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Perspective

Sensors for Emerging Water Contaminants: Overcoming Roadblocks to Innovation

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ABSTRACT: Ensuring water quality and safety requires the effective detection of emerging contaminants, which present significant risks to both human health and the environment. Field deployable low-cost sensors provide solutions to detect contaminants at their source and enable large-scale water quality monitoring and management. Unfortunately, the availability and utilization of such sensors remain limited. This Perspective examines current sensing technologies for detecting emerging contaminants and analyzes critical barriers, such as high costs, lack of reliability, difficulties in implementation in real-world settings, and lack of stakeholder involvement in sensor design. These technical and nontechnical barriers severely hinder progression from proof-of-concepts and negatively impact user experience factors such as ease-of-use and actionability using sensing data, ultimately affecting successful translation and widespread adoption of these technologies. We provide examples of specific sensing systems and explore key strategies to address the remaining scientific challenges that must be overcome to translate these technologies into the field such as improving sensitivity, selectivity, robustness, and performance in real-world water environments. Other critical aspects such as tailoring research to meet end-users' requirements, integrating cost considerations and consumer needs into the early prototype design, establishing standardized evaluation and validation protocols, fostering academia-industry collaborations, maximizing data value by establishing data sharing initiatives, and promoting workforce development are also discussed. The Perspective describes a set of guidelines for the development, translation, and implementation of water quality sensors to swiftly and accurately detect, analyze, track, and manage contamination.

KEYWORDS: *sensors, water monitoring, emerging contaminants, technology translation*

1. INTRODUCTION: INNOVATIONS IN SENSING TECHNOLOGIES TO IMPROVE WATER MONITORING

Water pollution by emerging contaminants poses a significant threat to human health and the environment.[1] These contaminants, spanning inorganic, organic, and biological substances, are characterized by highly dynamic concentrations depending on factors such as geographic locations, sources of contamination, environmental conditions, and treatment methods. For example, endocrine disrupting chemicals (EDCs), flame retardants, pharmaceuticals, and personal care products (PPCPs) are often found in urban areas and downstream of water treatment plants at concentrations ranging from ng/L to μg/L levels.[2] Similarly, microplastics and engineered nanomaterials are increasingly being identified as emerging contaminants with potentially harmful effects on ecosystems and public health.[3] Median concentrations of some of the most frequently detected compounds (atenolol, carbamazepine, estrone, sulfamethoxazole) in U.S. drinking water were typically less than 10 ng/L with some exceptions for tris(2-chloroethyl) phosphate (TCEP) at 120 ng/L in source water and atrazine concentrations in the range of 30−50 ng/L in source, finished, and distributed water.[4,5] Effective monitoring of water quality requires rapid and efficient testing in potentially contaminated environments.[6] However, the need to test a large number of samples across various times and widespread locations puts a considerable burden on specialized laboratories, which rely primarily on traditional centralized instrumentation. This lack of effective detection methods hinders swift intervention and management of water resources.[7]

Traditional analytical methods for water quality monitoring, such as solid-phase extraction coupled with liquid chromatography-tandem mass spectrometry, have been proven effective in

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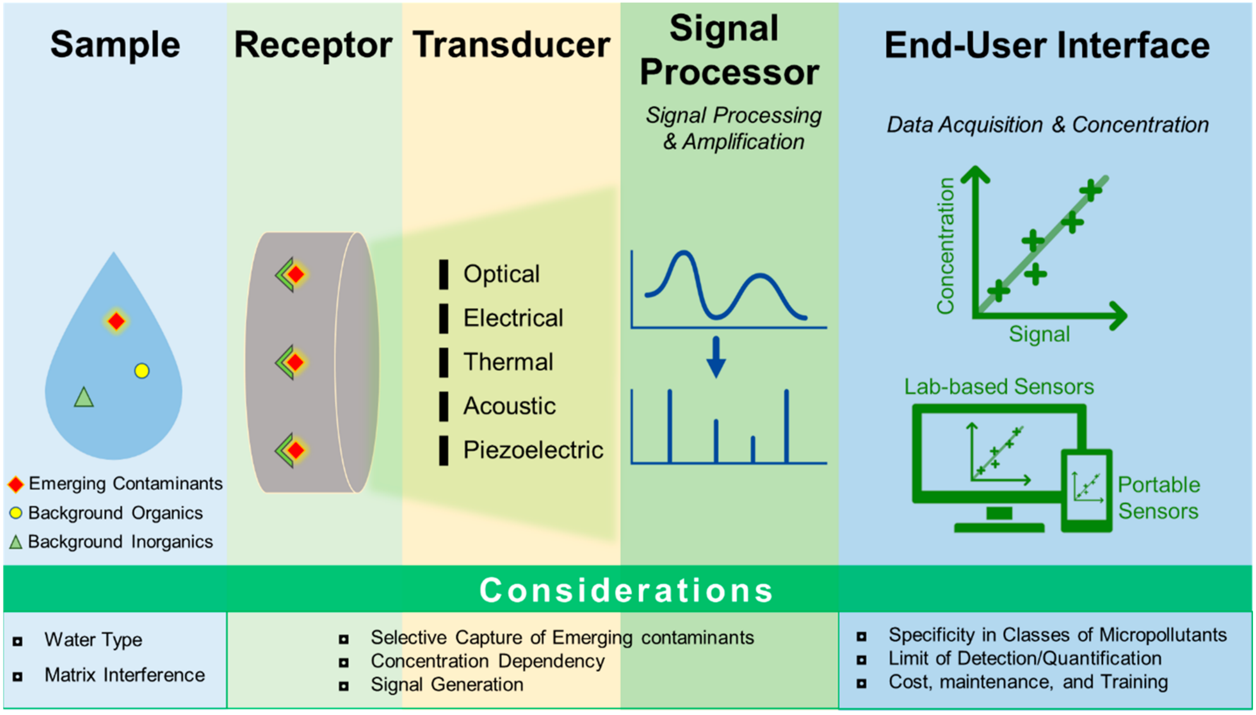

Figure 1. Conceptual design and principal components of an integrated sensor device, incorporating a molecular receptor, transducer, signal processor, and end-user interface, for emerging contaminant detection in water.

targeted analysis of known emerging contaminants.[8] These traditional methods typically feature a low limit of quantification (LOQ), high precision and accuracy, and established operational and quality assurance and quality control (QA/QC) protocols. However, these methods can be expensive and time-consuming and require specialized equipment with highly trained personnel, making them unsuitable for field monitoring purposes. Current methods require grab sampling and the shipment of samples to centralized laboratories for analysis, which are both labor-intensive and cumbersome. Additionally, most samples involve laborious pretreatment with toxic solvents that by themselves can contaminate the environment.[9] For many contaminants, there is a lack of environmental survey data and methods that can rapidly monitor their presence in the field.[9,10]

Sensor technology is a promising area of technological development that can revolutionize water quality monitoring by offering affordable, rapid solutions with unprecedented spatiotemporal resolution.[11,12] Sensors utilize chemical or biological molecular receptors that are designed to selectively respond to specific targets. A typical sensor integrates these molecular receptors with transducers (e.g., optical or electrochemical devices), signal processors, and end-user interfaces customized for a wide range of applications (Figure 1). They hold the potential to measure various contaminants relevant to water quality, such as heavy metals, pesticides, pharmaceuticals, EDCs, as well as biological substances (e.g., bacteria or viruses).[13−15] Despite progress in academic research on sensing technologies for water quality monitoring, their practical implementation in the market, households, the public domain, or regulatory frameworks remains limited.

There are many technical articles and reviews on sensors for water monitoring.[16−23] For the purpose of this Perspective, we focus primarily on the translational aspects of sensors for emerging contaminants that can be deployed and used in field settings, households, and treatment facilities. We discuss the status of these technologies in the context of technology innovation for water quality testing, focusing on devices that facilitate high-throughput analysis and have the potential to bring them from the laboratory to the field for rapid intervention. Although sensors for emerging water contaminants have been extensively reported, their implementation for routine monitoring has been limited. Most studies do not progress beyond the proof-of-concept or laboratory validation stages, with only a handful receiving validation in real-world settings and even fewer advancing to commercialization and broad adoption.[24−26] This landscape contrasts sharply with the maturely commercialized water sensors that measure basic physicochemical parameters, such as pH, temperature, dissolved oxygen, and turbidity.[27] Despite significant progress in academic research and a deeper understanding of fundamental principles, there has been no systematic discussion regarding why emerging contaminant sensors have not achieved successful market translation or widespread adoption in the industry, public, and regulatory domains.

This Perspective identifies key scientific, technical, regulatory, and economic challenges to transitioning research-driven sensor advancements into validated field-ready devices.[18,28] Specifically, we focus on the translational aspects of these technologies, investigate advantages and limitations, identify roadblocks, and provide solutions to realizing their potential for real-world applications. In addition to technical challenges, we discuss some of the strategies to advance implementation such as fostering academia-industry partnerships, considering stakeholder engagement and affordability alongside other design criteria, as well as addressing regulatory requirements.[29] We also propose strategies to overcome these challenges by leveraging collaborative efforts among academia, industry partners, policymakers, and other important stakeholders (e.g., impacted communities and public institutions). Through these endeavors, we aim to demonstrate the potential impact of emerging

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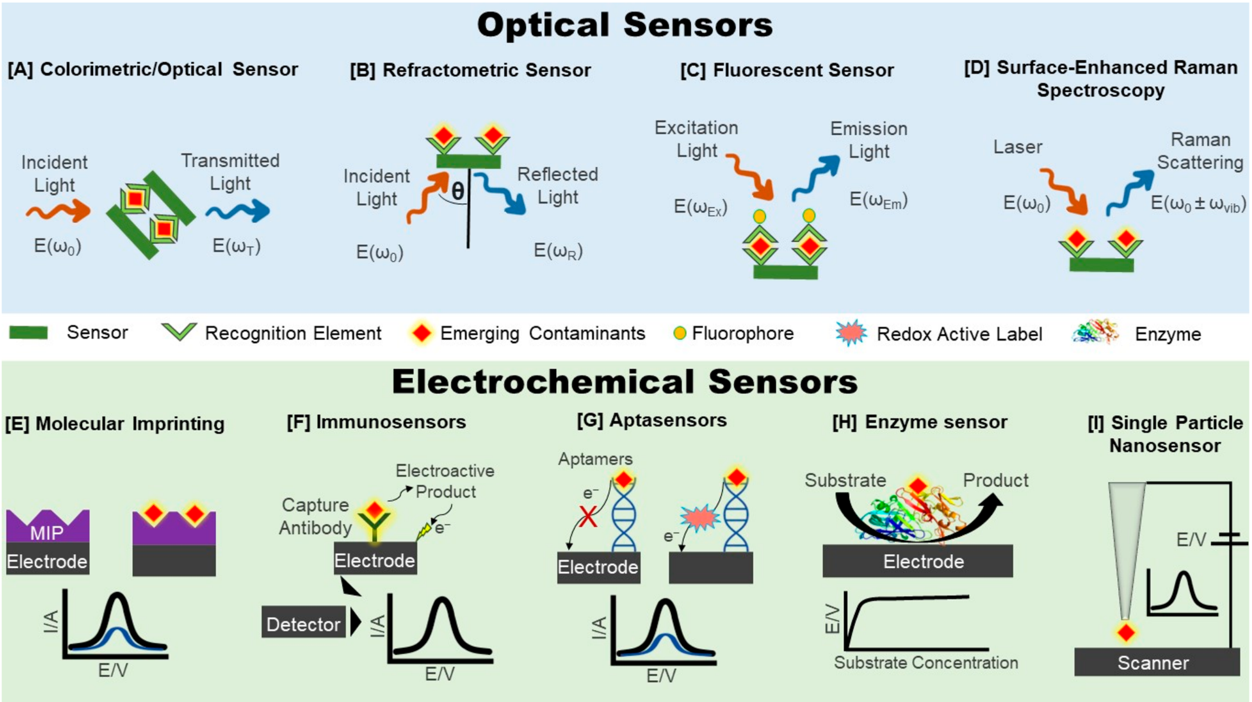

Figure 2. Working principles of typical optical and electrochemical sensors for emerging contaminant detection, showing spectroscopic sensors based on colorimetric (A), refractometric (B), fluorescent (C) and surface-enhanced Raman spectroscopic (D) transduction methods; and electrochemical sensors based on molecular imprinting (E), immunosensors (F), aptasensors (G), enzyme sensors (H) and single particle collisions (I).

contaminant sensors in revolutionizing water quality monitoring and ultimately safeguarding our invaluable water resources.

