Advances in Sensorics for Ecological Monitoring: Trends, Challenges, and Future Perspectives

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Abstract: *Environmental monitoring plays a critical role in the sustainable management of natural resources and the protection of ecosystems. The integration of sensorics- the science and technology of sensors- with ecology offers advanced tools for real-time data collection, analysis, and decision-making. This review highlights recent developments in sensor technologies applied to ecological studies, including water quality monitoring, biodiversity assessment, habitat evaluation, and climate impact analysis. Special attention is given to the development of IoT-based sensors and smart monitoring networks, sensors, wireless sensor networks, and smart monitoring systems, which enable continuous data collection and remote observation. Despite these advances, several challenges remain, such as sensor durability under extreme environmental conditions, data standardization, integration of heterogeneous datasets, and scalability for large and complex ecosystems. This review identifies current research gaps, highlights emerging trends, and proposes future perspectives to enhance the effectiveness and applicability of sensorics in ecological research and environmental management. By synthesizing multidisciplinary insights, this work aims to guide researchers, engineers, and policymakers in leveraging sensorics for sustainable ecosystem monitoring and decision-making.*

Keywords*: Sensorics, ecology, environmental monitoring, IoT sensors, biodiversity assessment, water quality monitoring, smart monitoring systems*

1. Introduction

Since the nineteenth century, rapid industrialization and urban expansion have placed increasing pressure on natural resources and ecological systems. The unregulated use of fossil fuels has driven a significant rise in greenhouse gas emissions, disrupting the Earth’s atmospheric energy balance [1-4]. This disruption has accelerated global warming, and from the second half of the twentieth century onward, observable shifts in climatic patterns have become evident [5]. In other words, the long-term natural cycle of climate variability has been forced into. an abrupt trajectory by human activities-one that progresses too rapidly for ecosystems to adapt [6].

Sudden and persistent changes in temperature and precipitation regimes are expected to trigger migrations of plants, animals, and even human populations [7]. The melting of polar ice masses will continue to raise sea levels, posing serious risks to coastal zones, river deltas, and island nations [8,9]. Furthermore, the frequency and intensity of meteorological disasters are projected to increase, amplifying risks to life and property.

In this context, innovative strategies are urgently needed to address human-induced climate change, environmental pollution, deforestation, and biodiversity loss. Environmental monitoring plays a critical role by providing data-driven insights essential for understanding these impacts and informing sustainable development, resource conservation, and policy design [10]. Traditionally, environmental monitoring relied heavily on manual sampling and laboratory analyses. Although accurate, these methods are often time-consuming, costly, and limited in spatial and temporal coverage.

Technological advancements have led to a paradigm shift in monitoring methodologies. Recent innovations in IoT-based sensors, wireless sensor networks, and smart monitoring technologies enable remote observation, automated data processing, and long-term continuous measurement [11,12]. Sensors now facilitate real-time acquisition of environmental parameters such as water quality, soil moisture, air composition, and habitat conditions. When integrated with ecological research, sensorics enhances high-resolution monitoring, supports rapid detection of environmental disturbances, and enables more effective ecosystem management.

Remote sensing technologies-augmented by satellite imagery and geographic information systems (GIS)-provide large-scale insight into deforestation, urban expansion, and climate patterns [13]. Artificial intelligence and machine learning further improve the analysis of complex environmental datasets, enabling predictive modeling for sustainable resource allocation. Additionally, blockchain technologies contribute to transparency and data security, which are essential for accountability in environmental initiatives [14]. Despite these advances, important challenges remain, including sensor durability under extreme conditions, the need for standardization and integration of heterogeneous datasets, and scalability limitations for monitoring large and complex ecosystems.
This review aims to provide a comprehensive overview of recent developments in sensorics as applied to ecological research, highlighting emerging trends, persistent challenges, and future research directions. By synthesizing multidisciplinary perspectives, the study seeks to guide researchers, engineers, and policymakers in leveraging sensor-based technologies for sustainable environmental monitoring and ecosystem management.

2. Sensor Technologies

Sensor technologies have evolved into indispensable tools for environmental research, offering precise, continuous, and real-time monitoring capabilities across diverse ecological systems. Modern sensorics encompasses a broad range of sensor types-including chemical, biological, environmental, and IoT-based sensors-each designed to detect specific physicochemical or biological parameters with high sensitivity and selectivity. Chemical sensors are widely applied for quantifying contaminants such as heavy metals, nutrients, and organic pollutants in water and soil environments. Biological sensors (biosensors) employ biological recognition elements to detect microorganisms, toxins, or biochemical markers, enabling highly specific measurements that are particularly valuable in ecological risk assessment. Environmental sensors, including optical, thermal, acoustic, and gas-sensing platforms, enable large-scale monitoring of air quality, temperature, humidity, particulate matter, and other ecosystem-related indicators. With rapid digitalization, IoT-based sensor systems have further enhanced monitoring efficiency by enabling wireless communication, remote data acquisition, and integration into smart environmental networks.
The applications of these sensor technologies span multiple ecological domains. In water quality assessment, sensors provide rapid detection of parameters such as pH, dissolved oxygen, turbidity, conductivity, and emerging contaminants. For air quality monitoring, advanced sensors can measure pollutants including CO_2, NO_x, SO_2, volatile organic compounds, and particulate matter ($PM_{2.5}$ and PM_{10}), supporting both local environmental management and global climate studies [15]. Soil moisture and nutrient sensors contribute significantly to sustainable agriculture and land-use planning by offering real-time insights into soil health and water availability. Furthermore, sensors play a crucial role in biodiversity monitoring, enabling automated tracking of species presence, habitat conditions, and ecosystem dynamics through acoustic sensors, camera traps, and bio-loggers [16]. Despite their wide applicability, each sensor type presents inherent advantages and limitations. Key advantages include high temporal resolution, scalability, cost-efficiency, and the ability to operate in remote or hazardous environments with minimal human intervention. However, limitations persist in terms of calibration requirements, sensitivity to environmental interference, limited lifespan of biological components, and data management challenges associated with large-scale deployments [17]. Additionally, sensor accuracy may degrade under extreme climatic conditions, and IoT-based systems may be constrained by power supply, connectivity, and cybersecurity issues. Understanding these strengths and constraints is essential for selecting appropriate sensor technologies and ensuring reliable ecological data acquisition. A hierarchical summary of the major sensor categories discussed above is shown in Figure 1.

