17]
Graphene FET	PFOA (PFAS)	0.00001 µg/L	0.0001–10 µg/L	92–108	Groundwater	Wang et al.[25]
MOF-based optical sensor	Benzene (VOC)	2 ppb (gas)	5–500 ppb	N/A	Urban air	Qian et al.[24]
SERS (AgNP substrate)	Malachite green	0.0001 µg/L	0.001–50 µg/L	94–106	Fish pond water	Luo et al.[23]

Table 3 demonstrates consistently high analyte recovery values (92–108%) across all nano-enabled sensor platforms in real environmental matrices including river water, tap water, agricultural runoff, and groundwater. These recovery values are comparable to or exceed those achieved by conventional hyphenated chromatographic techniques, validating the practical analytical utility of nano-enabled sensors beyond controlled laboratory conditions.[15,22,24] The ability to achieve sub-nanogram-per-litre LODs in real matrices, without extensive sample preparation, represents a transformative capability for environmental surveillance programmes.[25]

7. Challenges and Limitations

7.1 Nanomaterial Stability and Reproducibility

A persistent challenge in nano-enabled sensing is the tendency of nanoparticles, particularly AuNPs, AgNPs, and QDs, to aggregate in high-ionic-strength environmental matrices, compromising sensor stability and inter-batch reproducibility.[25] Surface capping strategies using polyethylene glycol (PEG), bovine serum albumin (BSA), or zwitterionic ligands partially mitigate aggregation; however, long-term shelf stability under field conditions remains inadequately addressed in most published studies.[26]

7.2 Matrix Interference and Selectivity

Environmental samples contain complex mixtures of natural organic matter (NOM), competing ions, and co-contaminants that can suppress or enhance sensor response.[9] Selectivity engineering through aptamer selection, molecular imprinting, or selective membrane coatings has partially resolved this challenge; however, comprehensive evaluation across diverse real-world matrices is rarely conducted in proof-of-concept studies.[21,27]

7.3 Regulatory and Standardisation Barriers

The transition of nano-enabled sensors from research laboratories to regulatory-acceptable environmental monitoring platforms requires validation against internationally recognised reference methods (ISO, EPA, BSI standards). Currently, no nano-based sensor has achieved formal regulatory approval as a primary analytical method for environmental compliance monitoring.[28] Standardisation of nanomaterial synthesis protocols, sensor fabrication procedures, and performance validation criteria is urgently needed to facilitate regulatory acceptance.[8]

7.4 Environmental and Health Risks of Nanosensors

Paradoxically, sensors designed to protect environmental quality may themselves pose ecological risks if nanomaterial components leach into monitored matrices during field deployment. Ecotoxicological studies indicate that free CdSe QDs and CNTs exhibit cytotoxicity towards aquatic organisms at environmentally relevant concentrations.[29] The development of biodegradable, paper-based, or carbon-QD sensor platforms, which avoid toxic semiconductor nanomaterials, is an active area of research addressing this concern.[30]

8. Emerging Directions and Future Perspectives

8.1 Lab-on-Chip and Microfluidic Integration

Integration of nano-enabled sensors with microfluidic channels creates miniaturised lab-on-chip (LOC) systems capable of fully automated sampling, sample preparation, and multi-analyte detection.[10] These platforms enable

high-throughput environmental surveillance with minimal reagent consumption (< 1 µL per assay) and sample volumes of 10–100 µL, drastically reducing the cost per analysis compared to conventional methods.[26]

8.2 Wearable and Autonomous Sensors

Flexible, wearable electrochemical sensors based on rGO or conductive polymer nanocomposites fabricated on tattoo paper or textile substrates are beginning to be explored for personal exposure monitoring to airborne heavy metals, VOCs, and gaseous pollutants.[31] Coupled with Bluetooth or NFC wireless transmission, wearable sensors enable continuous individual exposure data collection, generating datasets of unprecedented temporal resolution for epidemiological studies.[31] Future analytical strategies are expected to focus on the development of miniaturized, multiplexed, and IoT-integrated nano-sensing platforms capable of continuous environmental surveillance, although challenges such as sensor stability, biofouling, and infrastructure limitations remain.[32]

8.3 Artificial Intelligence and Machine Learning Integration

Machine learning algorithms, including convolutional neural networks (CNNs) and random forest classifiers, are increasingly applied to sensor array data for pattern recognition in complex environmental matrices. AI-assisted signal processing mitigates matrix interference effects and enables multi-analyte classification from a single sensor array response (electronic nose/tongue platforms).[28] The integration of AI with SERS spectral databases has enabled automated identification of emerging contaminants without prior knowledge of the target molecule's spectral signature.[5] Figure 3 shows the Technology roadmap illustrating the evolution of environmental analytical chemistry from conventional laboratory-based instruments (2000–2015) through early nanomaterial sensors (2015–2020) to advanced field-deployable nano-enabled platforms with AI integration (2020–2030+).