2. MECHANISMS OF ENVIRONMENTAL WATER SENSORS

Emerging contaminant sensors, despite their promising advantages, face several impediments in practical deployment. One key limitation involves the necessity for sample pretreatment, introducing time and resource-intensive processes. The associated costs and lengthy fabrication protocols further impede efficiency and scalability, challenging widespread adoption. Automation and remote-control capabilities, critical for real-time monitoring, are often absent, limiting adaptability. Financial constraints arise as these sensors tend to be expensive, raising concerns about their affordability, particularly in low resource setting and large-scale applications over extensive geographical areas.[22] Additionally, their performance in real environmental matrices encounters obstacles such as interference from other substances and the need for frequent calibration, compromising accuracy and reliability. Addressing these multifaceted challenges is paramount for unlocking the full potential of environmental sensors, ensuring their seamless integration into diverse monitoring scenarios and advancing their effectiveness in detecting and managing emerging environmental contaminants.

A diverse range of sensors is currently under active development for detecting emerging water contaminants, encompassing an array of mechanisms and methodologies, among which optical and electrochemical sensors are the most prevalent (Figure 2).[18,28,30] To enable selective binding, recognition elements such as antibodies, aptamers, molecularly imprinted polymers (MIPs), or alternative natural and synthetic receptors are utilized.[31,32] Among these, biosensors exhibit the highest selectivity by relying on biomolecular recognition through affinity (e.g., immunosensors, aptasensors) or catalytic (enzyme-based) binding mechanisms. Nevertheless, maintaining the stability and functionality of immobilized bioreceptors for long-term use in operational environments remains a challenge. By translating binding events into electrical or optical signals, these sensors can effectively detect the presence of contaminants. Optical sensors utilize light to probe and collect information, eliminating the need for direct contact between water samples and costly sensing elements. This advantage reduces the maintenance requirements and makes optical sensors an ideal modality for online, nondestructive, and real time sensing. Electrochemical sensors, which monitor redox reactions at electrode surfaces via voltammetry, amperometry, or impedance, often demonstrate sensitivity greater than that of their optical counterparts. Additionally, electrochemical sensors can be miniaturized for *in situ* use and are insensitive to interference from light-absorbing molecules and turbidity. Both electrochemical and optical modalities can be integrated into portable platforms such as lateral flow devices, miniaturized and multiplexed probes, microfluidic systems (i.e., "lab on a chip" devices), and can even be connected to digital platforms or satellite imagery for remote assessment of expansive bodies of water.[33] An overview of these diverse detection mechanisms and sensor types is provided below.

Optical sensors utilize the interaction between light and the target analyte to generate a measurable light signal. Specifically, these sensors provide the electronic or vibrational structures of emerging contaminants as well as variations in light extinction or refractive index induced upon binding with the target analytes. Figure 2A demonstrates the operation of colorimetric sensors that detect changes in a broadband spectrum of light transmitted through a sensing medium when a target analyte is present. Low cost colorimetric sensors have been demonstrated for the detection of a variety of contaminants, such as of bisphenol A,[34] heavy metals,[35,36] pesticides, and other toxicants,[37] but such sensors typically cannot meet the regulatory requirements due to their low sensitivity and limited quantitative performance. Refractometric sensors, illustrated in Figure 2B, measure variations in the incident light angle that results in minimal reflected light intensity, known as a "surface plasmon resonance (SPR) dip", upon binding between the target analyte and the sensor surface.[38,39] Although refractometric sensors demonstrated high sensitivity and quantitative performance for various water pollutant analysis,[38,40,41] they need sophisticated optical setup and are prone to interferences from complex water matrices. Fluorescent sensors measure changes in fluorescence intensity or lifetime of a fluorophore in the presence of the target analyte (Figure 2C).[42] Despite having high sensitivity for detecting water pollutants, fluorescent sensors are subject to photobleaching and lack multiplexing capabilities.[43,44] Surface-enhanced Raman spectroscopy (SERS)-based sensors detect Raman scattering from the target analytes or probe molecules that indicate the presence of the target (Figure 2D).[45] SERS-based sensors exhibits single-molecular/cellular sensitivity and fingerprinting selectivity for water pollutant/pathogen analysis,[46−49] but they require costly Raman spectrometer and plasmonic substrates.

Electrochemical sensors monitor the electrical properties (e.g., current and voltage) generated by redox reactions involving the target analyte. There are several types of electrochemical sensors, including amperometric (current measurement), potentiometric (voltage measurement), conductometric (conductance measurement) devices, and more recently developed single particle nanosensors (Figure 2E−I).[18,50] Different types of recognition elements, such as molecular imprinted polymers, antibodies, aptamers, and enzymes, can be functionalized onto electrode surfaces to improve selectivity for target analytes (Figure 2E−H). A wide variety of electrochemical sensors have been reported for the detection of pharmaceuticals,[51] phenols, pesticides, and heavy metals.[15,52−54]

Biosensors utilize biological recognition elements (e.g., enzymes, aptamers, and antibodies) to selectively bind target analytes, resulting in a measurable response that is transduced into an electrical or optical signal (e.g., enzyme-based sensors, aptasensors, and immunosensors).[55] Many examples of biosensors have been reported for water pollutants,[16] such as pesticides,[56] antibiotics, heavy metals, and endocrine disrupting chemicals.[53] Challenge of biosensing technologies in real world environments include stability of the bioreceptor and the nonspecific binding or passivation of other contaminants or water constituents.

Acoustic wave sensors detect changes in mechanical properties (e.g., mass loading or viscoelasticity) caused by the adsorption or binding of target analytes onto a sensing surface. Common acoustic wave sensor types include quartz crystal microbalances (QCMs) and surface acoustic wave (SAW) devices.[57]

Ion-selective electrodes (ISEs) are one type of electrochemical sensor that measures ion concentrations in water samples using a selective membrane designed to target specific ions, such as heavy metals or nutrient ions. The potential difference across the ion-selective membrane is indicative of the concentration of the target ion in the solution, which can be described by the Nernst equation.[58] Several examples of low-cost paper-based potentiometric sensors based on ISEs have been reported for chloride,[59] cadmium, silver, sodium,[60] and heavy metals.[61]

Microfluidic sensors integrate fluid handling, sample processing, and sensing elements within miniaturized devices to enable rapid and efficient water quality analysis. Microfluidic sensors rely on principles such as laminar flow, capillary forces, and diffusion in small-scale channels to manipulate liquids and perform complex analytical tasks within compact devices.[62]

Lab-on-a-chip (LOC) systems combine various sensor technologies, along with microfluidics into a single platform for multiplexed detection of multiple analytes in environmental water samples. LOC systems typically involve integrating multiple sensing elements (e.g., optical or electrochemical), sample processing components (e.g., filtering or preconcentration), and microfluidic channels into a single device for portable and high-throughput analysis.[63]

Remote sensing technologies use satellite imagery or aerial photography to assess large-scale water quality parameters such as turbidity, algal blooms, and temperature variations. Remote sensing relies on the analysis of reflected or emitted electromagnetic radiation from water bodies to infer information about their physical, chemical, or biological properties.[64]

Smartphone reading devices enable the integration of low-cost optical chemical and biological sensors with cameras, color-reading applications, or image processing software from smartphone devices. These devices provide a user-friendly interface, allowing for easy operation. However, achieving high levels of accuracy and sensitivity in analysis can be challenging.[65]

Lateral flow devices (LFDs) provide rapid, affordable, and simple analysis for a variety of targets binding to receptor molecules stored on nitrocellulose membranes or wax-printed chromatographic paper strips through colorimetric reactions. LFDs have been well established and are currently used in many clinical applications, providing qualitative analysis of many targets (e.g., pregnancy test and COVID testing),[66] but have received less attention in the environmental field. LFD devices provide qualitative information through naked-eye readout within 5−30 min, depending on configuration, and can be used by nontrained community users because of their simplicity.[67]

3. DEVELOPMENT CYCLES AND PRACTICAL STRATEGIES FOR ADVANCING MARKET-READY SENSORS

The successful development of portable sensors necessitates the integration of multiple components, including the immobilization of chemical or biological receptors, optimization of a physical transducer, and establishing communications between the physical transducer with the signal amplification and processing units. Furthermore, portable sensors require an independent power source for field operations as well as hardware/software to convert signals into a readable format. Advanced sensors could in principle be interfaced with the Internet of Things (IoT) and incorporate wireless communication units, automated sampling and data transmission, and modern data analytics to aid in decision-making.[68] While frameworks for water monitoring using remote sensing and big data have been developed,[69] several limitations prevent the widespread adoption of chem/bio sensing technologies with the growing IoT. These include lack of integration of individual components which prevents all-in-one analysis and operation by nontechnical users, and the low spatiotemporal resolution for measurements in real world environments to provide data at relevant scales. Nevertheless, several examples of successful

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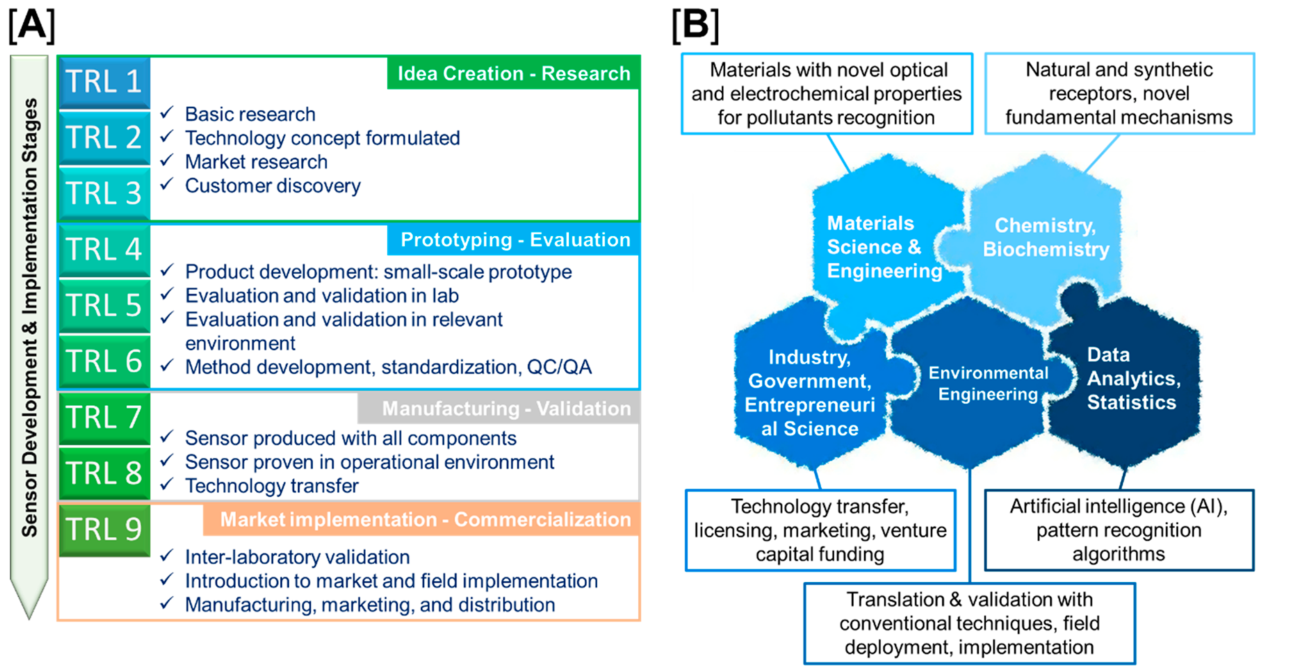