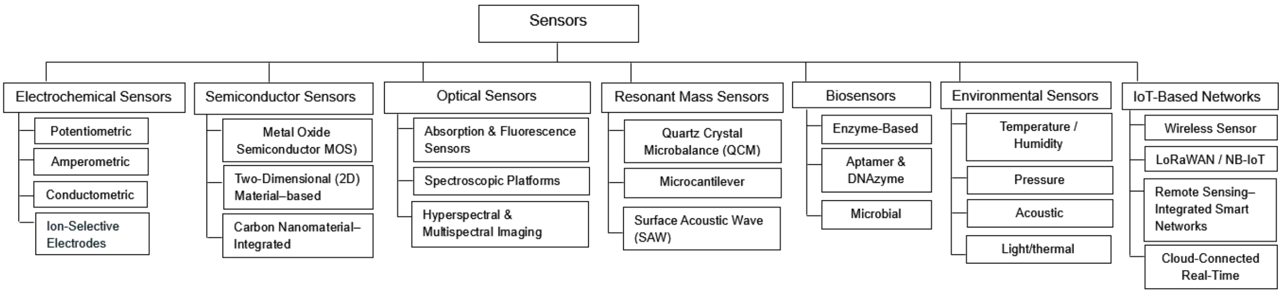

Fig. 1. Classification Scheme of Modern Sensor Technologies

3. Ecological Applications

Sensor technologies now play a transformative role in ecological research and environmental management by enabling high-resolution, real-time observations across aquatic, terrestrial, and atmospheric systems. In water and wastewater management, advanced optical, electrochemical, and biosensing platforms allow continuous monitoring of physicochemical parameters, early detection of pollutants, and rapid identification of contamination events, thereby improving treatment efficiency and safeguarding public health. Optical sensors commonly operate based on Beer-Lambert absorption principles or fluorescence-based mechanisms, where light attenuation or emission intensity correlates with analyte concentration. Electrochemical sensors-including amperometric, potentiometric, and conductivity-based platforms-function through ion transfer and redox reactions occurring at the electrode–electrolyte interface, enabling selective and sensitive quantification of dissolved species. Recent advancements in material science, particularly the integration of nanomaterials such as ZnO, TiO_2, graphene oxide, and carbon nanotubes, significantly enhance sensing performance through increased surface area, improved charge-transfer kinetics, and higher catalytic activity.

In habitat and biodiversity monitoring, sensor-based tools-such as acoustic recorders, GPS-enabled bio-loggers, camera traps, and environmental DNA (eDNA) devices-provide automated species detection, behavioral tracking, and long-term ecosystem surveillance with minimal disturbance to natural environments. Modern eDNA sensors employ surface-functionalized bioreceptors and hybridization-based molecular recognition, enabling highly specific detection of genetic material in complex environmental matrices. Climate-related applications also benefit substantially from sensor-based measurements, where atmospheric sensors, greenhouse gas detectors, and remote sensing networks provide critical information on temperature trends, carbon fluxes, and ecosystem responses to climatic stressors.

Moreover, soil moisture, nutrient, and microclimate sensors support precision agriculture and land management by optimizing irrigation strategies, enhancing crop productivity, and reducing environmental impact. Across all domains, robust sensor calibration protocols-including multi-point calibration, drift compensation, and temperature or ionic-strength corrections-ensure data accuracy under variable field conditions. Additionally, modern sensor networks rely on advanced communication infrastructures such as LoRaWAN, NB-IoT, ZigBee, and Bluetooth Low Energy to enable low-power, long-range wireless data transmission. Collectively, these applications demonstrate how sensorics has become a cornerstone of modern ecological assessment, enabling data-driven decision-making and fostering more resilient environmental systems.

3.1. Water and Wastewater Monitoring and Management

Water and wastewater management has become one of the most dynamic fields benefiting from recent advances in sensor technologies, particularly due to increasing pressures on freshwater resources and the need for rapid detection of contaminants in natural and engineered systems. Modern water-quality monitoring relies heavily on in situ chemical sensors capable of measuring parameters such as pH, oxidation–reduction potential, dissolved oxygen, turbidity, and nutrient concentrations with real-time precision. Turbidity sensors typically employ nephelometric configurations based on 90° light-scattering detection, which allow precise quantification of suspended particulate matter even at low concentrations.