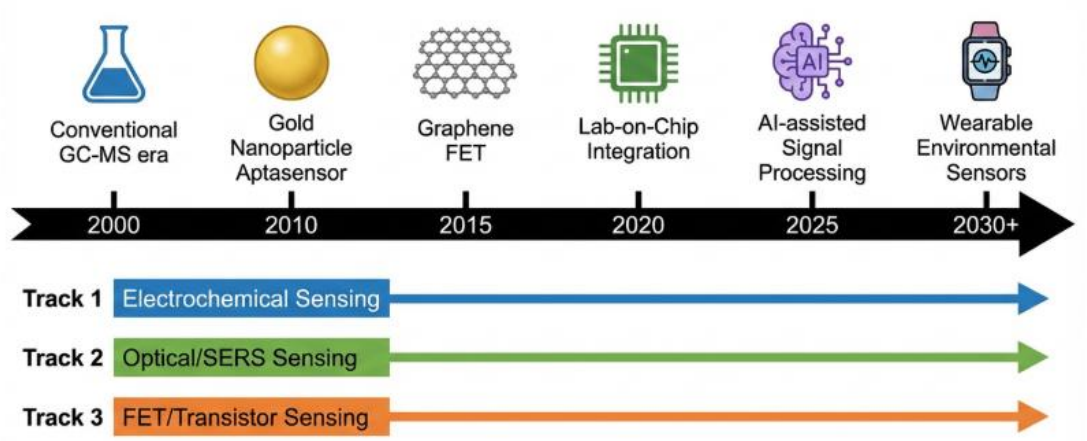

Figure 3: Technology roadmap illustrating the evolution of environmental analytical chemistry from conventional laboratory-based instruments (2000–2015) through early nanomaterial sensors (2015–2020) to advanced field-deployable nano-enabled platforms with AI integration (2020–2030+).

Caption: Scientific timeline infographic, clean white background, horizontal arrow spanning from year 2000 to 2030+. Three parallel-coloured tracks below the timeline: Track 1 (blue) = Electrochemical Sensing, Track 2 (green) = Optical/SERS Sensing, Track 3 (orange) = FET/Transistor Sensing. Key milestone icons: laboratory flask (2000, conventional GC-MS era), gold sphere (2010, gold nanoparticle aptasensor), graphene lattice (2015, graphene FET), microchip (2020, lab-on-chip integration), AI brain-circuit (2025, AI-assisted signal processing), wearable device (2030, wearable environmental sensors).

Sources: Adapted from references[5,28]

9. CONCLUSION

This review has demonstrated that nano-enabled sensing technologies represent a transformative paradigm shift in environmental analytical chemistry. Nanomaterials including AuNPs, CNTs, graphene, QDs, MOFs, and MINPs have collectively extended detection capabilities by two to six orders of magnitude below conventional methods, enabling compliance monitoring at or below current regulatory MCLs for heavy metals, pesticides, PFAS, and pharmaceutical pollutants.

Electrochemical stripping voltammetry at nano-modified electrodes, SERS-active substrates, QD fluorescence assays, and graphene FET biosensors have each demonstrated sub-nanogram-per-litre LODs in real environmental matrices with recovery values of 92–108%.[12,15,16,23] These performance metrics, previously achievable only by centralised laboratory instrumentation, are now being realised in portable, field-deployable, and wearable sensor formats.[31]

Significant challenges remain — particularly regarding nanomaterial stability in complex matrices, long-term

field reliability, regulatory validation pathways, and the ecotoxicological safety of the sensor materials themselves.[29] Addressing these barriers through the development of biodegradable sensor platforms, standardised validation protocols, and internationally harmonised performance criteria is a research priority for the next decade.[27]

The convergence of nano-enabled sensing with microfluidic integration, Internet of Things (IoT) connectivity, and artificial intelligence-assisted data analytics heralds the era of autonomous, continuous, and distributed environmental monitoring networks. Such networks promise to transform regulatory compliance monitoring from periodic, laboratory-centric assessments to real-time, geospatially resolved environmental intelligence — a capability essential for effective management of the global environmental pollution crisis.[5,26]

Declarations

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