Figure 3. (A) The development phases and technology readiness level (TRL) for the manufacturing and implementation of field-deployment water sensors and (B) diversity of fields and strategic partnerships necessary to advance technology innovation for water sensors.

development of wireless low cost smartphone-based portable sensors have been demonstrated for the spatiotemporal mapping of nitrite[70] and mercury[71] contamination in water, showing the potential of such systems for water quality monitoring. Careful consideration of availability, cost, and seamless integration of these components into a portable and deployable unit are vitally important for field-ready system manufacturing and large-scale implementation.[72] An overview of the different development phases associated with environmental sensors' technology readiness levels is summarized in Figure 3A.

Innovation in sensing technologies builds upon a robust foundation of fundamental science, typically originating from university research supported by public or governmental funding. This initial development stage corresponds to technology readiness levels (TRLs) 1−3, during which proof-of-concept prototypes are created, guided by established working principles and subjected to preliminary performance evaluations.[73] The vast majority of sensing technologies for emerging contaminant detection are currently at TRLs 1−3 (Phase 1). Advancing to the next phase, which involves commercial product development (Phase 2), requires market research and customer discovery assessments to evaluate market need, size, and target customer base. Further development involves evaluation, validation, and standardization in relevant environments (TRLs 4−5), which results in the development of a Minimum Viable Product (MVP) with design and performance characteristics based on customer feedback. TRLs 7−8 (Phase 3) focus on demonstrating capabilities in intended operational environments and manufacturing individual and integrated components. Alongside market research and customer discovery efforts, this process is essential for technology translation from early prototypes developed within university laboratories to field-validated solutions. Effective translation into portable systems with manufacturable components enables large-scale market implementation and commercialization (TRL 9).

The objective of developing market-ready sensors is to ensure accurate measurements that reflect the true concentration of analytes upon field deployment, fulfill the requirements of intended application scenario, and do so within an acceptable cost and time frame.[74,75] We provide a step-by-step framework for the development and validation of market-ready sensors for emerging contaminant analysis, delineating four critical stages: (1) identification of stakeholder needs, (2) designing and conducting performance tests, (3) validating the analytical method, and (4) executing field deployment alongside long-term performance evaluations (Figure 4).

Stage I includes setting up key milestones and performance requirements for the sensor, including sensitivity, selectivity, stability, portability, user friendliness, and response time within

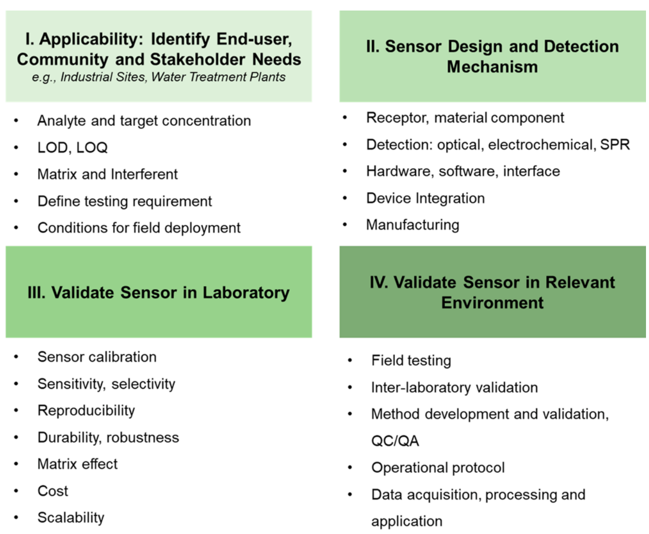

Figure 4. Roadmap illustrating the development stages of market-ready sensors for the analysis of emerging contaminants in water.

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the intended operational environment to ensure that the developed sensors meet market needs and stakeholder expectations. It is crucial to precisely define the sensitivity goals, such as the limit of detection (LOD) and limit of quantification (LOQ), based on typical emerging contaminant concentrations found in specific matrices, as well as any existing health advisory levels and maximum contaminant levels established by health and regulatory authorities. Additionally, when determining sensitivity goals, it is important to clearly specify the water matrix and identify potential interfering substances that could impact the sensor's selectivity or longevity, such as analogs of the target analytes or natural organic matter. Component availability, cost and manufacturability should also be considered in selecting sensor materials, transducers, and interfaces to ensure that scale up is feasible and affordable. Early stakeholder engagement, cocreation and coproduction of design specifications, and collaboration in technology entrepreneurship have been shown to positively impact and speed up translation to market, and improve innovation performance.[76,77] Therefore, collaboration between sensor developers and stakeholders is essential for incorporating user needs into sensor development at this stage.

Stage II involves the actual development of the sensor and selection and integration of recognition elements, transducers, and detection mechanisms. The utilization of advanced materials and technologies, such as the use of nanoscale materials and micro- and nanofabrication, has been shown to facilitate miniaturization and improve the overall capabilities of sensors for environmental contaminants detection.[78,79] For example, nanomaterials such as nanoparticles, nanotubes, nanowires, porous and functionalized nanointerfaces and nanophotonic devices have demonstrated increased sensitivity due to their large surface-area-to-volume ratio and unique optoelectronic properties, and recent developments demonstrate promise of nanosensing technologies for environmental analysis.[37,80,81] However, first generations of nanotechnology-enabled sensors still require improvement to address questions related to nonspecific adsorption, potential aggregation, and stability of nanomaterials[78] as well as scalability of design components and operability in complex environmental samples. Advanced technologies, such as microfluidic liquid processing device and machine learning, are pivotal in facilitating sensor miniaturization, efficient deployment, and automation in both sensor operations and data analysis and (near) real-time emerging contaminant analysis. During this stage, the sensors undergo testing with both standard and spiked samples, which contain varying concentrations of targeted emerging contaminants. Key parameters, such as the LOD, LOQ, dynamic range, response time, and cost, are determined experimentally. These parameters must meet the objectives set in Stage I for the subsequent development stage.

Once the market and customer needs have been identified and an initial prototype has been developed, **Stage III** involves further refinements and validation of the prototype and creation of an early minimum viable product (MVP) tested in the laboratory. At this stage, real samples, which are thoroughly characterized and representative of the intended application scenario, will be tested using both the novel sensors and conventional techniques (e.g., LC-MS) to acquire the key parameters of emerging contaminant analysis, such as recovery, accuracy, and precision. Interlaboratory studies to demonstrate robustness and broad applicability should also be performed at this stage. Primary interferent components with emerging contaminant analysis should be identified and minimized by necessary sample pretreatment (e.g., membrane filtration to improve selectivity). Quantitative performance can be further improved by iterations and optimizations in sensor/real sample interfaces and precisely controlling and optimizing the properties of the transducer and receptor materials. Following laboratory validation, **Stage IV** involves extensive field testing to assess the sensor's longevity and robustness. This stage includes validation by multiple independent laboratories over an extended period. Once the sensor successfully passes field validation, the development of standardized operational protocols for end users will be undertaken. During initial tests by end users, additional improvements may involve the development of customized algorithms for data analysis and visualization. These improvements are designed to facilitate easier interpretation of data, particularly benefiting less experienced users.

4. WHY MOST SENSORS DO NOT MOVE FROM LAB TO MARKET

The translation of proof-of-concept sensors for water contaminant detection into practical applications has faced various technical and nontechnical challenges. Technical challenges include managing batch-to-batch variations, minimizing interferences, ensuring robustness, and designing and integrating receptors, transducers, and other device components to achieve high precision, accuracy, longevity, and ease of operation in analysis. Academic research often focuses on addressing specific technical aspects of sensors such as enhancing the stability of bioreceptors or improving the physicochemical performance of transducers. However, a holistic consideration of the integration of different components, including the user interfaces, merits equal attention. Additionally, sensor validation under environmentally relevant settings by standard analytical methods is crucial for decision-making purposes. While some prototypes may demonstrate satisfactory performance under controlled laboratory conditions, their performance in the field may not be as exemplary.[74,82]

Sensors that utilize synthetic or biological receptors are especially vulnerable to selectivity and stability issues due to their high sensitivity and potential for degradation.[83] Challenges including nonspecific adsorption and inability to operate in complex water matrices further compound these problems. Furthermore, factors like cost, scalability, and manufacturability pose additional hurdles to large-scale implementation and should be taken into consideration during sensor design. Unfortunately, the resources required for advancing sensor manufacturing and performance validation in environmental conditions are scarce since academic laboratories typically prioritize fundamental scientific research over applied development. Similar obstacles extend to sensor validation and quality assurance/quality control (QA/QC), as a majority of reported studies rely on standard solutions or, at best, spiked samples. Rarely are the developed sensors tested with actual environmental samples, and even more seldom is their validation against standard analytical methods accompanied by the reporting of accuracy and precision in adherence to stringent QA/QC standards. Figure 5 provides an overview of technical challenges faced by the developers of colorimetric, electrochemical, and SERS-based sensors as well as potential areas for improvement that will facilitate the successful translation of proof-of-concept sensors into market-ready devices capable of accurately and

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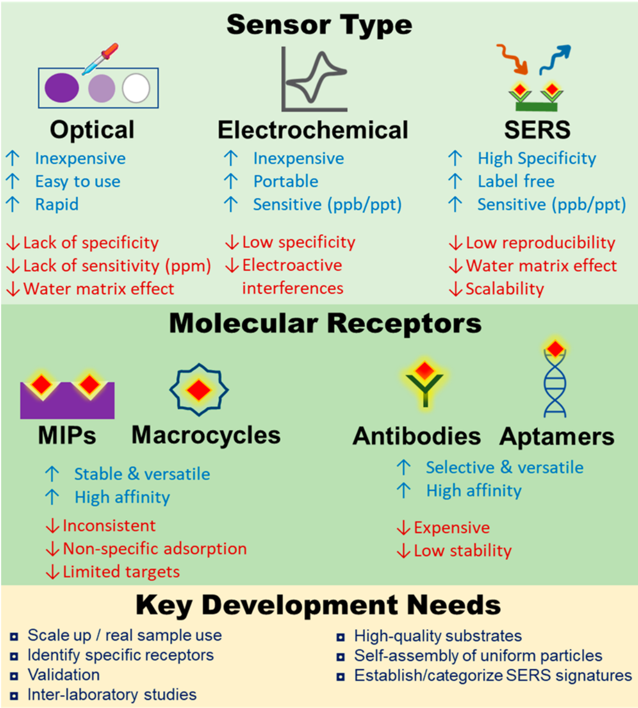

Figure 5. Key challenges and development needs for the most commonly reported types of sensors with optical, electrochemical, and SERS-based detection for emerging contaminants. In this context, we separate SERS from other types of optical sensors because of its unique advantages, including fingerprinting selectivity, label-free detection, and multiplexed detection capabilities.

efficiently detecting emerging contaminants in water systems.[75,80−82]

Nontechnical challenges mainly revolve around interdisciplinary collaborations, market drivers, academic entrepreneurship culture, and various partnerships with businesses, industries, and governmental or regulatory communities (Figure 3B). Researchers seldom engage with key stakeholders, such as government agencies, water industry representatives, citizen scientists, communities, and public institutions (e.g., schools), in the early stages of sensor development. Consequently, the sensors created may not align with the actual needs of these stakeholders. Given the absence of a universal sensing technology or toolbox, it is essential to foster widespread communication to identify specific niches where these sensors can be effectively deployed for broad-based applications. Simultaneously, several translational challenges hinder progress in this area, such as the absence of standard operating procedures, market validation, consistent interlaboratory reproducibility, and well-defined accuracy profiles, all of which are critical elements for sensor validation. This deficiency in robust validation practices has undermined investor and user confidence, thus decelerating the commercialization of sensors for detecting emerging contaminants. Moreover, the small market size of emerging contaminant monitoring, coupled with a shortage of professionals skilled in commercialization and entrepreneurship in this area, further suppresses the rate of technology transfer and stifles innovation in sensor-based enterprises.

