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Advances and Gaps in Real-Time Chemical Sensor Systems for Safeguarding U.S. Water Supplies from Emerging Contaminants

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ABSTRACT: Emerging contaminants including per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, microplastics, and heavy metals pose escalating threats to drinking water safety in the United States. Conventional laboratory-based monitoring methods lack the temporal resolution and rapid response capabilities needed for effective early warning and contamination prevention, creating critical vulnerabilities in water safety infrastructure. This systematic review synthesizes recent advances in real-time chemical sensor technologies for detecting emerging contaminants in drinking water systems. It involves evaluating their analytical performance, field deployment readiness, and translation potential for protecting public water supplies. Following PRISMA guidelines twenty-four (24) studies were analyzed encompassing electrochemical, optical, biosensor, microfluidic, and integrated IoT-based sensing platforms. Data extraction focused on sensor types, target analytes, analytical performance metrics, deployment contexts, and identified limitations. Electrochemical sensors demonstrated detection limits ranging from ng/L to µg/L for heavy metals and arsenic with response times under 10 minutes. Optical methods including surface-enhanced Raman spectroscopy achieved ultra-sensitive detection (pg/L to ng/L) but faced substrate reproducibility challenges. A critical gap emerged in PFAS detection, where current sensors fall 2-3 orders of magnitude short of EPA's 4 ng/L health advisory levels. Field deployment remained limited, with fewer than 30% of technologies reporting real-world testing. Biofouling, calibration drift, and matrix interference emerged as universal challenges. Real-time sensor technologies show considerable progress for heavy metal monitoring and integration with smart water systems. Critical gaps remain in ultra-trace contaminant detection, field validation, and regulatory acceptance pathways. Achieving PFAS detection at regulatory levels represents the most urgent research priority. Successful translation requires coordinated efforts in anti-fouling innovation, standardization, long-term field studies, and policy framework development.

KEYWORDS: Real-time sensors, water quality monitoring, emerging contaminants, PFAS detection, biosensors, Internet of Things.

INTRODUCTION

Access to safe drinking water remains a fundamental determinant of public health and ecosystem stability but has since faced a persistent and evolving challenge from emerging contaminants (ECs) (Roy et al., 2025). This broad category of contaminants encompasses synthetic chemicals such as per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, personal care products, cyanotoxins, and industrial compounds that are increasingly detected in U.S. water sources (Yeih and Kaiser, 2025; Asantewaa and Oduro, 2025). The threat posed by these substances is multifaceted and many are biologically active at low concentrations, environmentally persistent, and their long-term health effects are not fully understood (Yeih et al, 2025). The United States operates one of the world's most extensive drinking water infrastructure systems, serving its population through approximately 150,000 public water systems (Levin et al., 2023). Recent high-profile contamination incidents from the Flint, Michigan have resulted in PFAS contamination across military bases and industrial sites, exposing critical vulnerabilities in water safety surveillance systems and eroded public trust in water quality (Singh et al., 2025).

Traditional water quality monitoring relies predominantly on discrete grab sampling followed by laboratory analysis using techniques like liquid chromatography-mass spectrometry (LC-MS). While highly accurate, this approach is fundamentally ill-suited for managing dynamic contamination events. It is characterized by excessive costs, significant delays from sample collection to result (often days or weeks), and results availability, creating blind spots during which contamination events can go undetected while populations remain exposed and public health risks accumulate (Adebayo et al., 2025; Nofil & Periasamy, 2025). The economic burden of water contamination extends beyond immediate public health costs to encompass healthcare expenditures, lost productivity, property value depreciation, litigation, and remediation expenses which runs into billions annually (Simonetti et al., 2025).

Real-time chemical sensor systems for water represent a transformative technological class designed to provide in situ, continuous, or near-continuous quantitative or semi-quantitative data on specific water quality parameters. These systems move beyond simple physical probes (e.g., for pH, conductivity) to target complex molecular entities like ECs. The sensor landscape encompasses electrochemical sensors exploiting reactions at electrode surfaces (Rivera et al., 2025), optical or spectroscopic methods including SERS, fluorescence, and UV-visible techniques (Chen et al., 2024). The core concept involves a recognition element (e.g., a synthetic receptor, enzyme, molecularly imprinted polymer, or antibody) interfaced with a transducer (optical, electrochemical, piezoelectric) that converts a chemical binding event into a measurable electronic signal. The historical development of environmental sensors has accelerated markedly post-2020, driven by convergent advances in several fields. Innovations in materials science and nanotechnology have yielded novel sensing substrates with enhanced sensitivity and selectivity, such as graphene-based electrodes or plasmonic nanoparticles (Simonetti et al., 2025). Simultaneously, the proliferation of the Internet of Things (IoT), cloud computing and artificial intelligence, wireless communication protocols have enabled the deployment of distributed sensor networks capable of telemetric data transmission (Rubaba & Walingo, 2025; Adebayo et al., 2025). This evolution marks a shift from laboratory curiosities towards rugged, field-deployable platforms intended for autonomous operation in real-world aqueous environments, from source waters to distribution networks.

Despite substantial research activity, critical knowledge gaps constrain translation from laboratory innovation to operational deployment. This systematic review explicitly focuses on technological advancements in chemical sensor systems (as opposed to biological biosensor) designed for the detection of EC in aqueous environments relevant to U.S. drinking water supplies. This includes source waters (rivers, reservoirs, groundwater), treatment plant process streams, and finished water in distribution systems. The objective of this review is to systematically evaluate sensor technologies for emerging contaminant detection against regulatory requirements and deployment needs, examine field deployment experiences characterizing laboratory-to-field translation gaps and analyze IoT and AI integration addressing traditional limitations. By addressing these objectives, this review synthesized from recent literature (2020 - present) aims to serve as a comprehensive resource for researchers, water utility engineers, and policymakers, charting the current frontier of a technology essential for building more resilient and responsive water infrastructure.

