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Full Length Research Article

FROM STATIC SAMPLING TO DYNAMIC INSIGHTS: THE FUTURE OF WATER QUALITY MONITORING WITH SENSORS, IOT, AND DRONES

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ABSTRACT
Traditional water quality monitoring systems face significant limitations, including labour-intensive processes, high costs, and inadequate real-time data acquisition, which lead to gaps in detecting rapid changes and contamination events. Recent advancements in sensor technology, the Internet of Things (IoT), and drones have introduced innovative solutions to address these challenges. High-sensitivity sensors, such as nano-sensors and bio-sensors, detect pollutants at trace levels. At the same time, multi-parameter platforms offer detailed insights into key indicators like turbidity, dissolved oxygen, and microbial contamination. IoT systems integrate these sensors into interconnected networks, leveraging cloud computing and artificial intelligence for real-time analysis, decision-making, and efficient monitoring. Drones with advanced sensors, including multispectral and hyperspectral cameras, provide high-resolution, spatially comprehensive data, overcoming accessibility challenges in remote and hazardous areas. These technologies collectively enable holistic and adaptive water quality monitoring frameworks. However, challenges such as high implementation costs, cybersecurity risks, and the lack of standardized protocols persist. This review critically evaluates the state of sensor technologies, IoT applications, and drone systems, highlighting their transformative potential. By addressing existing barriers and fostering interdisciplinary collaboration, these advancements pave the way for improved water resource management, environmental sustainability, and resilience against global water quality crises.

Keywords: Water Quality Monitoring, Sensor Technology, Internet of Things (IoT), Drone Applications, Sustainable Water Management, Artificial Intelligence (AI)

INTRODUCTION
Water quality is an essential factor in maintaining the health of aquatic ecosystems, supporting human life, and sustaining economic and agricultural activities. However, the increasing global concerns regarding pollution, climate change, and industrialization have placed unprecedented pressures on water resources, leading to contamination and degradation. Effective and timely water quality monitoring is crucial for safeguarding public health and managing water resources sustainably. Traditional water quality monitoring methods, such as manual sampling and laboratory analysis, have significant limitations. These methods are labour-intensive, expensive, and cannot provide real-time data, critical for detecting rapid environmental changes or contamination events (Park et al., 2020; Nishan et al., 2024). As a result, there is an urgent need for more innovative and efficient water quality monitoring solutions.

In recent years, advancements in sensor technology, the Internet of Things (IoT), and drone systems have significantly transformed the landscape of water quality monitoring. Sensor technologies, such as nano-sensors, bio-sensors, and multi-parameter systems, are capable of detecting pollutants at trace levels with higher precision and sensitivity (Xavier et al., 2022; Martinez Paz et al., 2022; Long, 2024; He et al., 2024). These sensors, when integrated into IoT-based platforms, enable the continuous, real-time monitoring of key water quality indicators such as temperature, pH, turbidity, dissolved oxygen, and microbial contamination (Nishan, 2024; Liu et al., 2020). Furthermore, the integration of artificial intelligence (AI) into IoT systems has enhanced decision-making capabilities, enabling real-time anomaly detection, trend analysis, and predictive modeling (Primantara et al., 2021; Liu et al., 2020).

Meanwhile, the application of drones in water quality monitoring is an emerging and promising innovation. Drones equipped with advanced sensor payloads, such as multispectral and hyperspectral cameras, enable high-resolution and spatially comprehensive data collection over large or inaccessible water bodies (Parjuangan et al., 2019; Pujar, 2019). This capability is particularly valuable for monitoring remote areas or bodies of water that are difficult or unsafe to reach using traditional methods. While these technological advancements offer significant benefits, challenges remain. The high implementation costs, cybersecurity risks, and lack of standardized protocols are notable barriers that need to be addressed for wide-scale adoption (Zhou et al., 2017; Ferreira et al., 2021).