Another significant challenge stems from the increasing number of unregulated emerging contaminants, with uncertainties surrounding their health and environmental impacts, along with the lengthy and complex environmental studies required to establish safety limits. In addition, the criteria for regulating pollutants differ across various water matrices, such as drinking water, surface water, and wastewater effluents, but these criteria remain ill-defined for most emerging contaminants. Consequently, there is often no clear sensitivity target or defined application scenario for the development of sensors for many of these substances. This ambiguity further delays the progression and thorough evaluation of new sensing technologies. Although many sensors have been developed and some have been validated,[84] analysis is still largely done with conventional laboratory techniques, while efforts in the sensing field concentrate on advancing capabilities through the use of new materials such as carbon nanotubes[85] rather than addressing market drivers, manufacturing, industry and customers' needs. In other cases, such as the class of the more recently identified contaminants, i.e., PFAS, although the need for sensors is widely recognized,[86] reported sensors lack the required selectivity and sensitivity, in some cases by several orders of magnitude (e.g., 10 ppm with a colorimetric paper based approach[87]) as compared to the EPA advisory limits in the low ppt. Other more sensitive MIP-based electrochemical sensors report LODs down to 20 ppt but lack selectivity and are prone to interferences from cocontaminants such as chloride and humic acid.[88−90] Consequently, delays in identifying technological needs and testing requirements for sensing devices further impede progress.[25,27]

To facilitate rapid technology translation from research to application, it is vital to prioritize strategic investment in intellectual property (IP) protection, going beyond just academic publication. According to a recent study, although publications in the field of nanosensors have increased in recent years, patent applications for nanosensors have seen a concurrent decline.[91] This may be attributed to insufficient research funding and a lack of incentives for studies on sensor validation, prototyping, and field testing—activities typically of greater interest to industry than academia. The predominance of basic research, driven more by scientific curiosity than by stakeholder or market needs, can impede timely technology translation. To overcome this challenge, there is a need to establish an iterative feedback loop process that fosters collaboration among researchers, industry experts, governmental/environmental professionals, community members, and citizen scientists, especially those in disadvantaged, low-resource areas highly impacted by chemical exposures. Such engagement of key stakeholders and groups often excluded from technology development is crucial to ensure emerging detection tools meet the real-world needs of communities most affected but lacking a means for assessing water contaminants. This collaborative process allows stakeholders to provide input during the early design stages, ensuring that device specifications align with market demands. Overcoming roadblocks requires addressing not only technical aspects but also business strategies, stakeholder influence, regulations, legal considerations, and the availability of human and financial resources. Aligning these factors will accelerate the conversion of proof-of-concept devices into field deployment.[76,77]

5. STRATEGIC OBJECTIVES AND BEST PRACTICES TO OVERCOME ROADBLOCKS

The presented overview of sensing technologies for emerging contaminant detection highlights the requirements for significant advancements in addressing both technical and non-

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Table 1. Challenges and Considerations to Translate Proof-of-Concept Sensors to Commercialization

Challenges	Special considerations and potential solutions
	Technical
Field deployment, durability, and robustness in real-world environments	Performance metrics for sensors should be established in real operational environments. Ideally, sensors should achieve long-term functionality in real water environments without requiring frequent calibration, maintenance, and replacement. It is crucial to identify major interfering substances in actual samples and implement strategies that can minimize these interferences and prevent sensor surface fouling.
Precision, accuracy, and reproducibility	The precision, accuracy, and reproducibility of sensor measurements and manufacturing should be quantitatively evaluated under intended application scenarios by multiple independent laboratories. It is important to establish standard operating procedures for conducting these evaluations.
Sensitivity, selectivity, and matrix effect	LOD/LOQ should be determined through actual experimental data rather than relying on extrapolation from signal-to-noise ratios. Selectivity testing should be conducted using real water matrices to ensure accurate performance. Reliable sampling should be accounted for in design stage to minimize matrix effects.
Component integration, user interface, portability and cost to create market-ready MVP	Field deployment implies component miniaturization and integration with user-friendly interfaces. However, challenges lie in the holistic design and integration of the sensor components in consideration of targeted performance, cost, and complexity for field deployment. Addressing these challenges requires collaborative efforts from different disciplines and stakeholders.
Scalability, component availability, and manufacturability	Scalability and large-scale manufacturing considerations should be considered in the design stage. It is important to strike a balance between performance and cost based on specific application requirements when scaling up production.
Interlaboratory validation and standardized testing protocols	Standardized testing and QA/QC protocols should be developed and implemented. Such protocols should be validated using standard analytical methods and multiple independent laboratories to ensure the reliability, robustness, and transferability of sensor measurements.
	Non-technical
Partnerships	Academia should identify and establish strategic partnerships with potential end users, including water treatment plants, industries, federal/state agencies, and local communities.
Funding to bridge fundamental research to application	It is essential to leverage funding through federal agencies, e.g., *SBIR/STTR* and *NSF-PFI* programs, and industry partners to support research focused on scaling-up, prototyping, and field validation.
Stakeholder needs with product and customer discovery	Sensors should be designed according to feedback from stakeholders to ensure that they address market needs. Engaging in customer discovery processes, such as through NSF *I-Corps* and entrepreneurial programs and attending industry-focused workshops and innovation forums such as *TechConnect*, can help establish connections with stakeholders and gather valuable insights.
Market drivers and go-to-market (GTM) strategy	It is essential to establish the market need and understand the competitive landscape. By defining sensor specifications that align with the required capabilities of the target market, the development process can be tailored to meet specific needs. To create effective go-to-market strategies, it is crucial to seek guidance from business/entrepreneurial experts, and innovation centers.
Intellectual property (IP)	To protect IP related to the sensor technologies, it is necessary to file provisional and full patent applications or consider licensing agreements.
Human capital with commercialization and entrepreneurial experience	Develop workforce by encouraging internships in industry, providing training in technology-based entrepreneurship programs, and inclusion in customer discovery teams.

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technical challenges to accelerate innovation (Table 1). In this section, we identify nine key objectives and propose potential solutions that can facilitate bridging the gap between the laboratory and the market.

Objective 1: Improving Sensitivity and Selectivity of Current Sensor Technologies. Achieving the necessary sensitivity and selectivity in complex environmental matrices while differentiating among various contaminants remains a persistent challenge. To address this, ongoing research focuses on the development of advanced transducer materials/modalities and receptor interfaces,[31,92] which involves collaborations between material scientists, biochemists, analytical chemists, and engineers. By leveraging interdisciplinary expertise, sensor development can focus on enhancing the sensitivity, selectivity, and stability for detecting trace levels of emerging water contaminants in compliance with regulatory standards. Innovative approaches such as employing novel synthetic receptors and biorecognition elements like aptamers and peptides show promise in increasing selectivity.[32] On the transducer side, the integration of hybrid materials combining the advantageous properties of organic and inorganic components can improve transduction and sensing performance.[80] Introducing new surface functionalities and coatings to enhance analyte capture and prevent nonspecific adsorption offers a way to reduce false positives and enhance the accuracy of analysis. To further enhance detection capabilities, integration of diverse transduction methods, such as optical and electrochemical techniques, into a single platform can be explored. By combination of the advantages of both techniques, a comprehensive and reliable approach for water contaminant detection can be created. Developing multianalyte sensor arrays and biosensors utilizing different biorecognition elements with high selectivity toward specific target analytes enables simultaneous detection and identification of various classes of water contaminants. In-line sample pretreatment modules, e.g., membrane filtration or hydrogen peroxide oxidation, may efficiently reduce the fouling of sensor surfaces. In terms of data processing, machine learning-driven sensing proves valuable in systematically categorizing data and training systems for prediction and deconvolution of responses toward specific targets. Multivariate chemometric techniques like principal component analysis enable rapid differentiation of multiple contaminants. To ensure a reliable and accurate sensor performance, comprehensive validation is necessary. Sensor testing should be conducted in real water matrices, such as wastewater and surface water, in addition to synthetic water samples. Comparative validation against established analytical methods allows for the assessment of relative sensitivity, selectivity, and accuracy. Furthermore, operational and long-term testing of sensors should be conducted under various environmental conditions, including temperature and humidity encountered in field applications.[93]

Objective 2: Integrating Real-Time, In Situ Monitoring Capabilities. To improve the field performance of sensors under diverse environmental conditions, it is essential to address several key considerations. First, many existing sensors lack real-time, continuous, and autonomous operating capabilities. While low-cost colorimetric or electrochemical strips can be used as point-of-use sensors in specific locations such as water treatment plants, these chemical assays require humans to perform experiments and data inspection, significantly limiting their throughput. Advanced designs with the potential for integration with wireless communication and IoT technologies can overcome this limitation. Collaborating with IoT experts can help leverage the full potential of connected sensing devices that incorporate low-power wireless communication protocols (e.g., LoRaWAN, Sigfox) and enable real-time data transmission and analysis, which is particularly valuable for remote sensing purposes.[94] Additionally, to facilitate continuous and autonomous monitoring, sensors should be equipped with energy harvesting modules such as solar cells to eliminate the need for battery replacement or recharging. Developing user-friendly software platforms for data visualization, analysis, and management is essential for real-time water monitoring. By integration of machine learning algorithms into the software design, automated data processing can be achieved, facilitating informed decision-making. From a manufacturing and business perspective, designing modular sensing platforms that can be easily upgraded or adapted to monitor different contaminants as needed provides a customizable solution for diverse markets. Calibration is critical in sensor implementation, as sensor drifts may occur in field applications. To address this, calibration strategies should be developed and standardized to account for variations in environmental conditions, including the temperature, pH, salinity, and humidity during real-time monitoring applications. It is important to test and optimize the capabilities, communication ranges, and data transmission of these sensors under various environmental conditions. The operational protocol of the minimum viable product (MVP) should include protocols for regular maintenance and calibration of deployed sensors to ensure long-term monitoring accuracy.