METHODOLOGY

This systematic review followed PRISMA 2020 guidelines ensuring transparency and reproducibility.

Search Strategy and Information

A comprehensive searched was done across multiple databases including PubMed, Scopus, Web of Science, ScienceDirect and Google and ResearchGate. Search period was limited to literature from 2020 to present, capturing current capabilities while maintaining manageable scope.

Specific Boolean operators were employed to maximize search specificity and sensitivity such as; "real-time" OR "real time" OR "online" OR "continuous" OR "in-situ" OR "in situ" OR "automated" OR "autonomous" AND sensor OR biosensor OR detector OR "analytical method" OR monitoring OR "detection system" AND "water quality" OR "drinking water" OR "potable water" OR "water supply" OR "water system" OR "surface water" OR groundwater AND "emerging contaminant" OR PFAS OR "per- and polyfluoroalkyl" OR perfluoro* OR pharmaceutical OR pesticide OR microplastic OR "heavy metal" OR arsenic OR lead OR cadmium OR mercury OR chromium.

Inclusion and Exclusion Criteria

A rigorous selection process defined the scope of acceptable papers:

Inclusion Criteria

- Peer-reviewed original research, reviews, or technology assessments
- Published 2020-2025 in English
- Describes real-time or near-real-time chemical sensor development, validation, or deployment
- Targets emerging contaminants or priority pollutants in water
- Provides quantitative performance data (LOD, response time, selectivity, accuracy, precision)
- Addresses water-relevant matrices (drinking, surface, ground, wastewater, simulated)
- Discusses sensor mechanism, design, or operational considerations

Exclusion Criteria

- Conference abstracts, editorials, non-peer-reviewed reports (except documented operational deployments)
- Pre-2020 publications
- Non-English without available translations
- Exclusive focus on biological contaminants without chemical detection
- Laboratory techniques requiring extensive offline sample preparation
- Batch analysis without real-time capability
- Sensors only for conventional parameters (pH, turbidity) without emerging contaminants
- Purely computational studies without experimental validation

2.3 Screening Process

A stepwise PRISMA workflow was employed as follows:

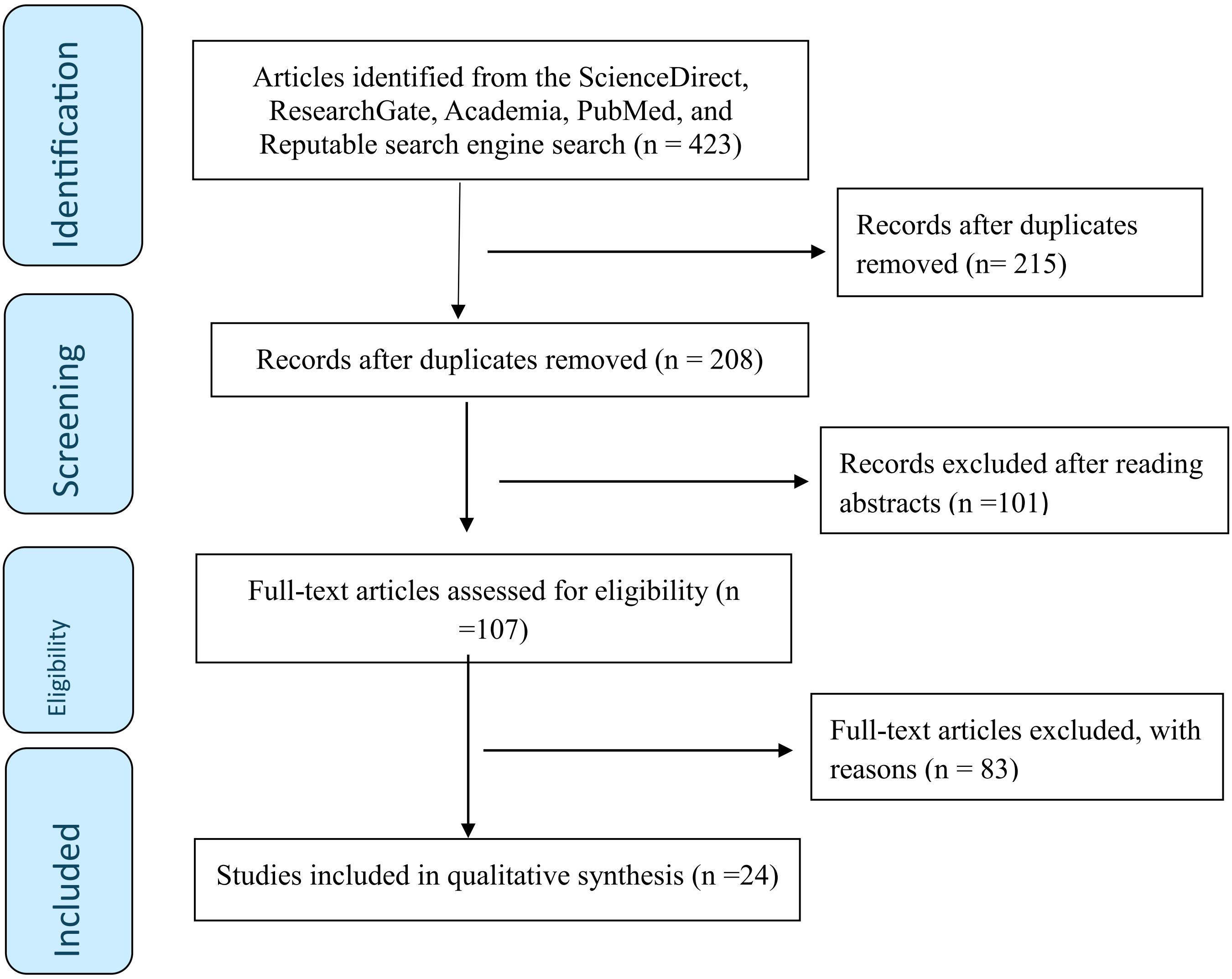

Figure 1: PRISMA Flow diagram showing the article selection process in the study.
Sources; Author's Construct 2020.