Miniaturized electrochemical sensors, including ion-selective electrodes and voltammetric platforms, have been widely applied for detecting heavy metals such as Pb^{2+}, Cd^{2+}, U(VI), and Cs^{+} in both surface waters and treated effluents. Conductivity sensors, another essential class, utilize alternating current (AC) excitation to measure the total ionic strength of water while preventing electrode polarization through optimized frequency modulation. Dissolved oxygen measurements are commonly performed using two major approaches: (i) optical sensors based on luminescence quenching of oxygen-sensitive dyes, which offer high stability and minimal flow dependence; and (ii) electrochemical Clark-type electrodes that rely on oxygen diffusion through a membrane before electrochemical reduction at the cathode.

Optical sensors based on UV–Vis absorbance, fluorescence, and Raman spectroscopy provide non-destructive and continuous monitoring of organic pollutants, cyanotoxins, and dissolved organic matter, enabling rapid identification of episodic contamination events. In addition, advanced electrochemical nanosensor platforms have been particularly impactful, especially those utilizing surface-modified electrodes incorporating gold nanoparticles (AuNPs), reduced graphene oxide (rGO), and metal–organic framework (MOF) structures to enhance electron-transfer kinetics, surface area, and analyte binding affinity.

Real-time monitoring systems have increasingly adopted IoT-based architectures, where sensors are integrated with data loggers, wireless transmission modules, and cloud-based supervisory platforms. Such systems enable remote monitoring, automated alerts, and continuous data archiving for regulatory and operational decision-making. In municipal and industrial wastewater treatment, sensors are often embedded within SCADA-controlled infrastructures, allowing automated management of aeration, chemical dosing, and sludge processing. The incorporation of machine learning (ML) and artificial intelligence (AI) algorithms further enhances process optimization by predicting contaminant loads, identifying anomalies, and dynamically adjusting treatment parameters based on real-time sensor feedback.