Objective 3: Reduce Cost and Complexity of Current Analytical Methods. Sensing research aims to create cost-effective, portable, and miniaturized platforms that complement and expedite analysis in large-scale water quality monitoring. To achieve this, strategies must be implemented to reduce the cost and complexity associated with the current analytical methods. One approach is the mass production of affordable sensor components by leveraging advanced manufacturing tools such as 3D- and screen-printing, which can lower production cost and increase scalability. Integration of individual sensor components such as receptors, transducers, and data processing units is crucial for successful field deployment. Microfluidics technology offers opportunities for miniaturization and the integration of multiple sensors into a single device. Ideally, fully integrated chip-based sensing systems should seamlessly integrate with existing water quality monitoring infrastructure and may even include sampling units to streamline analysis workflows. To ensure the reliability and cost-effectiveness of integrated sensors, their performance should be benchmarked against established laboratory methods, demonstrating analytical quality without compromising affordability. The cost of maintenance during long-term water quality monitoring can rival that of sensor manufacturing. Consequently, research into strategies that reduce the frequency of sensor calibration and replacement, such as integrating soft and hard sensors, should be prioritized on par with sensor development.[95] Technology evaluation and validation should involve stakeholder engagement, including water utilities and regulatory agencies, to identify target contaminants and prioritize platform development efforts accordingly. Prototype designs and performance goals should align with market analysis, ensuring that the developed sensors address the market needs effectively. Assessing the market viability and exploring potential commercialization pathways are key steps in this process. Early collaboration between academic researchers, industry partners, and end-users during the design

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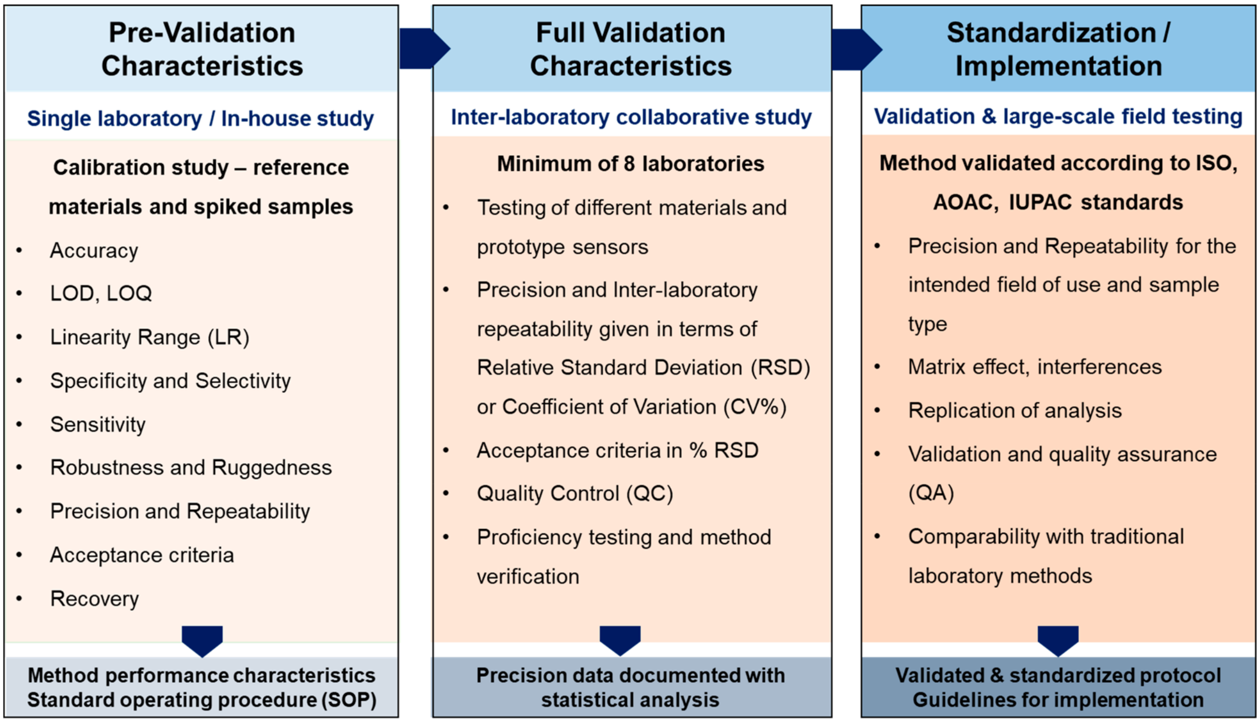

Figure 6. Overview of validation objectives and relationship between method performance and validation requirements according to the International Standards Organization (ISO), Association of Official Analytical Collaboration (AOAC), and International Union of Pure and Applied Chemistry (IUPAC).

stage is highly recommended to align technology development with the specific needs of end-users. Industry-academia workshops and training sessions that educate relevant stakeholders on the use of the developed sensing platforms are particularly effective in fostering collaboration and coproduction of knowledge.

Objective 4: Ensure Robustness, Operational Performance, and Applicability in Complex Environmental Matrices. The primary objective of sensor research is to engineer robust sensors that perform reliably across diverse environmental conditions and water matrices. However, many sensors developed in the laboratory falter under field conditions due to matrix effects and signal drift. To address these challenges, implementing efficient sample pretreatment techniques, such as solid-phase extraction and membrane filtration, is critical to remove interfering substances from environmental samples. Calibration strategies must be developed to account for matrix effects and varying environmental conditions encountered during field applications to ensure accurate analysis. Furthermore, sensor aging and fouling should be considered in long-term monitoring studies within complex environmental matrices. The implementation of advanced materials, such as antifouling coatings, can minimize biofouling and prevent deterioration of sensor performance over time.[96] It is crucial to evaluate sensor performance and stability in various environmental matrices, including wastewater, surface water, and groundwater, to assess their general applicability across diverse conditions. Exploring the use of reference materials or internal standards can help compensate for potential matrix effects or device-intrinsic signal drift and improve analytical accuracy. Regular maintenance, cleaning, and calibration of deployed sensors are essential to ensuring reliable operation in challenging environments. Benchmarking sensor performance against established methods for blind water sample testing during the development stage is necessary to demonstrate robustness and suitability for field applications before commercialization.

Objective 5: Include Component Integration, Portability, and Scalability in Early Prototype Design. When developing field-deployable water sensors are developed, it becomes imperative to consider cost, portability, and manufacturability as crucial factors for large-scale utilization and commercialization. It is essential to bridge the gap between academic sensing research and market viability by addressing these factors early in the design stage. Oftentimes, academic research tends to prioritize sensor performance, e.g., reducing the LOD/LOQ, while overlooking the cost of materials, individual components, integration, miniaturization, and adaptability. As a result, laboratory prototypes may meet the required performance criteria but are insufficient for market acceptance. Tailoring solutions to meet the specific demands of various application scenarios requires effective balancing of cost and performance effectively. To ensure the marketability and commercial viability of laboratory-developed prototypes, it is recommended that considerations of cost and manufacturability be incorporated from the outset of the design process. This entails evaluating the cost of materials and components, optimizing the design for enhanced portability, and assessing the feasibility of mass production. Collaborating with business experts can facilitate the development of a pricing strategy and a comprehensive plan for scaling up production, thereby ensuring that the sensors are not only effective but also economically viable for large-scale deployment. Additionally, consulting with potential end users early in the design process can yield valuable insights into the preferred size, portability, and pricing of the final product.

Objective 6: Develop Standardized Testing Protocols and Interlaboratory Studies for Evaluating Sensor

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Performance. To enable field deployability and commercialization of environmental water sensors, the development of universally accepted performance metrics and testing protocols is crucial. These protocols should encompass representative sample matrices (e.g., wastewater, surface water) and relevant environmental conditions (e.g., temperature and pH). Collaborative efforts involving researchers, industry partners, and end-users can be instrumental in forming expert committees that develop consensus-based standards for evaluating environmental water sensors. Defining universally accepted performance metrics such as sensitivity, selectivity, and response time is equally important for facilitating meaningful comparisons among different sensor technologies. Furthermore, as sensing technologies and minimum viable products (MVPs) reach the deployment stage, interlaboratory comparison studies should be promoted to validate the developed protocols and ensure their applicability across diverse research groups and institutions.[97,98] Engaging international standards organizations, such as the International Organization for Standardization (ISO), in the validation efforts will foster global harmonization and acceptance of the established testing protocols. By establishing standardized testing protocols and performance metrics, the environmental sensing community can facilitate technology validation, comparison, and adoption. This concerted effect will contribute to the field deployability and commercial viability of environmental water sensors, providing stakeholders with reliable and consistent data for effective water quality monitoring and management.

Objective 7: Validate and Deploy Sensor and Collect Data on the Occurrence, Fate, and Effects of Emerging Contaminants in Relevant Environments, Side-by-Side with Conventional Methods. The data generated by sensors can greatly assist water monitoring communities in identifying areas of contamination and in facilitating swift intervention. To ensure effective comparison and integration of results, it is essential to employ standardized procedures for data collection and reporting across different research groups and communities, in accordance with guidelines for method performance requirements as per ISO, AOAC, and IUPAC validation criteria. Figure 6 summarizes the hierarchy of validation objectives for single and interlaboratory validation and relationship with performance specification and implementation. Many excellent resources exists which provide guidelines for analytical method development and determination of validation parameters.[74,75,82,99−101] If sensors are to be implemented at large scale, the generation of large volumes of data necessitates the utilization of advanced data analysis techniques, such as machine learning and geographic information systems (GIS), to integrate diverse data sets and uncover valuable insights into the occurrence, fate, and impacts of emerging contaminants. Integration of low-cost sensors with smartphones and the IoT infrastructure shows promise for the remote water quality monitoring, particularly for monitoring physical parameters,[102,103] and analytes like nitrite and metal ions[70,71] but several challenges need to be addressed for large scale adoption of IoT-enabled chem/bio sensors. These include the need for sample treatment, multistep analysis, and a lack of capabilities to provide continuous real-time monitoring with high spatiotemporal resolution when deployed. For these sensors to be utilized in large community mapping initiatives, it is crucial to establish interdisciplinary collaborations among sensor developers, electrical engineers and computational experts, analytical chemists, ecotoxicologists, and policymakers. Such collaborations will enable the generation of comprehensive data sets on the presence and effects of emerging contaminants in various aquatic ecosystems, thereby providing valuable information to stakeholders and communities. Furthermore, fostering data sharing initiatives (e.g., cloud servers and open-access databases) will facilitate data collection through citizen science and provide access to comprehensive data sets. These initiatives create standardized platforms that offer valuable insights into the occurrence, fate, and effects of emerging contaminants in water. This holistic approach maximizes the value of sensor data and contributes to a deeper understanding of emerging water contaminants for the benefit of stakeholders and communities.

Objective 8: Increase Public Awareness about the Presence and Risks Associated with Emerging Water Contaminants. Promoting citizen science initiatives that utilize innovative sensor technologies can effectively increase public awareness and engagement in environmental monitoring efforts. User-friendly sensing platforms specifically designed for nonexperts are ideal for citizen science projects. Collaborating with schools and community organizations and conducting workshops, training sessions, and webinars can educate citizens about the significance of emerging water contaminants and their role in monitoring efforts. Integrating citizen science data into broader research projects and regulatory decision-making processes serves as a compelling way to showcase the value of public involvement in environmental monitoring. Educational materials emphasizing the importance of monitoring emerging contaminants and providing guidance for citizen scientist participation should be developed and widely disseminated to reach a broad audience. Online platforms that facilitate data sharing and collaboration among citizen scientists engaged in water quality monitoring initiatives can enhance the dissemination of information and foster a knowledge exchange. In addition, media coverage and public awareness campaigns focused on citizen science projects can further increase awareness about emerging water contaminants. By actively promoting citizen science initiatives, involving the public, and leveraging their contributions, a stronger understanding of and response to emerging water contaminants can be achieved.