3.0 RESULTS AND DISCUSSION

The field of environmental contaminant (EC) monitoring is undergoing a transformative shift, driven by the convergence of advanced materials science, microfabrication, and data analytics. Literature work analyzed from 2020 to 2025 has been marked by significant technological demonstrations in controlled settings, yet the translation of these laboratory breakthroughs into reliable, field-deployable systems for water quality assessment remains the central, unresolved challenge. This discussion synthesizes recent findings, highlighting that while sensor modalities have achieved unprecedented theoretical sensitivity, their practical utility is often constrained by system-level integration hurdles and a profound performance gap when exposed to real-world aqueous matrices. The core controversy no longer revolves solely around detection limits, but rather the trade-offs between sensitivity, selectivity, operational robustness, and cost, which ultimately dictate a technology's viability for widespread adoption by water utilities and regulatory bodies. Below are some of the chemical sensors discussed in this review.

3.1 Electrochemical Sensor Technologies

Electrochemical sensors have since emerged as a dominant platform for addressing emerging water contaminants. This prevalence reflects electrochemical sensing's inherent advantages for water quality monitoring due to its high sensitivity, rapid response, cost-effectiveness, and compatibility with continuous monitoring configurations. Electrochemical sensors operate through electrochemical reactions at electrode-electrolyte interfaces, transducing chemical information into electrical signals (current, voltage, or impedance) quantitatively related to analyte concentrations. Major subcategories include voltametric sensors (measuring current as a function of applied potential), potentiometric sensors, and impedimetric sensors (measuring impedance changes). Each approach offers distinct advantages for specific applications and analytes.

Rivera et al. (2025) comprehensively examined challenges in achieving continuous electrochemical monitoring, emphasizing fundamental advantages while candidly addressing persistent obstacles. Their analysis highlighted that electrochemical sensors offer: (1) direct transduction of chemical information to electrical signals without complex optical components or biological reagents; (2) amenability to miniaturization through microfabrication, enabling multi-electrode arrays and lab-on-chip integration; (3) low power consumption compatible with battery or solar power

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for remote deployment; and (4) real-time or near-real-time response (seconds to minutes). These characteristics position electrochemical platforms favorably for distributed monitoring networks. **Table 1** provides a comprehensive discussion of electrochemical sensor technology and its sensitivity towards some contaminants.

Table 1: Electrochemical sensor technology and sensitivity on emerging contaminants.

Finding	Details	References
Dominant Platform	High sensitivity, rapid response, miniaturization potential, low power, cost-effectiveness, and continuous monitoring compatibility.	Rivera et al. (2025)
Heavy Metal & Arsenic Detection	Anodic stripping voltammetry enables low µg/L to sub-µg/L detection for Pb, Cd, Hg, As, and Cr. State-of-the-art sensors achieve 0.1-10 µg/L for arsenic, approaching or surpassing EPA's 10 µg/L MCL. Challenges remain in arsenic speciation (As (III) vs. As(V)).	Anchidin-Norocel et al. (2025), Bhat et al. (2025), Ferrão & Sahu (2025)
Challenges in Complex Matrices	Interference from dissolved organics, competing ions, and pH variations. Need for enhanced selectivity through molecularly imprinted polymers, specific ligands, and multi-electrode arrays. Gaps in simultaneous multi-metal detection, field robustness, and long-term stability.	Goyal & Nigam (2025), Robert & Kalpathy (2025)
MIP Enhancement	Molecularly Imprinted Polymers (MIPs) offer antibody-like selectivity without biological stability limitations, creating specific binding sites. Achieve high selectivity and sensitivity (ng/L detection limits). Advantages include chemical stability, longevity, cost-effectiveness, versatility, and regenerability. Limitations include fabrication complexity, variable imprinting efficiency, reduced effectiveness in aqueous media, and incomplete cross-reactivity elimination.	Mukendi et al. (2025)
Continuous Monitoring Challenges	**Biofouling:** Most significant obstacle, involving accumulation of microorganisms, organic matter, and inorganic precipitates. Mitigation strategies are only partially effective. **Calibration Drift:** Sensors exhibit drift from electrode material changes, reference potential shifts, and temperature variations. Fully autonomous sensors maintaining accuracy over months remain aspirational. **Matrix Effects:** Complex environmental waters contain myriad interfering species. Sensors perform well in simple matrices but show degraded selectivity and sensitivity in real waters.	Rivera et al. (2025)

3.2 Optical and Spectroscopic Sensor Platforms

Optical and spectroscopic methods offer complementary capabilities to electrochemical approaches, often achieving superior sensitivity for organic molecules while presenting different challenges for field deployment. Chen et al. (2024) provided a comprehensive review of advanced sensors for emerging contaminants, devoting substantial attention to optical methods including surface-enhanced Raman spectroscopy (SERS), fluorescence, and other light-based techniques.

3.2.1 Surface-Enhanced Raman Spectroscopy (SERS)

SERS emerged as particularly promising for emerging contaminant detection, offering molecular fingerprinting capabilities with extraordinary sensitivity. When molecules adsorb onto or near rough metal surfaces (typically gold or silver nanostructures), Raman scattering intensities can increase by factors of 10^6 to 10^{14}, enabling detection down to single-molecule levels under optimal conditions. Chen et al. (2024) highlighted SERS as especially suitable for PFAS detection, where the technique's sensitivity and ability to distinguish structurally similar compounds address key analytical challenges.