He et al. synthesized a bismuth/MXene nanocomposite designed for sensitive electrochemical detection of multiple heavy metals in aqueous systems. The MXene substrate provided high conductivity and layered structure, while bismuth nanoparticles improved metal-ion affinity. The sensor successfully quantified Zn^{2+}, Pb^{2+}, and Cd^{2+} with remarkably low detection limits of 0.52 μg L^{-1}, 0.31 μg L^{-1}, and 0.49 μg L^{-1}, respectively, across a linear range of 2–200 μg L^{-1}. Recovery values between 92-104% and reproducibility below 4% RSD demonstrated high analytical reliability in environmental water samples [18]. Similarly, hybrid metal oxide–carbon nanomaterials offer high surface area and rapid electron transfer, making them excellent platforms for heavy-metal sensing in complex matrices. Hao et al. developed a self-assembled Co_3O_4/graphene oxide (GO) composite for the electrochemical detection of heavy metals in water. The integration of Co_3O_4 with GO enhanced electron transfer and increased the density of active sites. The sensor demonstrated high sensitivity toward Pb^{2+} and Cd^{2+}, achieving detection limits of 0.12 μM and 0.15 μM, respectively, with linear ranges extending up to 100–120 μM. The method showed strong repeatability (RSD < 3.2%) and high recovery rates (95-103%) in natural water samples, confirming its suitability for real-world monitoring [19]. Inam et al. developed a flexible, screen-printed electrochemical sensor functionalized with electrodeposited copper nanostructures for detecting nitrate in environmental waters. The authors optimized the Cu electrodeposition parameters, enabling high catalytic activity toward nitrate reduction. Analytical validation demonstrated a wide linear range of 1–200 mg/L and a detection limit of 0.5 mg/L, showing suitability for real-world water quality monitoring. The sensor also exhibited good mechanical stability under bending, with less than 5% signal loss after 100 bending cycles, underlining its potential for wearable or field-deployable monitoring platforms [20]. Nanoparticle-enhanced multi-channel electrochemical arrays address the challenge of metal speciation, enabling simultaneous detection of chemically distinct analytes. Zhao et al. designed a dual-channel electrochemical sensor array modified with Au-Ag bimetallic nanoparticles, enabling simultaneous detection of Cr(III) and Cr(VI) in wastewater samples. The bimetallic nanostructure enhanced electron transfer kinetics and provided distinct redox signatures for each chromium species. The device achieved detection limits of 0.12 μM for Cr(III) and 0.08 μM for Cr(VI), with linearity maintained up to 100 μM. The sensor performed reliably in complex matrices, including industrial wastewater, demonstrating high selectivity even in the presence of Fe^{3+}, Cu^{2+}, and organic matter. The study highlighted the potential of nanoparticle-enhanced sensor arrays for heavy-metal speciation in ecological monitoring [21]. Additionally, Motaghedifard et al. developed an electrochemical sensor based on a polyaniline/sulfated zirconium dioxide/multi-walled carbon nanotube nanocomposite, achieving highly selective and sensitive detection of Cr(VI) in wastewater, further reinforcing the potential of nanostructured electrode materials for advanced heavy-metal monitoring [22]. Fluorescence-based multi-metal sensing arrays expand detection capabilities to ultra-trace levels and allow simultaneous multi-contaminant recognition through pattern analysis. Ihde et al. developed an ultrasensitive fluorescence-based sensor array capable of distinguishing multiple heavy metals in seawater through pattern-recognition algorithms. The array effectively detected Hg^{2+}, Pb^{2+}, Cd^{2+}, and Cu^{2+} at nanomolar concentrations, with detection limits as low as 0.5-2.4 nM depending on the analyte. Their approach achieved discrimination accuracies above 95%, even in complex ionic matrices, demonstrating superior performance in multi-metal environments common to marine ecosystems [23]. Electrochemical sensing is equally powerful for detecting organic pollutants; reviews have emphasized its scalability and cost effectiveness. Olayiwola et al. presented a comprehensive review of electrochemical strategies for detecting organic pollutants, including pharmaceuticals, pesticides, dyes, and endocrine-disrupting compounds in wastewater systems. The review emphasized the superior sensitivity of nanomaterial-modified electrodes such as carbon nanotubes, metal-organic frameworks (MOFs), and molecularly imprinted polymers (MIPs). Reported detection limits for emerging contaminants were frequently in the nanomolar to picomolar range, with electrochemical oxidation/reduction signatures enabling rapid quantification. The authors concluded that electrochemical platforms offer cost-effective, highly scalable alternatives for real-time monitoring, though challenges remain in electrode fouling, complex matrices, and standardization for regulatory use [24]. Optical plasmonic sensors, particularly portable SPR systems, provide rapid and multiplexed heavy-metal detection for on-site applications. Hossea and Rugumira proposed a portable surface plasmon resonance (SPR) sensor using a divergence-beam optical configuration to enable real-time, multi-metal detection in water. Their device simultaneously measured Pb^{2+}, Hg^{2+}, and Cd^{2+}, providing high sensitivities of 154°/RIU, 131°/RIU, and 118°/RIU, respectively. The measurement time was under 40 s, and the system maintained an error margin below 3%, indicating its potential as a rapid, field-deployable tool for heavy-metal assessment in drinking and surface waters [25]. AI-enhanced sensor networks now play a critical role in wastewater treatment plant (WWTP) management, improving failure prediction and operational efficiency. Ciuccoli et al. developed an early-warning system for wastewater treatment plants (WWTPs) by integrating sensor data streams with multitask learning and long short-term memory (LSTM) neural networks. Simulated and real operational datasets from WWTP sensors (e.g., DO, NH_4^+, COD, flow rate) were used to train predictive models capable of forecasting process anomalies. The LSTM-based system achieved prediction accuracies above 92%, and early-warning alerts were generated 2–6 hours before sensor failure or process disturbances. The model significantly outperformed conventional single-task neural networks and rule-based threshold methods. This work demonstrates how AI-enhanced sensor systems can improve resilience and operational stability in environmental infrastructures [26]. Distributed water-level sensors, when combined with interpretable deep-learning models, provide powerful tools for urban hydrology and infrastructure diagnostics. Zheng et al. investigated rainfall-induced inflow and infiltration (RDII) dynamics in urban sewer networks by integrating distributed water-level sensors with an interpretable deep-learning framework. The model utilized multi-node sensor measurements to identify spatial heterogeneity in RDII contributions across sewer subcatchments. The interpretable learning approach (SHAP-based) revealed critical zones contributing up to 35–50% of system-wide infiltration peaks, particularly in aging pipe segments. The system achieved over 90% accuracy in identifying RDII hotspots and reduced false alarms compared to hydrological modeling alone. The study highlighted how sensor networks combined with AI can significantly improve urban water infrastructure management and ecological risk mitigation [27]. In addition to sensing-based approaches, photocatalytic nanomaterial systems provide complementary pathways for monitoring and mitigating organic pollutants. Abbasi et al. evaluated the dependence of methyl orange degradation efficiency on the TiO_2 nanoparticle content in a MWCNTs–TiO_2 photocatalyst, demonstrating that nanoparticle loading strongly influences pollutant removal rates. Their statistical assessment, including Duncan's multiple range test, further underscores the importance of material optimization for effective treatment of dye-contaminated wastewater [28].

In wastewater treatment plants, IoT-integrated sensor networks facilitate automated process control by tracking biochemical oxygen demand (BOD), ammonia, nitrate, microbial activity, and membrane fouling indicators. These systems allow early detection of process failures, optimization of aeration, reduction of chemical consumption, and improved effluent quality. Recent

developments also include biosensors incorporating enzymes, antibodies, or whole cells for the selective detection of pathogens, endocrine-disrupting chemicals, and antibiotic-resistant genes-offering powerful tools to assess biological risks in treated wastewater. Furthermore, remote sensing platforms combined with ground-based sensors provide a multi-scale approach to monitoring harmful algal blooms, thermal pollution, and freshwater ecosystem degradation.
Despite these advancements, challenges remain related to long-term stability, biofouling, calibration drift, and the integration of high-frequency sensor data into centralized management systems. Nevertheless, ongoing innovations in nanomaterials, low-power electronics, and AI-based data processing are expected to further enhance the accuracy and durability of water-quality sensors, positioning them as essential tools for next-generation water and wastewater management systems.

Table 1: Examples of water pollutants, analytes, and their detection methods.