Objective 9: Educate Workforce and Develop Strategic Partnerships to Tackle Interdisciplinary Sensor Development Efforts. The role of human capital in advancing innovation and technological entrepreneurship is well recognized.[104] Interdisciplinary collaboration, strategic partnerships, and a qualified workforce are crucial for advancing the development of field-ready sensors for detecting emerging water contaminants. Bridging the gap between scientific fields, including researchers, product development engineers, data scientists, business professionals, and policymakers, is essential to drive sensor innovation. Developing a workforce capable of working across disciplines and effectively applying their knowledge is vital to support sensor development efforts. Promoting cross-disciplinary training and providing opportunities for researchers in academic settings, such as internships and exposure to practitioners working on different aspects of emerging contaminants, can equip them with the foundational skills needed to contribute to the development and innovation of next-generation sensors. Beyond technical skills, abilities such as relationship building, creativity, problem-solving, time management, adaptability, and critical thinking are essential for the future workforce. Creating entrepreneurship opportunities, such as involving graduate students in NSF Innovation Corps (I-Corps) teams, can empower them to engage in entrepreneurial

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activities and foster innovation. To bridge the gap between fundamental research and the market, increased funding opportunities for translational research are necessary. The establishment of the Technology, Innovation and Partnerships (TIP) directorate at the National Science Foundation (NSF) and U.S. EPA's small business technology development programs (SBIR/STTR) provides avenues for supporting entrepreneurial activities and startups, stimulating technology innovation. Additionally, programs like the I-Corps offer intensive entrepreneurial training, accelerating the commercialization of university-created work and contributing to the development of an entrepreneurial workforce. These initiatives incentivize translational work and are expected to enhance the conversion rate of fundamental research into marketable products.[105,106]

6. IMPLICATIONS AND OUTLOOK

The accurate and timely detection of emerging contaminants is essential for the safeguarding of water quality. However, several challenges, related to cost, complexity, limited sensitivity and selectivity, and lack of real-time monitoring, impede the advancement and commercialization of low-cost sensors and innovative solutions. Enhancing sensor performance through the development of advanced nanomaterials, receptor interfaces, and diverse transduction methods can improve the sensitivity, selectivity, and stability of the sensors. Future development of innovative recognition elements that ensure high selectivity for target binding within complex water matrices should also be a priority for future research. To improve stability and analysis time, alternative receptors and recognition elements could be explored to provide more rapid and specific binding affinity. The use of low-cost electrodes or supporting materials to create sensors, integrate separation units, and simplify measurement protocols could also be useful to reduce sample pretreatment and improve accuracy. The use of hand-held potentiostats and spectrometers connected to a smartphone should be considered when developing electrochemical and optical sensors to enable easy operation and reduce equipment costs for field deployment. By combining the multiplexed analytical capabilities of vibrational sensors, e.g., SERS-based sensors, with advanced data analytics, there is significant potential to extract quantitative information from a mixture of emerging contaminants in complex water matrices. Integration of IoT technologies and modern data analytics for real-time data collection and analysis enable continuous and autonomous monitoring. Scalability can be achieved by optimizing manufacturing processes and tools while ensuring sensor performance under complex environmental conditions for commercial viability.

Sensor development should encompass four distinct stages: design, laboratory testing, laboratory validation, and field testing. Involving stakeholders and potential end-users during the design phase is crucial to establishing the desired performance metrics, cost considerations, and user-interfaces of the sensors. Standardized testing protocols and interlaboratory studies are essential for validating sensor performance in real-world scenarios. Interdisciplinary collaborations and data sharing initiatives provide comprehensive insights into the occurrence and impacts of emerging contaminants. Advanced data analysis and visualization techniques such as machine learning and GIS can integrate diverse data sets and generate actionable insights. Increasing public awareness and promoting citizen science initiatives through user-friendly sensing platforms and educational materials empower communities in monitoring efforts. Cross-disciplinary training, internships, and entrepreneurship programs are crucial for developing a qualified workforce capable of bridging scientific fields and facilitating the deployment of sensor technologies in the field. Strategic partnerships and improved funding opportunities can support the growth of environmental sensing technologies and solutions, facilitating their translation from laboratory research to real-world applications. Through concerted efforts to address these challenges, the development and deployment of sensor technologies for detecting emerging water contaminants can be accelerated.

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■ REFERENCES

(1) Richardson, S. D.; Kimura, S. Y. Water analysis: emerging contaminants and current issues. *Anal. Chem.* **2020**, *92* (1), 473−505.
(2) Morin-Crini, N.; Lichtfouse, E.; Liu, G.; Balaram, V.; Ribeiro, A. R. L.; Lu, Z.; Stock, F.; Carmona, E.; Teixeira, M. R.; Picos-Corrales, L. A.; et al. Worldwide cases of water pollution by emerging contaminants: a review. *Environmental Chemistry Letters* **2022**, *20* (4), 2311−2338.
(3) Ateia, M.; Ersan, G.; Alalm, M. G.; Boffito, D. C.; Karanfil, T. Emerging investigator series: microplastic sources, fate, toxicity, detection, and interactions with micropollutants in aquatic ecosystems-a review of reviews. *Environmental Science: Processes & Impacts* **2022**, *24* (2), 172−195.
(4) Benotti, M. J.; Trenholm, R. A.; Vanderford, B. J.; Holady, J. C.; Stanford, B. D.; Snyder, S. A. Pharmaceuticals and endocrine disrupting compounds in U.S. drinking water. *Environ. Sci. Technol.* **2009**, *43* (3), 597−603.
(5) Russo, G.; Laneri, S.; Di Lorenzo, R.; Ferrara, L.; Grumetto, L. The occurrence of selected endocrine-disrupting chemicals in water and sediments from an urban lagoon in Southern Italy. *Water Environ. Res.* **2021**, *93* (10), 1944−1958.
(6) Li, S.; Liu, Y.; Wu, Y.; Hu, J.; Zhang, Y.; Sun, Q.; Sun, W.; Geng, J.; Liu, X.; Jia, D.; et al. Antibiotics in global rivers. *National Science Open* **2022**, *1* (2), 20220029.
(7) Khan, S.; Naushad, M.; Govarthanan, M.; Iqbal, J.; Alfadul, S. M. Emerging contaminants of high concern for the environment: Current trends and future research. *Environmental Research* **2022**, *207*, 112609.
(8) Zwiener, C.; Frimmel, F. H. LC-MS analysis in the aquatic environment and in water treatment technology-a critical review. Part II: Applications for emerging contaminants and related pollutants, microorganisms and humic acids. *Anal Bioanal Chem.* **2004**, *378* (4), 862−874.
(9) Rodriguez-Mozaz, S.; Lopez de Alda, M. J.; Barcelo, D. Advantages and limitations of on-line solid phase extraction coupled to liquid chromatography-mass spectrometry technologies versus biosensors for monitoring of emerging contaminants in water. *J. Chromatogr A* **2007**, *1152* (1−2), 97−115.
(10) Thavarajah, W.; Verosloff, M. S.; Jung, J. K.; Alam, K. K.; Miller, J. D.; Jewett, M. C.; Young, S. L.; Lucks, J. B. A primer on emerging field-deployable synthetic biology tools for global water quality monitoring. *npj Clean Water* **2020**, *3* (1), 18.
(11) Manivannan, B.; Nallathambi, G.; Devasena, T. Alternative methods of monitoring emerging contaminants in water: A review. *Environmental Science: Processes & Impacts* **2022**, *24*, 2009−2031.
(12) Johnson, K. S.; Needoba, J. A.; Riser, S. C.; Showers, W. J. Chemical sensor networks for the aquatic environment. *Chem. Rev.* **2007**, *107* (2), 623−640.
(13) Ahmad, I.; Weng, J.; Stromberg, A. J.; Hilt, J. Z.; Dziubla, T. D. Fluorescence Based Detection of Polychlorinated Biphenyls (PCBs) in Water Using Hydrophobic Interaction. *Analyst* **2019**, *144* (2), 677−684.
(14) Sri, V. R.; Shwetharani, R.; Mohammed, J.; Mabkhoot, A.; Balakrishna, R. G.; Harraz, F. A. Review on electrochemical sensing of