SERS advantages include ultra-high sensitivity (pg/L to ng/L detection limits achievable, rapid response (seconds to minutes), minimal sample preparation, and potential for multiplexing through spectral deconvolution. These characteristics position SERS favorably for emerging contaminants present at trace levels with complex structural diversity. However, Chen et al. (2024) also acknowledged significant SERS challenges limiting deployment. Substrate reproducibility remains problematic SERS enhancement depends critically on nanostructure geometry, and achieving consistent, reproducible substrates through scalable manufacturing proves difficult. Substrate cost can be substantial, particularly for optimized nanostructures. In complex environmental matrices, non-specific adsorption of non-target molecules can overwhelm signals or complicate spectral interpretation. Additionally, SERS requires relatively sophisticated instrumentation (lasers, spectrometers, detectors) that, while increasingly miniaturized, still exceeds cost and complexity of simple electrochemical systems.

Chen et al. (2024) noted emerging solutions such as paper-based SERS substrates for low-cost, smartphone-integrated Raman systems reducing instrumentation costs, machine learning for spectral interpretation in complex matrices and optimized nanostructure designs balancing enhancement with reproducibility. Despite challenges, they concluded SERS holds promise for applications requiring ultimate sensitivity and molecular identification capabilities, such as early-stage PFAS contamination detection or pharmaceutical screening.

3.2.3 Fluorescence-Based Methods

Fluorescence sensing, exploiting molecules' light emission following excitation, offers high sensitivity with relatively simple instrumentation. Chen et al. (2024) and Alavi-Borazjani and Shafique (2025) discussed fluorescence approaches including native fluorescence of analytes (e.g., aromatic compounds), fluorescent indicators that change emission upon analyte binding and quantum dot-based sensors where nanoscale semiconductor particles serve as fluorophores.

Fluorescence sensors achieve detection limits in the ng/L to µg/L range for fluorescent analytes, with quantum dot-based sensors sometimes reaching sub-ng/L levels. Response times are rapid (seconds to minutes) and relatively simple optical configurations (LED excitation, photodiode detection) enable miniaturization and cost reduction. Smartphone-based fluorescence detection has emerged as particularly promising for democratizing water quality testing. Limitation includes not all contaminants fluoresce, turbidity/color interference, photobleaching, background fluorescence, and selectivity depends on indicator specificity. Alavi-Borazjani and Shafique (2025) emphasized that fluorescence works best for screening and semi-quantitative analysis rather than regulatory compliance monitoring requiring high accuracy.

3.3 Biosensor Platforms

Biosensors employ biological recognition elements coupled with transducers. Fdez-Sanromán et al. (2025) talked about biosensor technologies for water quality, focusing on the detection of emerging contaminants and pathogens. Their work synthesized advances in enzymatic biosensors, immunosensors, Aptamer-Based Sensors, whole-cell biosensors, and hybrid biological-synthetic systems. **Table 2** captures the detailed review of these biosensors for biologically recognized contaminants.

Table 2: Biosensors for biologically recognized contaminants.

Biosensors	Details	References
Enzymatic Biosensors	Exploit enzyme-substrate specificity. Detection limits ng/L to low µg/L. **Advantages:** exceptional selectivity, high sensitivity, biological relevance, and various transduction methods. **Limitations:** enzyme instability, limited operational lifetime (hours to days), storage requirements, limited reusability, and narrow operating conditions.	Fdez-Sanromán et al. (2025)
Immunosensors	Employ antibodies for recognition. Detection limits pg/L to ng/L. Promising for PFAS due to extreme sensitivity requirements. **Challenge:** A vast number of PFAS compounds requires separate antibodies for each target.	Fdez-Sanromán et al. (2025)
Aptamer-Based Sensors	Alternatives to antibodies. **Advantages**: chemical synthesis, stability, re-generability, versatility, and modifiability. **Limitations:** time-intensive selection, sometimes inferior performance in complex matrices, enzymatic degradation vulnerability, and nascent libraries.	Fdez-Sanromán et al. (2025)
Whole-Cell Biosensors	Genetically engineered microorganisms produce measurable signals. Offer biological relevance, bioavailability assessment, early warning, and self-repair potential. **Limitations:** slow response (hours), lack of specificity, cell viability maintenance, complex sample preparation, and interference from sample toxicity.	Fdez-Sanromán et al. (2025)
Critical Assessment	Field deployment remains limited despite impressive laboratory performance. Biological recognition elements struggle with continuous operation in variable environmental conditions. Best for periodic monitoring, rapid screening, laboratory environments, or disposable formats.	Fdez-Sanromán et al. (2025)

Table 3: Microfluidic and Lab-on-Chip Systems

Finding	Details	References
Miniaturization and Integration	Enable miniaturization and integration of multiple analytical functions on chip-scale platforms. **Advantages:** low sample/reagent volumes, rapid analysis, integration of multiple operations, parallel processing, mass manufacturing amenability, and portability.	Zhang et al. (2024)
Applications	Heavy metals (electrochemical sensors with fluidic manipulation), organics (separation with detection), microplastics (particle counting, sizing, polymer identification). Fabrication evolved from expensive lithography to accessible methods (PDMS soft lithography, thermoplastics molding, paper-based microfluidics, 3D printing, glass etching).	Zhang et al. (2024)
Challenges	Clogging and fouling, surface interactions, fabrication-to-application gap, interface complexity, limited operational lifetime, and validation gap (poorly characterized performance in real, complex waters).	Zhang et al. (2024)
Promise	Particular promise for multiplexed analysis requiring separation, portable field systems, microplastic characterization, and research applications valuing flexibility. Conventional sensors may be more practical for simple continuous monitoring of single analytes.	Zhang et al. (2024)