Type of Water Contaminant	Representative Examples	Sensor Technologies	Principle of Detection/ Explanation	References
Toxic Metals	Pb, Cd, Hg, Cr(VI), V	Electrochemical platforms	Techniques such as differential pulse voltammetry and linear sweep voltammetry monitor current changes generated during redox reactions, enabling ultra-trace metal quantification.	[29-36]
Organic Micropollutants	Pesticides, industrial chemicals	Electrochemical sensing units	Modulated voltage inputs promote electron-transfer reactions with the target molecules, and the resulting electrochemical signatures are used to determine pollutant levels.	[37]
Dissolved Ions	Nitrate, ammonium, heavy-metal ions	Ion-selective electrodes (ISEs)	Changes in membrane potential reflect the activity of specific ions; the measured potential shift is correlated with ion concentration through calibration.	[38]
Molecular Contaminants & Chromophores	Organic dyes, pharmaceuticals, natural organic matter	Optical spectroscopic sensors	Light absorption, fluorescence, or scattering patterns vary with the presence of specific compounds, enabling qualitative and quantitative assessment.	[39-41]
Biologically Active Pollutants	Pathogens, enzymes, toxins, endocrine disruptors	Biosensor technologies	A biological recognition element (e.g., enzyme, antibody, whole cell) interacts specifically with the analyte; the biochemical event is converted into an electrical or optical response via a transducer.	[42]
General Organic and Inorganic Species	Dissolved organics, nutrients	Optical detection systems	Interaction of analytes with light-responsive materials alters optical properties, which are measured using different photonic methods to determine concentration.	[43]

3.2. Air Pollution Monitoring and Management

Air pollution poses significant environmental and public-health risks, necessitating high-resolution, continuous, and spatially explicit monitoring systems. To provide a comprehensive technological foundation for the subsequent sections, the following overview summarizes the operating principles, detection mechanisms, and analytical capabilities of contemporary air-quality sensing platforms [44]. Recent developments in sensing technologies allow accurate detection of atmospheric pollutants such as particulate matter, nitrogen oxides, sulfur compounds, ozone, volatile organic compounds, and greenhouse gases. Advanced monitoring tools-including ground-based electrochemical and semiconductor sensors, satellite-borne spectroradiometers, remote-sensing platforms, and UAV-mounted multispectral units-enable precise quantification of pollutant concentrations, dispersion patterns, and temporal variability.

Semiconductor-based metal oxide (MOS) gas sensors-such as SnO_2, ZnO, and WO_3-operate through adsorption-desorption interactions occurring on the material surface, which induce measurable conductivity changes as gas molecules donate or withdraw electrons from the depletion layer. For volatile organic compounds, photoionization detectors (PID) employ high-energy ultraviolet photons to ionize molecules whose ionization potentials fall below the lamp energy, enabling rapid and selective VOC detection. Non-dispersive infrared (NDIR) sensors constitute another essential technology, particularly for greenhouse gases such as CO_2 and CH_4; these sensors measure gas-specific absorption at characteristic infrared wavelengths without requiring wavelength-dispersive optical components.

Electrochemical gas sensors commonly adopt a three-electrode configuration (working, reference, counter electrodes) in which target gases undergo redox reactions at the working electrode, with the resulting faradaic current directly proportional to gas concentration. For particulate matter ($PM_{2.5}$ and PM_{10}), optical particle counters rely on laser-light scattering principles that align with Mie scattering theory, allowing estimation of particle size and mass concentration based on scattering intensity and angle.

Despite the capabilities of modern sensor systems, low-cost devices often suffer from signal drift, environmental cross-sensitivities, and temperature–humidity dependencies. To mitigate these issues, advanced noise filtering, temperature/humidity compensation algorithms, multivariate calibration models, and periodic multi-point recalibration procedures are increasingly incorporated into air-quality networks. These data-driven systems support air-quality forecasting, early-warning networks, source-apportionment analyses, and evidence-based management strategies aimed at reducing emissions and mitigating adverse environmental and health impacts.

Fournier et al. developed a miniaturized optical sensor designed for high-sensitivity particulate matter detection. The device utilizes micro-optical components and an optimized light-scattering geometry, enabling detection down to sub-µg/m³ levels despite its compact size. Experimental findings confirmed stable long-term operation and low energy consumption, making the sensor highly suitable for portable environmental monitoring platforms essential for climate impact studies [45]. Dubey et al. evaluated the performance of the low-cost particulate matter sensors OPC-N2 and PM Nova under various aerosol conditions. Their study compared these optical sensors with reference-grade instruments for $PM_{2.5}$ and PM_{10} detection. The results indicated that although both sensors tend to deviate at higher concentrations, appropriate calibration can significantly improve accuracy. The study also demonstrated that temperature and humidity have notable influences on sensor responses, confirming their relevance for large-scale environmental and climate-impact monitoring [46]. Adotey et al. introduced an ultrasensitive fluorescent carbon dot (CD) sensor capable of detecting both soluble and insoluble Cr(VI) fractions in particulate matter. The fluorescence-quenching mechanism enabled ppt-level detection limits, outperforming many conventional analytical techniques. The method is rapid, cost-effective, and demonstrates high selectivity against interfering ions, offering a powerful tool for assessing toxic heavy metal exposure and its environmental impacts under changing atmospheric conditions [47]. Chen and colleagues fabricated a VOC sensor based on $Ti_3C_2T_x$ MXene sheets decorated with noble metal nanoparticles. The enhanced surface charge density and plasmonic interactions significantly improved VOC sensitivity, particularly for toluene and formaldehyde, reaching ppb-level detection. With rapid response and recovery at room temperature, this MXene-based architecture presents strong potential for monitoring volatile pollutants associated with air quality degradation and climate-related environmental risks. Their findings showed a 3–5-fold increase in sensitivity, lower detection limits, and enhanced selectivity compared with pristine MXene layers. The sensor exhibited minimal sensitivity to humidity fluctuations, reinforcing its suitability for deployment in real environmental monitoring networks that support climate change and impact assessments [48]. Beyond technological advancements, urban-scale air quality improvement also relies on effective governance and policy measures. In this context, Ţălu and Nazarov highlighted the importance of local political strategies for reducing urban air pollution within sustainable development frameworks, emphasizing that monitoring data must be integrated with regulatory decision-making to achieve long-term environmental outcomes [49].