triclosan using nanostructured semiconductor materials. *ChemElectroChem.* **2022**, *9* (4), No. e202101664.
(15) Hara, T. O; Singh, B. Electrochemical Biosensors for Detection of Pesticides and Heavy Metal Toxicants in Water: Recent Trends and Progress. *ACS EST Water* **2021**, *1* (3), 462−478.
(16) Sahu, S.; Roy, R.; Anand, R. Harnessing the Potential of Biological Recognition Elements for Water Pollution Monitoring. *ACS Sens* **2022**, *7* (3), 704−715.
(17) Sun, X.; Zhang, Y.; Shi, K.; Zhang, Y.; Li, N.; Wang, W.; Huang, X.; Qin, B. Monitoring water quality using proximal remote sensing technology. *Sci. Total Environ.* **2022**, *803*, 149805.
(18) Hassan, M. H.; Khan, R.; Andreescu, S. Advances in electrochemical detection methods for measuring contaminants of emerging concerns. *Electrochemical Science Advances* **2022**, e2100184.
(19) Sivaranjanee, R.; Senthil Kumar, P.; Saravanan, R.; Govarthanan, M. Electrochemical sensing system for the analysis of emerging contaminants in aquatic environment: A review. *Chemosphere* **2022**, *294*, 133779.
(20) Thakur, A.; Devi, P. A Comprehensive Review on Water Quality Monitoring Devices: Materials Advances, Current Status, and Future Perspective. *Crit Rev. Anal Chem.* **2022**, 1−26.
(21) Huang, Y.; Wang, X.; Xiang, W.; Wang, T.; Otis, C.; Sarge, L.; Lei, Y.; Li, B. Forward-Looking Roadmaps for Long-Term Continuous Water Quality Monitoring: Bottlenecks, Innovations, and Prospects in a Critical Review. *Environ. Sci. Technol.* **2022**, *56* (9), 5334−5354.
(22) Yadav, P.; Laddha, H.; Yadav, L.; Agarwal, M.; Gupta, R. Sustainable solution for recognition and quantification of environmental pollutants by chromofluorogenic and electrochemical sensors. *Inorganic Chimica Acta* **2023**, *553* (1), 121512.
(23) Rogers, K. R. Recent advances in biosensor techniques for environmental monitoring. *Anal. Chim. Acta* **2006**, *568* (1−2), 222−231.
(24) Li, F.; Yu, Z.; Han, X.; Lai, R. Y. Electrochemical aptamer-based sensors for food and water analysis: A review. *Anal. Chim. Acta* **2019**, *1051*, 1−23.
(25) Kruse, P. Review on water quality sensors. *J. Phys. D: Appl. Phys.* **2018**, *51* (20), 203002.
(26) Iftikhar, R.; Parveen, I.; Ayesha; Mazhar, A.; Iqbal, M. S.; Kamal, G. M.; Hafeez, F.; Pang, A. L.; Ahmadipour, M. Small organic molecules as fluorescent sensors for the detection of highly toxic heavy metal cations in portable water. *Journal of Environmental Chemical Engineering* **2023**, *11* (1), 109030.
(27) Water Sensors Toolbox. U.S. Environmental Protection Agency. https://www.epa.gov/water-research/water-sensors-toolbox (accessed 2023-05-10).
(28) Liu, B.; Zhuang, J.; Wei, G. Recent advances in the design of colorimetric sensors for environmental monitoring. *Env Sci. Nano* **2020**, *7*, 2195−2213.
(29) Chapman, J.; Truong, V. K.; Elbourne, A.; Gangadoo, S.; Cheeseman, S.; Rajapaksha, P.; Latham, K.; Crawford, R. J.; Cozzolino, D. Combining chemometrics and sensors: Toward new applications in monitoring and environmental analysis. *Chem. Rev.* **2020**, *120* (13), 6048−6069.
(30) Wei, H.; Hossein Abtahi, S. M.; Vikesland, P. J. Plasmonic colorimetric and SERS sensors for environmental analysis. *Environ. Sci.: Nano* **2015**, *2*, 120−135.
(31) Altug, H.; Oh, S. H.; Maier, S. A.; Homola, J. Advances and applications of nanophotonic biosensors. *Nat. Nanotechnol* **2022**, *17* (1), 5−16.
(32) Justino, C. I.L.; Freitas, A. C.; Pereira, R.; Duarte, A. C.; Rocha Santos, T. A.P. Recent developments in recognition elements for chemical sensors and biosensors. *TrAC Trends in Analytical Chemistry* **2015**, *68*, 2−17.
(33) Kuswandi, B.; Nuriman; Huskens, J.; Verboom, W. Optical sensing systems for microfluidic devices: a review. *Anal. Chim. Acta* **2007**, *601* (2), 141−155.
(34) Alkasir, R. S.; Ornatska, M.; Andreescu, S. Colorimetric paper bioassay for the detection of phenolic compounds. *Anal. Chem.* **2012**, *84* (22), 9729−9737.
(35) Kirk, K. A.; Andreescu, S. Easy-to-Use Sensors for Field Monitoring of Copper Contamination in Water and Pesticide-Sprayed Plants. *Anal. Chem.* **2019**, *91* (21), 13892−13899.
(36) Ding, R.; Cheong, Y. H.; Ahamed, A.; Lisak, G. Heavy Metals Detection with Paper-Based Electrochemical Sensors. *Anal. Chem.* **2021**, *93* (4), 1880−1888.
(37) Liu, B.; Zhuang, J.; Wei, G. Recent advances in the design of colorimetric sensors for environmental monitoring. *Environ. Sci.: Nano* **2020**, *7*, 2195−2213.
(38) Jiao, L.; Zhong, N.; Zhao, X.; Ma, S.; Fu, X.; Dong, D. Recent advances in fiber-optic evanescent wave sensors for monitoring organic and inorganic pollutants in water. *TrAC Trends in Analytical Chemistry* **2020**, *127*, 115892.
(39) Homola, J.; Yee, S. S.; Gauglitz, G. Surface plasmon resonance sensors. *Sens. Actuators, B* **1999**, *54* (1−2), 3−15.
(40) Yao, G.-H.; Liang, R.-P.; Huang, C.-F.; Wang, Y.; Qiu, J.-D. Surface plasmon resonance sensor based on magnetic molecularly imprinted polymers amplification for pesticide recognition. *Anal. Chem.* **2013**, *85* (24), 11944−11951.
(41) Homola, J. Surface plasmon resonance sensors for detection of chemical and biological species. *Chem. Rev.* **2008**, *108* (2), 462−493.
(42) Højris, B.; Kornholt, S.; Christensen, S.; Albrechtsen, H.-J.; Olesen, L. Detection of drinking water contamination by an optical real-time bacteria sensor. *H2Open Journal* **2018**, *1* (2), 160−168.
(43) Huber, C.; Klimant, I.; Krause, C.; Werner, T.; Wolfbeis, O. S. Nitrate-selective optical sensor applying a lipophilic fluorescent potential-sensitive dye. *Analytica chimica acta* **2001**, *449* (1−2), 81−93.
(44) Zheng, Z.; Yu, H.; Geng, W.-C.; Hu, X.-Y.; Wang, Y.-Y.; Li, Z.; Wang, Y.; Guo, D.-S. Guanidinocalix [5] arene for sensitive fluorescence detection and magnetic removal of perfluorinated pollutants. *Nat. Commun.* **2019**, *10* (1), 5762.
(45) Langer, J.; Jimenez de Aberasturi, D.; Aizpurua, J.; Alvarez-Puebla, R. A.; Auguie, B.; Baumberg, J. J.; Bazan, G. C.; Bell, S. E. J.; Boisen, A.; Brolo, A. G.; Choo, J.; Cialla-May, D.; Deckert, V.; Fabris, L.; Faulds, K.; Garcia de Abajo, F. J.; Goodacre, R.; Graham, D.; Haes, A. J.; Haynes, C. L.; Huck, C.; Itoh, T.; Kall, M.; Kneipp, J.; Kotov, N. A.; Kuang, H.; Le Ru, E. C.; Lee, H. K.; Li, J. F.; Ling, X. Y.; Maier, S. A.; Mayerhofer, T.; Moskovits, M.; Murakoshi, K.; Nam, J. M.; Nie, S.; Ozaki, Y.; Pastoriza-Santos, I.; Perez-Juste, J.; Popp, J.; Pucci, A.; Reich, S.; Ren, B.; Schatz, G. C.; Shegai, T.; Schlucker, S.; Tay, L. L.; Thomas, K. G.; Tian, Z. Q.; Van Duyne, R. P.; Vo-Dinh, T.; Wang, Y.; Willets, K. A.; Xu, C.; Xu, H.; Xu, Y.; Yamamoto, Y. S.; Zhao, B.; Liz-Marzan, L. M. Present and Future of Surface-Enhanced Raman Scattering. *ACS Nano* **2020**, *14* (1), 28−117.
(46) Cai, S.; Cho, S. W.; Wei, H. Rapid Prescreening of Trace Imidacloprid in Drinking Water via Concentration-Dependent Surface-Enhanced Raman Spectroscopic Patterns. *ACS ES&T Engineering* **2023**, *3*, 1875.
(47) Rule, K. L.; Vikesland, P. J. Surface-enhanced resonance Raman spectroscopy for the rapid detection of Cryptosporidium parvum and Giardia lamblia. *Environ. Sci. Technol.* **2009**, *43* (4), 1147−1152.
(48) Cho, S. W.; Wei, H. Surface-enhanced Raman spectroscopy for emerging contaminant analysis in drinking water. *Frontiers of Environmental Science & Engineering* **2023**, *17* (5), 57.
(49) Liu, S.; Chen, Y.; Wang, Y.; Zhao, G. Group-targeting detection of total steroid estrogen using surface-enhanced Raman spectroscopy. *Analytical chemistry* **2019**, *91* (12), 7639−7647.
(50) Sivaranjanee, R.; Senthil Kumar, P.; Saravanan, R.; Govarthanan, M. Electrochemical sensing system for the analysis of emerging contaminants in aquatic environment: A review. *Chemosphere* **2022**, *294*, 133779.
(51) Wang, G.; Zhang, S.; Wu, Q.; Zhu, J.; Chen, S.; Lei, Y.; Li, Y.; Yi, H.; Chen, L.; Shi, Z. Q.; Xiao, Y. Simultaneous detection of acetaminophen, catechol and hydroquinone using a graphene-assisted electrochemical sensor. *RSC Adv.* **2022**, *12* (37), 23762−23768.
(52) Narouei, F. H.; Livernois, L.; Andreescu, D.; Andreescu, S. Highly sensitive mercury detection using electroactive gold-decorated polymer nanofibers. *Sens. Actuators, B* **2021**, *329*, 129267.