Table 4: IoT Infrastructure for Sensor Networks

Finding	Details	References
Enabling Smart Water Systems	Integration with Internet of Things (IoT), artificial intelligence (AI), and automation.	Adebayo et al. (2025), Rubaba & Walingo (2025), La Cognata et al. (2025), Chen et al. (2024)
IoT Infrastructure	Distributed deployments with wireless communication, centralized aggregation, cloud storage, and remote access. **Key technologies**: communication protocols (LoRaWAN, cellular IoT, Wi-Fi, Bluetooth), edge computing, cloud platforms, and cybersecurity.	Adebayo et al. (2025)

Artificial Intelligence Applications	**Anomaly detection:** Identifies contamination, malfunctions, or unusual conditions. **Pattern recognition:** Distinguishes true contamination from benign variations. **Predictive analytics:** Forecasts future quality. **Sensor fusion:** Fuses multi-sensor data, compensates limitations, enhances accuracy, identifies faulty sensors. **Decision support:** AI-generated insights translate to actionable decisions. Requires high-quality training data, appropriate model selection/validation, integration with utility operations, and operator trust.	Rubaba & Walingo (2025), Chen et al. (2024)
Deployment Challenges	Operational deployments remain limited versus research demonstrations. Challenges: sensor reliability, communication disruptions, data management, false alarms, cost escalation, and interoperability. Success requires viewing sensors as components in sociotechnical systems.	La Cognata et al. (2025)

Table 5: Comparative Analysis of Chemical Sensor Systems

Parameter	Electrochemical Sensors	Optical & Spectroscopic Platforms	Biosensor Platforms	Microfluidic & Lab-on-Chip Systems
Primary Transduction	Electrical signal from chemical reaction	Light interaction (absorption, emission, scattering)	Biological recognition leading to measurable signal	Integration of various detection principles on microscale
Typical Sensitivity	µg/L to ng/L (MIPs)	pg/L to µg/L (SERS, Fluorescence)	pg/L to µg/L	Varies based on integrated detection
Selectivity	Good, improvable with MIPs/ligands	High (SERS), variable (Fluorescence)	Exceptional (biological specificity)	Varies based on integrated detection
Response Time	Rapid (seconds to minutes)	Rapid (seconds to minutes)	Slow (hours for whole cell), rapid for some others	Rapid
Miniaturization Potential	High	High	Moderate to High	Very High
Cost-Effectiveness	High	Moderate to High (SERS can be high)	Moderate to High (antibody production can be costly)	High (low reagent/sample use)
Continuous Monitoring Capability	Challenging (biofouling, drift, matrix effects)	Challenging (substrate stability, matrix interference)	Very Challenging (biological instability)	Challenging (clogging, fouling, interface, lifetime)
Target Contaminants	Heavy metals, some organics, pesticides	Organic molecules, PFAS, various with spectral signatures	Emerging contaminants, pathogens, pesticides, PFAS	Heavy metals, organics, microplastics, various
Field Robustness	Moderate (susceptible to environmental factors)	Moderate (instrumentation, matrix effects)	Low (due to biological component fragility)	Moderate (susceptible to clogging, interfaces)
Multi-Analyte Capability	Limited (requires arrays, chemometrics)	Good (SERS, some optical methods)	Limited (often single target)	Good (multiplexing potential)
Main Challenges	Biofouling, calibration drift, matrix effects, speciation	Substrate reproducibility, cost, matrix interference, instrumentation complexity	Biological instability, limited lifetime, storage, specificity, field deployment	Clogging, surface interactions, fabrication gap, interface complexity, validation
References	Rivera et al. (2025), Mukendi et al. (2025)	Chen et al. (2024), Alavi-Borazjani & Shafique (2025)	Fdez-Sanromán et al. (2025)	Zhang et al. (2024)

3.5 Critical Contaminant Focus: PFAS Detection Challenges and Progress

PFAS detection represents the most formidable sensor development challenge due to several factors.

3.5.1 The PFAS Detection Challenge

Ultra-low Regulatory Limits: EPA's proposed MCLs of 4 ng/L (ppt) for PFOA and PFOS are near or below conventional analytical limits and well below most real-time sensors. Achieving this sensitivity in complex environmental matrices with portable, low-cost sensors is an enormous challenge.

Chemical Diversity: Over 12,000 PFAS structures exist, with manufacturers continuously developing new compounds, making total PFAS detection difficult or requiring multiple sensor elements for specific priority PFAS (Simonetti et al.; 2025).

Chemical Stability: The strong C-F bonds make PFAS environmentally persistent but also complicate detection, as many principles rely on chemical reactivity. This stability eliminates entire categories of sensor approaches.

Matrix Complexity: PFAS co-occur with dissolved organic matter, minerals, and other contaminants at much higher concentrations, posing a daunting analytical challenge for sensor selectivity.

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3.5.2 Current Sensor Approaches and Limitations for PFAS

Simonetti et al.; 2025 have highlighted some of the current challenges for PFAS detection using real-time chemical sensors.

Immunosensors: Antibodies specific for PFOA, PFOS, and some other PFAS enable detection at 1-100 ng/L, approaching but not fully meeting the 4 ng/L requirement. Limitations include antibody cost, stability, and the need for separate antibodies for different PFAS.

SERS: Ultra-high sensitivity and molecular specificity make it attractive for PFAS, with reported detection limits in the ng/L range, occasionally sub-ng/L under optimal conditions. However, consistent performance in real waters is challenging due to substrate variability and matrix interference.