The aim of this review is to explore the state of sensor technologies, IoT-based systems, and drone applications for water quality monitoring. It critically examines the current capabilities of these technologies, discusses their limitations, and identifies future opportunities for integrating these systems into a comprehensive and adaptive framework for water resource management. This review also seeks to highlight the research gaps in the existing literature, which currently lacks sufficient data on the scalability and interoperability of these technologies across different geographical and socio-economic settings.

The following research questions guide this review:

(i) What are the recent innovations in sensor technologies for real-time water quality monitoring, and how do they overcome traditional method limitations?

(ii) How does IoT improve integration, scalability, and real-time data analysis in water quality monitoring systems, and what challenges arise?
(iii) How do drones with advanced sensors enhance water quality monitoring, and what practical limitations affect their use?
(iv) What is the potential of combining sensors, IoT, and drones to develop adaptive and sustainable water quality monitoring systems?

MATERIALS AND METHODS
This review article systematically analyzes advancements in sensor technologies, IoT systems, and drones for water quality monitoring. A comprehensive literature survey was conducted using the Scopus database to gather peer-reviewed articles. Key search terms included “water quality monitoring,” “sensor,” “IoT,” and “drone systems.” The inclusion criteria focused on studies that explored real-time water quality monitoring using advanced sensors, IoT-based platforms, and drones, while articles unrelated to water quality or lacking methodological rigor were excluded. Data were extracted on the technological specifics, application areas, and limitations of the systems discussed.
The reviewed studies were synthesized thematically to explore innovations in sensor technologies like nano-sensors and bio-sensors, IoT platforms for real-time data transmission, and drone systems for comprehensive monitoring of inaccessible water bodies. The analysis also identified key challenges such as high implementation costs, cybersecurity risks, and the lack of standardized protocols for system integration.

Sensor Technology
Sensor technology has undergone remarkable advancements over the past two decades, transitioning from simple, single-parameter tools to advanced multi-parameter systems for water quality monitoring (Hall et al., 2007). Early devices measured parameters like temperature, pH, and dissolved oxygen but required manual operation, limiting scalability and real-time use (Kruse, 2018). Between 2011 and 2015, breakthroughs in microelectronics, materials science, and wireless communication introduced sensitive optical, chemical, and biological sensors capable of detecting turbidity, nutrients, heavy metals, and microbial contaminants (Alam et al., 2021). Multi-sensor platforms integrating IoT systems and remote sensing technologies emerged, offering a holistic approach to water quality monitoring (Wu et al., 2020; Cao et al., 2020). From 2016 onward, advancements in nano-sensors, bio-sensors, and real-time monitoring systems revolutionized the field, enabling trace detection of contaminants like pharmaceuticals and microplastics while leveraging AI, IoT, and blockchain for large-scale, interconnected water management systems (Zhou et al., 2017; Pasika & Gandla, 2020; Ferreira et al., 2021; Zhang et al., 2023).
To systematically examine these developments, the Scopus database was utilized due to its extensive coverage of high-quality, peer-reviewed literature across relevant disciplines. Using the search string *(TITLE ("water quality monitoring" OR "water quality management") AND TITLE ("sensor"))*, the query retrieved publications from 2000 to 2025. The results (Figure 1) reveal a consistent increase in research outputs, reflecting the evolution of sensor technology and its critical role in addressing global water quality challenges. Notably, there is a surge in publications after 2013, correlating with advancements in IoT-enabled multi-sensor platforms and nano-sensor technologies. These findings underscore the growing academic and practical interest in sensor-based solutions for sustainable water resource management, driven by technological innovations and increasing environmental awareness.