(53) Azzouz, A.; Hejji, L.; Kumar, V.; Kim, K. H. Nanomaterials-based aptasensors: An efficient detection tool for heavy-metal and metalloid ions in environmental and biological samples. *Environ. Res.* **2023**, *238* (Pt 1), 117170.
(54) Berkal, M. A.; Nardin, C. Pesticide biosensors: trends and progresses. *Anal Bioanal Chem.* **2023**, *415* (24), 5899−5924.
(55) Kadam, U. S.; Hong, J. C. Recent advances in aptameric biosensors designed to detect toxic contaminants from food, water, human fluids, and the environment. *Trends in Environmental Analytical Chemistry* **2022**, *36*, No. e00184.
(56) Warner, J.; Andreescu, S. An acetylcholinesterase (AChE) biosensor with enhanced solvent resistance based on chitosan for the detection of pesticides. *Talanta* **2016**, *146*, 279−284.
(57) Länge, K. Bulk and surface acoustic wave sensor arrays for multi-analyte detection: A review. *Sensors* **2019**, *19* (24), 5382.
(58) Tang, X.; Wang, P.-Y.; Buchter, G. Ion-selective electrodes for detection of lead (II) in drinking water: A mini-review. *Environments* **2018**, *5* (9), 95.
(59) Herrero, E. J.; Troudt, B. K.; Buhlmann, P. The Effect of Paper on the Detection Limit of Paper-Based Potentiometric Chloride Sensors. *Anal. Chem.* **2022**, *94* (43), 14898−14905.
(60) Ruecha, N.; Chailapakul, O.; Suzuki, K.; Citterio, D. Fully Inkjet-Printed Paper-Based Potentiometric Ion-Sensing Devices. *Anal. Chem.* **2017**, *89* (19), 10608−10616.
(61) Ding, R.; Krikstolaityte, V.; Lisak, G. Inorganic Salt Modified Paper Substrates Utilized in Paper Based Microfluidic Sampling for Potentiometric Determination of Heavy Metals. *Sens. Actuators, B* **2019**, *290*, 347−356.
(62) Jaywant, S. A.; Arif, K. M. A comprehensive review of microfluidic water quality monitoring sensors. *Sensors* **2019**, *19* (21), 4781.
(63) Pol, R.; Céspedes, F.; Gabriel, D.; Baeza, M. Microfluidic lab-on-a-chip platforms for environmental monitoring. *TrAC Trends in Analytical Chemistry* **2017**, *95*, 62−68.
(64) Sagan, V.; Peterson, K. T.; Maimaitijiang, M.; Sidike, P.; Sloan, J.; Greeling, B. A.; Maalouf, S.; Adams, C. Monitoring inland water quality using remote sensing: Potential and limitations of spectral indices, bio-optical simulations, machine learning, and cloud computing. *Earth-Science Reviews* **2020**, *205*, 103187.
(65) Yang, K.; Peretz-Soroka, H.; Liu, Y.; Lin, F. Novel developments in mobile sensing based on the integration of microfluidic devices and smartphones. *Lab Chip* **2016**, *16* (6), 943−958.
(66) Budd, J.; Miller, B. S.; Weckman, N. E.; Cherkaoui, D.; Huang, D.; Decruz, A. T.; Fongwen, N.; Han, G.-R.; Broto, M.; Estcourt, C. S.; et al. Lateral flow test engineering and lessons learned from COVID-19. *Nature Reviews Bioengineering* **2023**, *1*, 13−31.
(67) Wang, Z.; Zhao, J.; Xu, X.; Guo, L.; Xu, L.; Sun, M.; Hu, S.; Kuang, H.; Xu, C.; Li, A. An Overview for the Nanoparticles-Based Quantitative Lateral Flow Assay. *Small Methods* **2022**, *6* (1), 2101143.
(68) Martinez Paz, E. F.; Tobias, M.; Escobar, E.; Raskin, L.; Roberts, E. F. S.; Wigginton, K. R.; Kerkez, B. Wireless Sensors for Measuring Drinking Water Quality in Building Plumbing: Deployments and Insights from Continuous and Intermittent Water Supply Systems. *ACS EST Eng.* **2022**, *2* (3), 423−433.
(69) Chen, J.; Chen, S.; Fu, R.; Li, D.; Jiang, H.; Wang, C.; Peng, Y.; Jia, K.; Hicks, B. J. Remote Sensing Big Data for Water Environment Monitoring: Current Status, Challenges, and Future Prospects. *Earth's Future* **2022**, *10* (2), No. e2021EF002289.
(70) Xu, K.; Chen, Q.; Zhao, Y.; Ge, C.; Lin, S.; Liao, J. Cost-effective, wireless, and portable smartphone-based electrochemical system for on-site monitoring and spatial mapping of the nitrite contamination in water. *Sens. Actuators, B* **2020**, *319*, 128221.
(71) Wei, Q.; Nagi, R.; Sadeghi, K.; Feng, S.; Yan, E.; Ki, S. J.; Caire, R.; Tseng, D.; Ozcan, A. Detection and spatial mapping of mercury contamination in water samples using a smart-phone. *ACS Nano* **2014**, *8* (2), 1121−1129.
(72) Menger, R. F.; Funk, E.; Henry, C. S.; Borch, T. Sensors for detecting per-and polyfluoroalkyl substances (PFAS): A critical review of development challenges, current sensors, and commercialization obstacles. *Chemical Engineering Journal* **2021**, *417*, 129133.
(73) Boulart, C.; Connelly, D.; Mowlem, M. Sensors and technologies for in situ dissolved methane measurements and their evaluation using Technology Readiness Levels. *TrAC Trends in Analytical Chemistry* **2010**, *29* (2), 186−195.
(74) Taverniers, I.; De Loose, M.; Van Bockstaele, E. Trends in quality in the analytical laboratory. II. Analytical method validation and quality assurance. *TrAC Trends in Analytical Chemistry* **2004**, *23* (8), 535−552.
(75) Gustavo Gonzalez, A.; Angeles Herrador, M. A practical guide to analytical method validation, including measurement uncertainty and accuracy profiles. *TrAC Trends in Analytical Chemistry* **2007**, *26* (3), 227−238.
(76) Markovic, S.; Bagherzadeh, M. How does breadth of external stakeholder co-creation influence innovation performance? Analyzing the mediating roles of knowledge sharing and product innovation. *Journal of Business Research* **2018**, *88*, 173−186.
(77) Loureiro, S. M. C.; Romero, J.; Bilro, R. G. Stakeholder engagement in co-creation processes for innovation: A systematic literature review and case study. *Journal of Business Research* **2020**, *119*, 388−409.
(78) Willner, M. R.; Vikesland, P. J. Nanomaterial enabled sensors for environmental contaminants. *J. Nanobiotechnol.* **2018**, *16*, 95.
(79) Abu Hatab, N. A.; Oran, J. M.; Sepaniak, M. J. Surface-enhanced Raman spectroscopy substrates created via electron beam lithography and nanotransfer printing. *ACS Nano* **2008**, *2* (2), 377−385.
(80) Willner, M. R.; Vikesland, P. J. Nanomaterial enabled sensors for environmental contaminants. *J. Nanobiotechnology* **2018**, *16* (1), 95.
(81) Hairom, N. H. H.; Soon, C. F.; Mohamed, R. M. S. R.; Morsin, M.; Zainal, N.; Nayan, N.; Zulkifli, C. Z.; Harun, N. H. A review of nanotechnological applications to detect and control surface water pollution. *Environmental Technology & Innovation* **2021**, *24*, 102032.
(82) Taverniers, I.; De Loose, M.; Van Bockstaele, E. Trends in quality in the analytical laboratory. I. Traceability and measurement uncertainty of analytical results. *TrAC Trends in Analytical Chemistry* **2004**, *23* (7), 480−490.
(83) Ligler, F. S.; Gooding, J. J. Lighting Up Biosensors: Now and the Decade To Come. *Anal. Chem.* **2019**, *91* (14), 8732−8738.
(84) Alkasir, R. S.; Rossner, A.; Andreescu, S. Portable Colorimetric Paper-Based Biosensing Device for the Assessment of Bisphenol A in Indoor Dust. *Environ. Sci. Technol.* **2015**, *49* (16), 9889−9897.
(85) Alam, A. U.; Deen, M. J. Bisphenol A Electrochemical Sensor Using Graphene Oxide and beta-Cyclodextrin-Functionalized Multi-Walled Carbon Nanotubes. *Anal. Chem.* **2020**, *92* (7), 5532−5539.
(86) Rehman, A. U.; Crimi, M.; Andreescu, S. Current and Emerging Analytical Techniques for the Determination of PFAS in Environmental Samples. *Trends in Environmental Analytical Chemistry* **2023**, *37*, e00198.
(87) Menger, R. F.; Beck, J. J.; Borch, T.; Henry, C. S. Colorimetric Paper-Based Analytical Device for Perfluorooctanesulfonate Detection. *Acs Es&T Water* **2022**, *2* (4), 565−572.
(88) Takayose, M.; Nishimoto, K.; Matsui, J. A fluorous synthetic receptor that recognizes perfluorooctanoic acid (PFOA) via fluorous interaction obtained by molecular imprinting. *Analyst* **2012**, *137* (12), 2762−2765.
(89) Karimian, N.; Stortini, A. M.; Moretto, L. M.; Costantino, C.; Bogialli, S.; Ugo, P. Electrochemosensor for Trace Analysis of Perfluorooctanesulfonate in Water Based on a Molecularly Imprinted Poly(o-phenylenediamine) Polymer. *ACS Sensors* **2018**, *3* (7), 1291−1298.
(90) Kazemi, R.; Potts, E. I.; Dick, J. E. Quantifying Interferent Effects on Molecularly Imprinted Polymer Sensors for Per- and Polyfluoroalkyl Substances (PFAS). *Analytical chemistry* **2020**, *92* (15), 10597−10605.
(91) Yang, T.; Duncan, T. V. Challenges and potential solutions for nanosensors intended for use with foods. *Nature Nanotechnol.* **2021**, *16* (3), 251−265.
(92) Smith, S.; Nagel, D. J. Nanotechnology-Enabled Sensors Possibilities, Realities, and Applications. In *Sensor Technology Handbook*; Wilson, J. S.; Elsevier, 2005; Chapter 14.

(93) Chapman, J.; Truong, V. K.; Elbourne, A.; Gangadoo, S.; Cheeseman, S.; Rajapaksha, P.; Latham, K.; Crawford, R. J.; Cozzolino, D. Combining Chemometrics and Sensors: Toward New Applications in Monitoring and Environmental Analysis. *Chem. Rev.* **2020**, *120* (13), 6048−6069.

(94) Meyer, D. D.; Hill, C.; McCain, K.; Smith, J. A.; Bessong, P. O.; Rogawski McQuade, E. T.; Wright, N. C. Embedding Usage Sensors in Point-of-Use Water Treatment Devices: Sensor Design and Application in Limpopo, South Africa. *Environ. Sci. Technol.* **2021**, *55* (13), 8955−8964.

(95) Shyu, H. Y.; Castro, C. J.; Bair, R. A.; Lu, Q.; Yeh, D. H. Development of a Soft Sensor Using Machine Learning Algorithms for Predicting the Water Quality of an Onsite Wastewater Treatment System. *ACS Environ. Au* **2023**, *3* (5), 308−318.

(96) Lin, P. H.; Li, B. R. Antifouling strategies in advanced electrochemical sensors and biosensors. *Analyst* **2020**, *145* (4), 1110−1120.

(97) Fornasaro, S.; Alsamad, F.; Baia, M.; Batista de Carvalho, L. A. E.; Beleites, C.; Byrne, H. J.; Chiado, A.; Chis, M.; Chisanga, M.; Daniel, A.; Dybas, J.; Eppe, G.; Falgayrac, G.; Faulds, K.; Gebavi, H.; Giorgis, F.; Goodacre, R.; Graham, D.; La Manna, P.; Laing, S.; Litti, L.; Lyng, F. M.; Malek, K.; Malherbe, C.; Marques, M. P. M.; Meneghetti, M.; Mitri, E.; Mohacek-Grosev, V.; Morasso, C.; Muhamadali, H.; Musto, P.; Novara, C.; Pannico, M.; Penel, G.; Piot, O.; Rindzevicius, T.; Rusu, E. A.; Schmidt, M. S.; Sergo, V.; Sockalingum, G. D.; Untereiner, V.; Vanna, R.; Wiercigroch, E.; Bonifacio, A. Surface Enhanced Raman Spectroscopy for Quantitative Analysis: Results of a Large-Scale European Multi-Instrument Interlaboratory Study. *Anal. Chem.* **2020**, *92* (5), 4053−4064.

(98) De Frond, H.; Thornton Hampton, L.; Kotar, S.; Gesulga, K.; Matuch, C.; Lao, W.; Weisberg, S. B.; Wong, C. S.; Rochman, C. M. Monitoring microplastics in drinking water: An interlaboratory study to inform effective methods for quantifying and characterizing microplastics. *Chemosphere* **2022**, *298*, 134282.

(99) *Appendix F: Guidelines for Standard Method Performance Requirements*. AOAC International, 2016. https://www.aoac.org/wp-content/uploads/2019/08/app_f.pdf.

(100) Ross, G. M. S.; Zhao, Y.; Bosman, A.J.; Geballa-Koukoula, A.; Zhou, H.; Elliott, C. T.; Nielen, M. W. F.; Rafferty, K.; Salentijn, G. I. Best practices and current implementation of emerging smartphone-based (bio)sensors - Part 1: data handling and ethics. *TrAC, Trends Anal. Chem.* **2023**, *158*, 116863.

(101) Geballa-Koukoula, A.; Ross, G. M. S.; Bosman, A. J.; Zhao, Y.; Zhou, H.; Nielen, M. W. F.; Rafferty, K.; Elliott, C.T.; Salentijn, G. I. Best practices and current implementation of emerging smartphone-based (bio)sensors- Part 2: Development, validation, and social impact. *TrAC Trends in Analytical Chemistry* **2023**, *161*, 116986.

(102) Miller, M.; Kisiel, A.; Cembrowska-Lech, D.; Durlik, I.; Miller, T. IoT in Water Quality Monitoring—Are We Really Here? *Sensors* **2023**, *23* (2), 960.

(103) Meyer, A. M.; Klein, C.; Funfrocken, E.; Kautenburger, R.; Beck, H. P. Real-time monitoring of water quality to identify pollution pathways in small and middle scale rivers. *Sci. Total Environ.* **2019**, *651* (Pt 2), 2323−2333.

(104) Wright, M.; Hmieleski, K. M.; Siegel, D. S.; Ensley, M. D. The Role of Human Capital in Technological Entrepreneurship. *Entrepreneurship Theory and Practice* **2007**, *31* (6), 791−806.

(105) Technology, Innovation and Partnerships. U.S. National Science Foundation, 2023. https://new.nsf.gov/tip/latest.

(106) NSF's Innovation Corps (I-Corps). U.S. National Science Foundation, 2023. https://new.nsf.gov/funding/initiatives/i-corps.

https://doi.org/10.1021/acs.est.3c09889
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