Table 2: Examples of air pollutants, analytes, and their detection methods

Pollutant Category	Examples	Sensor Technologies	Detection Principle/ Explanation	References
Primary Air Pollutants	CO, NO_2, NH_3, SO_2, NO	Electrochemical sensors	Redox reactions at electrodes generate measurable current/voltage proportional to gas concentration.	[50-52]
Primary Air Pollutants	NO_2, NH_3,	Chemiresistive Semiconductor–Carbon Nanomaterial Sensors	Gas adsorption alters charge transfer on SnS_2/graphene surface → resistance change.	[53-55]
Secondary Air Pollutants	O_3, SO_3, NH_4^+	Semiconductor-based sensors	Interaction of the gaseous species with the semiconductor modifies its electronic properties-primarily resistance or capacitance-allowing sensitive detection of gas presence and levels.	[56]
Particulate Matter	$PM_{2.5}$, PM_{10}	Resistive and optical detection units	Light scattering or attenuation is quantified as airborne particles pass through the sensing region; alternatively, mass loading on resonant surfaces induces measurable frequency shifts.	[57]
Volatile Organic Compounds (VOCs)	Industrial solvents, aromatic hydrocarbons	Gas-resistive sensors & electrochemical detectors	VOC interactions modify the surface chemistry of the sensing layer, leading to changes in electrical resistance or producing identifiable electrochemical signatures.	[48,58,59]
General Gaseous Pollutants	Mixed urban/industrial emissions	Optical and resonant-mass sensor platforms	Detection is based on shifts in optical properties (e.g., absorption, fluorescence) or mass-induced variations in resonance frequency, providing selective and high-resolution monitoring.	[60]

3.3. Soil pollution Monitoring and Management

Soil pollution has emerged as a critical environmental concern due to increasing industrialization, intensive agriculture, urban expansion, and improper waste disposal practices. Contaminants such as heavy metals, pesticides, hydrocarbons, pharmaceuticals, microplastics, and persistent organic pollutants accumulate in soil matrices, threatening ecosystem stability, food safety, and human health. Recent technological advancements-including electrochemical probes, optical spectroscopy-based systems, portable X-ray fluorescence (pXRF) analyzers, biosensors, and remote-sensing platforms-enable high-resolution, rapid, and in situ assessment of soil contamination levels. These monitoring tools support the identification of pollution hotspots, quantification of contaminant mobility and bioavailability, and evaluation of remediation performance. Integrated management strategies, combining real-time sensing data with predictive modeling, promote effective regulatory planning, sustainable land-use practices, and long-term restoration of contaminated soils.
Recent advances in soil-quality sensing technologies have enabled highly sensitive, low-cost, and field-deployable detection of a wide range of pollutants. For example, hyperspectral satellite sensors have been increasingly used to assess heavy metal contamination in agricultural soils; by incorporating information on pollutant sources and migration pathways. Liwei et al. employed hyperspectral satellite sensor imagery to estimate agricultural soil heavy metal concentrations (e.g., Cr, Cd, Pb), demonstrating that integrating pollutant source pathways and migration

dynamics significantly improved prediction accuracy, achieving R^2 values exceeding 0.85 for several metals when optimized spectral indices were used. Complementing remote-sensing platforms, low-cost proximal sensors such as RGB color detectors also provide practical advantages for on-site measurements [61]. Guo et al. showed that an inexpensive RGB sensor can quantify bioavailable Cu(II) in field soils, with RGB ratio outputs exhibiting a strong linear correlation (R^2 = 0.97) to Cu(II) levels, highlighting its suitability for rapid, portable metal assessment [62]. Beyond metal pollution, emerging chemical-specific sensing approaches have improved the detection of energetic compounds; for instance, Yin et al. designed a label-free chemiluminescent aptamer sensor using Fe_3O_4@PDA–Co^{2+} magnetic nanospheres for sensitive TNT detection in soil, achieving a remarkably low limit of detection of 0.36 ng/mL and demonstrating high selectivity in complex soil matrices [63]. In nutrient monitoring, portable voltammetric sensors have provided reliable measurements of soil nitrate, as shown by Chen et al., whose differential-pulse voltammetric platform delivered LOD values below 0.05 mg/L and performance comparable to laboratory analyses [64]. Collectively, these studies demonstrate how diverse sensor modalities-from satellite-based hyperspectral imaging to optical, electrochemical, and chemiluminescent platforms-offer complementary advantages for detecting heavy metals, explosives, and nutrient pollutants in soil with increasing precision, portability, and sensitivity.