Electrochemical Approaches: Direct detection of PFAS is extremely difficult due to their electrochemical inertness. Indirect approaches generally achieve µg/L to ng/L, which is inadequate for current regulatory requirements.

Fluorescence Quenching: Quantum dot-based sensors achieve ng/L detection limits, but selectivity is limited, and environmental fluorophores create interference.

Miniaturized Mass Spectrometry: Portable systems can achieve ppt-level detection with high specificity but remain expensive, complex, and require skilled operation, functioning more as field-portable laboratories than autonomous sensors.

3.5.3 The Critical Gap

No currently available or near-commercial real-time sensor achieves 4 ng/L detection for PFAS in complex drinking water matrices with the required reliability, robustness, and cost-effectiveness for routine monitoring. Research sensors approach these requirements under laboratory conditions, but field validation demonstrating sustained ppt-level performance in real waters is lacking (Simonetti et al., 2025; Singh et al., 2025). PFAS sensor development is identified as an urgent research priority, requiring intensified investment, public-private partnerships, and potentially regulatory flexibility for multi-tiered monitoring strategies.

3.6 Cross-Cutting Challenges and Barriers to Deployment

3.6.1 Standardization Deficit

Absence of standardized validation protocols, performance metrics reporting, and quality assurance procedures creates multiple problems. Cross-study comparison proves difficult when detection limits are calculated differently, interference testing varies, and water matrices differ. Regulatory acceptance requires standardized validation following established protocols, yet no consensus protocols exist for emerging contaminant sensors. Interoperability, integrating sensors from different manufacturers into unified networks, suffers from lack of common communication protocols and data formats.

Nofil and Periasamy (2025) advocated for professional societies (AWWA, APHA, ISO) and regulatory agencies (EPA) to lead standards development. Initiatives like EPA's Environmental Technology Verification (ETV) Program provide frameworks but have limited resources and slow processes. International harmonization would benefit global sensor development but faces challenges from differing regulatory philosophies and priorities.

3.6.2 Regulatory Acceptance Pathways

Even well-validated sensors face unclear pathways to regulatory acceptance for compliance monitoring. EPA and state regulations specify approved methods typically laboratory-based techniques with long validation histories. New technologies must demonstrate equivalency, a lengthy and expensive process. For routine monitoring (as opposed to compliance), regulations are more flexible, but utilities remain cautious given liability concerns.

Diab et al. (2025), in their review of chlorine species sensing, noted that even for well-established parameters like free chlorine (continuously monitored for decades), sensor accuracy and precision requirements are stringent, requiring regular calibration against reference methods. For emerging contaminants with no established regulatory methods, defining equivalency criteria becomes challenging.

Several studies (Adebayo et al., 2025; La Cognata et al., 2025; Rubaba & Walingo, 2025) recommended tiered monitoring strategies: (1) real-time sensors for continuous screening and early warning; (2) confirmatory laboratory analysis when sensors indicate potential contamination; and (3) periodic validation of sensor performance against reference methods. This approach leverages sensors' temporal resolution while maintaining analytical rigor through laboratory confirmation.

3.6.3 Multi-Contaminant Detection Limitations

Most sensors target single contaminants or narrow contaminant classes, yet water quality threats involve diverse chemicals with unknown compositions. Comprehensive monitoring requires either: (1) deploying multiple single-analyte sensors; or (2) developing true multi-analyte sensors.

Option 1 (multiple sensors) is costly and logistically complex, deploying tens of sensors per location to cover priority contaminants, multiplying hardware, maintenance, and data management requirements substantially. Option 2 (multi-analyte sensors) involves technical trade-offs. Approaches include:

- Sensor arrays: Multiple sensors with different selectivity are analyzed collectively using chemometrics or pattern recognition. Cross-reactivity becomes a feature rather than a bug. Requires sophisticated data analysis and training datasets.
- Separation-coupled detection: Chromatographic or electrophoretic separation followed by detection (e.g., microfluidic LC-electrochemical detection). Enables multi-analyte capability but adds complexity and operational requirements (mobile phases, columns).
- Spectroscopic methods: Techniques like SERS or IR provide molecular fingerprints potentially identifying multiple compounds. Spectral deconvolution and databases are required. Sensitivity may be lower than that of single-analyte sensors.

Zhang et al. (2024) concluded that multi-analyte capability remains a frontier challenge, with no single approach providing comprehensive coverage, ultra-low detection limits, high selectivity, and field robustness simultaneously. Trade-offs are inevitable, and optimal approaches depend on specific monitoring objectives and acceptable compromises.

3.5.4 Data Management and Cybersecurity

High-frequency sensor networks generate massive data streams. Adebayo et al. (2025) noted that a single sensor recording every 15 minutes generates 96 data points daily, 35,000 annually. A network of 100 sensors produces 3.5 million data points yearly. Managing, storing, processing, analyzing, and archiving such data requires substantial IT infrastructure, database systems, cloud storage, analysis software, visualization tools, and backup systems.

Beyond volume, data quality assurance becomes paramount. Sensor malfunctions, communication errors, calibration drift, and fouling all create data quality issues requiring detection and correction. Automated QA/QC algorithms identifying anomalous data, sensor failures, and drift are essential but imperfect, requiring human oversight.

Cybersecurity represents an emerging concern. Sensor networks connected to the internet create attack vectors. Compromised sensors could provide false data, triggering unnecessary alarms, mask actual contamination, or map water system vulnerabilities. Denial-of-service attacks could disable monitoring. Protection requires encryption, authentication, intrusion detection, secure firmware updates, and network segmentation, all adding complexity and cost.

La Cognata et al. (2025) emphasized that cybersecurity cannot be an afterthought but must be integrated from system design inception, following frameworks like NIST Cybersecurity Framework adapted for water systems.

4. FUTURE DIRECTIONS AND RESEARCH GAPS

Evidence synthesized reveals substantial progress alongside persistent gaps limiting operational deployment. This section identifies critical gaps requiring research attention and proposes priority directions.

4.1 Critical Technical Research Needs

4.1.1 Ultra-Sensitive PFAS Detection

The most urgent technical need involves developing sensors achieving ppt-level (ng/L) PFAS detection in complex drinking water. Current EPA health advisories of 4 ng/L for PFOA/PFOS create requirements that most sensors fall 2-3 orders of magnitude short of meeting (Simonetti et al., 2025). Closing this gap requires:

Novel recognition strategies: Given PFAS chemical inertness, conventional approaches prove inadequate. Promising directions include molecularly imprinted polymers specifically designed for fluorinated compounds, engineered antibodies/aptamers with ultra-high affinity, fluorine-specific detection exploiting C-F bond properties, and pre-concentration integration. Research must move beyond proof-of-concept to validated performance in real drinking water.

Total PFAS approaches: Given thousands of PFAS structures and continuous emergence of novel compounds, approaches detecting total organofluorine or PFAS classes warrant investigation. While less specific, total PFAS measurements provide screening and early warning.

Field-deployable systems: Laboratory demonstrations achieving ppt-level detection exist but require complex preparation, sophisticated instrumentation, or conditions incompatible with autonomous deployment. Research must prioritize translating sensitive detection to continuous monitoring formats, simplified operation, automated calibration, anti-fouling resistance, and environmental robustness.

4.1.2 Anti-Fouling Innovation

Biofouling universally emerged as the primary barrier to long-term autonomous operation. Rivera et al. (2025) documented that current mitigation strategies prove only partially effective. Breakthrough solutions require:

Advanced anti-fouling materials: Biomimetic surfaces, stimuli-responsive polymers, ultra-low-adhesion materials, and nanoscale surface texturing, creating unfavorable attachment environments. Materials must be compatible with the sensor function.

Fouling detection and compensation: Rather than preventing fouling entirely (perhaps impossible), detecting onset and compensating through recalibration or signal correction could maintain accuracy despite fouling. Machine learning models learning fouling patterns and adjusting responses automatically could enable "fouling-tolerant" sensors.

4.1.3 Multi-Analyte Platforms

Practical surveillance requires monitoring multiple contaminants simultaneously. Research directions include:

Intelligent sensor arrays: Deploying partially selective sensors with chemometric analysis or machine learning for deconvolution. This "electronic nose/tongue" approach trades individual element specificity for comprehensive coverage through pattern recognition.

Microfluidic integration: As Zhang et al. (2024) discussed, chips integrating chromatographic separation with multi-point detection enable miniaturized multi-analyte analysis. Challenges include maintaining separation efficiency, reproducible retention, and handling complex matrices.

Multiplexed biosensors: Arrays with different recognition elements enable simultaneous detection with high selectivity. Challenges include biological stability, reproducibility, and minimizing crosstalk.

Spectroscopic multi-analyte sensing: Techniques providing molecular fingerprints inherently offer multi-analyte potential. Research improving deconvolution algorithms, building spectral libraries, and developing chemometrics for complex mixtures could realize this potential.

4.1.4 Calibration Stability and Speciation

Maintaining calibration over extended periods without manual intervention is essential yet rarely achieved. Research needs include self-referencing sensors with internal standards enabling automated recalibration, machine learning-based drift correction trained on sensor behavior over time, and fundamentally rethinking design to eliminate or minimize calibration requirements.

Many contaminants exist in multiple chemical forms with different toxicities. Speciation-capable sensors would substantially enhance water management: As (III) vs. As(V) for arsenic (Bhat et al., 2025), Cr (VI) vs. Cr (III) for chromium, different nitrogen species, and free vs. combined chlorine (Diab et al., 2025). Research developing sensors distinguishing species through selective recognition, sequential reactions, or selective membranes would enable more informed management.

4.2 Field Validation and Comparative Studies

4.2.1 Systematic Field Testing

The laboratory-to-field translation gap reflects lack of systematic field validation. Research establishing standard protocols would accelerate maturation.

Multi-site validation: Sensors should be tested across multiple systems with different water qualities, seasonal variations, and operational conditions. Single-site validation provides limited generalizability.

Extended deployment: Long-term deployments (>6 months, ideally >1 year) encompassing full seasonal cycles are essential for assessing viability. Short-term tests don't capture seasonal effects, long-term fouling, or cumulative degradation.

Comprehensive characterization: Field studies should thoroughly characterize deployment environments water chemistry, biological activity, temperature, flow, contamination events. This enables understanding context-performance relationships and predicting which sensors suit specific environments.

Failure analysis: Systematic investigation of failure mechanisms (fouling, drift, hardware failure) informs design improvements. Post-deployment examination provides valuable insights rarely reported.

4.2.2 Comparative and Hybrid Strategies

Head-to-head comparisons of different technologies under identical field conditions would guide selection and identify comparative advantages. Research evaluating combinations of real-time sensors with periodic conventional monitoring could optimize resource allocation. Questions include: What coverage density provides adequate warning? What confirmatory analysis frequency maintains confidence? How should alerts trigger sampling? Can machine learning optimize hybrid strategies?

4.3 Integration and System-Level Research

4.3.1 Advanced AI Applications

While AI integration is accelerating, opportunities remain:

Transfer learning: Models trained on one sensor/system rarely transfer directly due to site-specific conditions. Transfer learning adapting models to new contexts with minimal retraining could enable rapid expansion.

Explainable AI: Operators must understand and trust AI. Research developing interpretable models that explain reasoning would facilitate adoption through attention mechanisms, feature importance analysis, and counterfactual reasoning.