Table 3: Examples of soil pollutants, analytes, and their detection methods

Pollutant Category	Examples	Sensor Technologies	Detection Principle / Explanation	References
Heavy Metals	Pb^{2+}, Cu^{2+}, Cd^{2+}, Cr(VI), Zn^{2+}	Electrochemical sensors (nanocomposites, DNAzyme-based, ZIF-8 modified GCE), Ion-selective electrodes (ISEs), Optical/RGB sensors, Hyperspectral remote sensing	Redox reactions at modified electrodes; ion-selective membrane potential changes; RGB reflectance-intensity correlation; hyperspectral reflectance signatures linked to metal concentrations	[65,66]
Nutrients & Inorganic Ions	Nitrate (NO_3^-), Ammonium (NH_4^+-N)	ISEs; voltammetric sensors; microbial potentiometric sensor arrays	Membrane potential response to ions; electrochemical oxidation/reduction peaks for nitrates; microbial metabolic potential variations	[67,68]
Organic Pollutants	TNT, Nitrite, Energetic residues	Chemiluminescent aptasensors; portable tablet-based colorimetric sensors; electrochemical organic pollutant sensors	Aptamer–TNT binding induces chemiluminescent amplification; nitrite–reagent color change quantified optically; electrochemical recognition via specific functional layers	[69]
Plastic Pollution	Microplastics, agricultural plastic residues	NIR spectroscopy; HSI–NIR (transfer learning–supported)	NIR absorption peaks unique to plastic polymers; hyperspectral imaging enhanced through calibration transfer for high-throughput plastic identification	[70, 71]
Gas-Phase Soil Pollutants	NO_2, O_3 (near-soil gradients)	Low-cost gas sensors (electrochemical, optical)	Pollutant-induced electrical/optical signal variations calibrated to reference analyzers	[72]
Soil Properties Related to Pollution	Organic matter, minerals, elemental composition	MIR spectroscopy + pXRF; drone-assisted soil sensing	Spectral-elemental data fusion improves soil property prediction; machine-learning optimized spatial sensing	[73,74]
General Pore-Water Contaminants	Mixed ions, soil pore-water pollutants	Fiber microfluidic pore-water samplers + ISEs	Continuous extraction of soil pore water enabling real-time ion sensing	[75]

3.4. Habitat and Biodiversity Monitoring

Habitat and biodiversity monitoring has increasingly benefited from advanced sensor technologies capable of capturing ecological patterns across spatial and temporal scales. Camera traps, acoustic sensors, LiDAR platforms, GPS bio-loggers, and unmanned aerial vehicles (UAVs) now enable non-invasive, automated detection of species presence, abundance, and behavioral dynamics. Acoustic sensors are widely used to monitor birds, amphibians, and bats by identifying species-specific vocal signatures; these systems typically employ spectrogram analysis, fast Fourier transform (FFT)-based frequency decomposition, and machine-learning classifiers-including convolutional neural networks (CNNs)-to automatically distinguish species based on unique acoustic fingerprints. Camera traps rely on passive infrared (PIR) sensing mechanisms that detect heat and motion, enabling low-power, continuous field deployment and supporting night-time imaging through infrared illumination and low-light CMOS sensors.

Remote sensing tools-including multispectral and hyperspectral imaging mounted on UAVs or satellites-enable large-scale evaluations of vegetation health, land-cover changes, and ecosystem fragmentation. These platforms allow quantitative derivation of vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI), essential for assessing habitat quality and long-term ecological resilience. GPS bio-loggers, which use multi-constellation GNSS (GPS, GLONASS, Galileo) systems, provide high-accuracy animal movement data; configuration of sampling frequency and fix-interval optimization ensures extended battery life while capturing fine-scale behavioral patterns.

Emerging biological monitoring tools—such as environmental DNA (eDNA) sensors—further improve species detection by integrating microfluidic chips, isothermal amplification techniques such as loop-mediated isothermal amplification (LAMP), and microelectrode-based hybridization detection. These platforms enable rapid, field-deployable genome-level identification of species and are particularly valuable for detecting rare, cryptic, or invasive organisms.

Although environmental sensors such as air-quality monitors, soil-moisture probes, and microclimate stations do not directly measure biodiversity, they serve as critical indicators of habitat condition. Variations in temperature, humidity, particulate matter, or soil water availability strongly influence vegetation distribution, species richness, and ecological stress responses. The integration of these abiotic sensors with biological monitoring platforms has enabled the development of comprehensive ecosystem observation networks capable of linking species-level data with habitat dynamics. Such systems facilitate early detection of ecological disturbances-including drought stress, pollution-driven habitat degradation, invasive species expansion, and altered phenology-and can be coupled with automated classification frameworks such as YOLO-based species detection models and sensor-derived ecosystem health indices to support evidence-based conservation planning and adaptive ecosystem management.

Moulherat et al. introduced the OCAPI ("Observation de la biodiversité par des CAmeras Plus Intelligentes") system-a next-generation intelligent camera network designed for automated biodiversity observation. The project developed AI-enhanced camera traps capable of real-time species recognition, motion filtering, and event-triggered recording, significantly reducing manual data processing. Their findings demonstrated that intelligent image-processing pipelines can greatly improve the efficiency and accuracy of wildlife monitoring, particularly in remote or species-rich habitats [76]. Van Doren et al. demonstrated that automated acoustic monitoring can reliably quantify nocturnal bird migration. Using five acoustic sensors and detections for 14 species, the authors showed that an acoustic–meteorological model explained 75% of the variance in radar-measured migration intensity and that adding acoustic detections reduced prediction error by 33%. Acoustic data alone explained 57% of migration intensity, outperforming weather- and date-only models (48%). Species-level phenology derived from acoustic detections was strongly aligned with citizen-science observations, accounting for 71% of the variance. These findings indicate that low-cost acoustic systems can effectively monitor migration timing and intensity [77].