Multivariate time series: Methods specifically designed for interdependent parameters changing over time (recurrent networks, temporal convolutions, transformers) could capture complex relationships improving anomaly detection and source identification.

Predictive maintenance: Machine learning predicting maintenance needs based on history, conditions, and performance trends could optimize scheduling, reducing unnecessary visits while preventing failures.

4.3.2 Communication Optimization

Balancing communication frequency, data resolution, bandwidth, power, and latency involves complex trade-offs. Research optimizing through adaptive sampling (increasing frequency when anomalies are detected), edge computing (processing locally before transmission), and intelligent compression would improve network efficiency and reliability.

4.4 Standardization, Validation, and Economic Research

4.4.1 Performance Standards

Professional societies (AWWA, APHA, WEF) and standards organizations (ASTM, ISO) should lead sensor performance standards development. Research informing standards includes defining minimum performance requirements fit-for-purpose, consensus test methods for determining LODs, and characterizing performance, and practical QA protocols for utilities.

4.4.2 Regulatory Pathways

Research clarifying regulatory pathways for acceptance in compliance monitoring, identifying necessary evidence, and proposing streamlined processes would accelerate adoption. Case studies of successfully accepted technologies could identify best practices. Regulatory research should address liability and legal questions: Who is responsible if sensors fail to detect? What data quality/documentation requirements exist? How is sensor data admissible in enforcement?

4.4.3 Economic Frameworks

Rigorous cost-benefit analyses remain scarce (La Cognata et al., 2025; Adebayo et al., 2025). Research developing standardized economic evaluation frameworks would support informed decision-making. Frameworks should account for direct costs (capital, operation, maintenance, data management), opportunity costs (laboratory capacity freed), risk reduction benefits (events prevented, exposure reduced), operational benefits (enhanced control, reduced chemicals, energy optimization), and intangible benefits (public confidence, compliance, liability reduction). Probabilistic models accounting for uncertainty and scenarios would provide realistic expectations.

4.5 Emerging Technologies

4.5.1 Quantum Sensing, CRISPR, and Metamaterials

Quantum sensors exploiting quantum mechanical phenomena promise revolutionary sensitivity, though typically requiring cryogenic/vacuum conditions, creating deployment challenges. Research adapting quantum sensing for ambient aqueous environments could open frontiers.

CRISPR technology is being adapted for molecular detection. CRISPR systems' programmable specificity could be redirected toward small molecules through competitive binding, allosteric control, or aptamer integration. Fdez-Sanromán et al. (2025) mentioned CRISPR as an emerging frontier, though extensive development is needed.

Engineered metamaterials manipulating light at nanoscale could amplify spectroscopic signals beyond conventional materials. While mostly speculative for water sensors, metamaterial advances in other fields could translate.

4.5.2 Autonomous Robotic Monitoring

Integration with autonomous vehicles (surface vessels, underwater vehicles, crawling pipe robots) could revolutionize monitoring. Robots equipped with sensors could autonomously patrol water bodies, navigate distribution systems, or inspect facilities, conducting mobile surveys far more comprehensive than fixed sensors. Adebayo et al. (2025) discussed drones; extending to aquatic robots warrants investigation. Challenges include navigation, collision avoidance, power, communication, and handling complex environments.

4.6 Implementation Science and Policy Research

4.6.1 Sociotechnical Systems

Successful deployment requires understanding organizational, institutional, and human factors beyond technical performance. La Cognata et al. (2025) emphasized that sensors exist within sociotechnical systems. Implementation science research should address organizational readiness characteristics predicting adoption, workforce capacity and training requirements, change management addressing resistance, and technology-organization fit, ensuring technologies match capabilities.

4.6.2 Water Utility Co-Design

Engaging utilities as co-designers ensures technologies meet operational needs. Participatory design involving operators, managers, and engineers throughout development would identify constraints, prioritize features, and uncover unanticipated challenges. Research documenting co-design processes and outcomes would guide futures.

4.6.3 Policy Research

Research informing policy includes incentive structures (financial incentives, regulatory credits, rate structures encouraging investment); equity considerations (how sensors benefit disadvantaged communities and small systems through affordability, technical support, capacity building); and public engagement (how real-time data should be communicated, balancing transparency with avoiding alarm from transient anomalies).

CONCLUSION

The advancement in real-time chemical sensor systems for safeguarding U.S. water supplies reveals a transformative change yet grappling with fundamental challenges. While diverse sensor technologies such as electrochemical, optical, biosensor, and microfluidic platforms have demonstrated remarkable laboratory-scale sensitivity and rapid response for various emerging contaminants, their translation to robust, autonomous field deployment remains a critical hurdle. The pervasive issues of biofouling, calibration drift, and matrix interference consistently degrade performance in real-world aquatic environments, often by orders of magnitude, highlighting a significant gap between theoretical potential and practical utility.

A particularly urgent research priority lies in achieving ultra-sensitive detection of per- and polyfluoroalkyl substances (PFAS). Current sensor capabilities fall significantly short of stringent regulatory limits, underscoring the need for novel recognition strategies and field-deployable systems capable of ppt-level detection in complex matrices. Beyond individual sensor performance, the integration of these technologies into smart water systems, leveraging IoT and AI offers unparalleled opportunities for dynamic insights and proactive management. However, this necessitates addressing challenges in data management, cybersecurity, and ensuring operator trust through transparent AI. Ultimately, the successful deployment of these advanced sensor systems hinges not solely on technical innovation, but on a holistic approach that includes rigorous long-term field validation, the development of standardized protocols, clear regulatory acceptance pathways, and a deep understanding of the sociotechnical systems within which these technologies must operate. Bridging these gaps will be paramount to building resilient and responsive water infrastructure for the future.

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