Tuia et al. provided one of the most comprehensive reviews and demonstrations of machine-learning applications in wildlife conservation. The study showcased how deep learning, computer vision, and pattern-recognition algorithms can process massive datasets from camera traps, drones, and acoustic sensors. They presented multiple case studies where ML models achieved near-human levels of accuracy in species identification, behavioral tracking, and population estimation. Their work emphasized how AI-driven image and sound analysis can overcome traditional ecological monitoring limitations, enabling scalable and automated biodiversity assessments [78]. Zhao et al. investigated chlorophyll estimation in cotton canopy leaves using multispectral drone sensors combined with spectral information fusion algorithms. The researchers showed that integrating multiple spectral bands (red, green, blue, near-infrared) significantly enhanced the accuracy of chlorophyll content prediction, achieving high correlation coefficients ($R^2 > 0.90$). Although the study is agriculture-focused, its methodology is highly relevant to habitat monitoring because chlorophyll estimation is a key indicator of vegetation health and ecosystem stress [79]. Brüggemann et al. developed a territorial acoustic species estimation framework using distributed acoustic sensor networks designed to monitor wildlife vocalizations in real time. By deploying synchronized sensors across defined territories, the system was able to automatically classify species based on acoustic signatures with high spatial accuracy. Their results demonstrated significant improvements in detection precision, enabling reliable species mapping even in acoustically complex environments. This study highlights the potential of acoustic IoT networks for continuous, non-invasive biodiversity monitoring [80]. In addition to sensor-based ecological observation, broader conservation initiatives also play a critical role in sustaining regional biodiversity. Ţălu et al. emphasized that safeguarding Dagestan's biodiversity depends on combining advanced monitoring tools with coordinated, policy-focused ecosystem management [81].

4. Challenges and Future Directions

Despite notable advances in sensor innovation and environmental monitoring technologies, several critical challenges continue to limit large-scale deployment, long-term reliability, and integrative decision-making. A major constraint arises from sensor drift, cross-sensitivity, and environmental interference, particularly in harsh conditions such as chemically complex wastewaters, high-humidity air, or heterogeneous soil matrices. These issues frequently lead to measurement uncertainty, requiring frequent recalibration and limiting the capacity of low-cost sensors to provide regulatory-grade data. Additionally, the lack of harmonized calibration protocols across platforms-including electrochemical, optical, microfluidic, and satellite-based sensors-reduces data comparability, thereby hindering the development of unified monitoring frameworks.

Another significant challenge lies in the integration of multimodal data streams. Water, air, soil, and biodiversity monitoring systems increasingly generate large, heterogeneous datasets from in situ sensors, remote sensing satellites, UAV-mounted instruments, and machine learning–assisted analytical tools. However, limited interoperability between these systems and the absence of robust data-fusion algorithms impede the translation of raw sensor outputs into ecological insights and predictive models. Furthermore, environmental sensors deployed in remote areas often face energy limitations, maintenance difficulties, and limited network infrastructure, especially in developing regions where monitoring needs are greatest.

Looking ahead, future directions emphasize the development of self-calibrating, self-powered, and AI-enhanced sensing platforms capable of operating autonomously for extended periods. The integration of advanced materials-including metal-organic frameworks (MOFs), nanozymes, biocomposites, and quantum-dot–based optical elements-offers promise for achieving higher selectivity, lower detection limits, and improved resilience under field conditions. Machine learning and digital twins are expected to revolutionize sensor interpretation by enabling real-time anomaly detection, pollutant source mapping, and predictive ecological risk assessments. Additionally, the transition toward networked sensor ecosystems, including IoT-enabled environmental grids and satellite–ground integrated monitoring, will support more continuous, high-resolution, and spatially explicit environmental management strategies. These developments collectively point toward a future in which environmental sensing becomes more adaptive, interconnected, and capable of informing early-warning systems and sustainable policy frameworks.

5. Conclusions

Sensor technologies have become indispensable tools for modern environmental assessment, offering fast, sensitive, and scalable capabilities that surpass the limitations of traditional

laboratory-based monitoring. Across water and wastewater analysis, air quality assessment, soil contamination detection, and habitat–biodiversity evaluation, sensor innovations enable the acquisition of high-resolution, real-time data essential for understanding dynamic ecological processes. Electrochemical sensors provide robust and selective identification of heavy metals, nutrients, and organic contaminants in aquatic and terrestrial systems, while semiconductor and gas-resistive platforms facilitate precise air pollutant quantification under variable atmospheric conditions. Optical, hyperspectral, and microfluidic approaches further extend monitoring capabilities to complex matrices such as soil pore water, vegetation surfaces, and wildlife habitats.
The ecological applications reviewed in this work demonstrate that sensor-based monitoring directly supports climate adaptation, pollution control, and sustainable resource management. The capacity of sensor networks to generate continuous, spatially distributed datasets enhances environmental modeling, informs ecological restoration, and improves public health safeguards. However, realizing the full potential of these technologies requires addressing practical obstacles such as standardization, long-term stability, and integration with advanced computational tools.
Overall, sensor-enabled environmental monitoring represents a rapidly advancing and transformative field. Continued innovation—coupled with cross-disciplinary collaboration among engineers, ecologists, data scientists, and policymakers—will be essential for developing resilient environmental systems capable of responding to accelerating global change. As next-generation sensors become more autonomous, interconnected, and intelligent, they will contribute substantially to evidence-based decision-making and the sustainable stewardship of natural ecosystems.

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