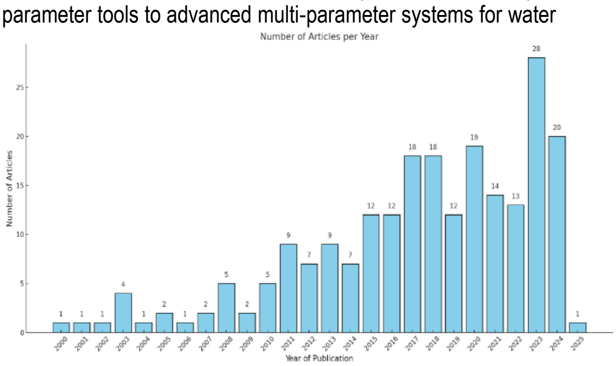

Figure 1 Trend of Publications on Sensor-based Water Quality Monitoring (2000–2024)

Classification of Sensors for Water Quality Monitoring: Applications and Limitations
Sensor technologies for water quality monitoring are diverse, encompassing optical, chemical, physical, and biological sensors. Each type is specifically designed to measure distinct water quality parameters and address different environmental monitoring needs.
Optical sensors utilize light-based techniques, such as absorption, fluorescence, and spectroscopy, to measure parameters like turbidity, colour, and organic compounds (e.g., chlorophyll-a). These sensors are particularly effective for the real-time detection of algal blooms and organic pollution in water bodies. Advanced tools, including fiber optic sensors and Surface Plasmon Resonance (SPR) sensors, allow for remote sensing and molecular-level detection of contaminants. However, these technologies face challenges, including biofouling and the need for frequent calibration, which can affect their long-term reliability (Kim et al., 2011).
Chemical sensors, which rely on electrochemical reactions, are crucial for detecting ions and pollutants in water. For example, potentiometric sensors (e.g., pH meters and ion-selective electrodes) are widely used due to their simplicity and ease of application. Amperometric sensors, on the other hand, provide real-time measurements of critical parameters such as dissolved oxygen and chlorine levels, which are essential for water quality monitoring and wastewater treatment (Chen & Chatterjee, 2013). Further advancements, such as conductivity sensors and ChemFETs, have enhanced the precision of ionic content measurements, making them invaluable for assessing water salinity and chemical pollutants.
Physical sensors measure parameters like temperature, pressure, and flow rate, using technologies such as thermistors, piezoresistive sensors, and ultrasonic flowmeters. These sensors are used in various applications, including flood risk assessment and ecosystem monitoring. Despite their high precision, physical sensors face challenges related to sediment

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interference and environmental variability, which can reduce their effectiveness in dynamic aquatic environments (Campbell & Hyslop, 2023).

Biological sensors, including enzyme- and antibody-based biosensors, are specialized in detecting pathogens and measuring biochemical oxygen demand (BOD) with high specificity. Recent advancements in DNA/RNA-based biosensors and whole-cell biosensors have significantly improved the sensitivity and miniaturization of these sensors. The integration of nanomaterials, such as graphene, has further enhanced their performance. However, maintaining biological stability under variable environmental conditions remains a significant challenge, which limits the long-term applicability of biological sensors in real-world monitoring scenarios (Raymundo-Pereira et al., 2018; Tharani et al., 2022).

Table 1 provides a detailed overview of the different types of sensors, highlighting their applications, technological advancements, and the challenges they face in water quality monitoring.

Table 1 Sensor Types for Water Quality Monitoring: Applications, Technological Advances, and Challenges

Sensor Type	Parameter Measured	Description	Example Applications	Technological Advances	Challenges	References
Optical Sensors	Turbidity	Measure cloudiness or haziness caused by suspended particles. Indicate water clarity and pollution levels.	Drinking water treatment, wastewater treatment, and environmental monitoring.	Surface Plasmon Resonance (SPR) sensors for molecular-level detection.	Biofouling, periodic calibration, sensitivity to environmental variations.	(Sharar et al., 2023)
	Chlorophyll-a, Dissolved Organic Matter	Detect organic compounds using fluorescence-based techniques.	Environmental monitoring, aquaculture.	Advanced fluorescence-based sensors for dynamic environmental conditions.	Decreased performance in highly turbid waters.	(Leal-Junior et al., 2022)
Physical Sensors	Temperature	Measure water temperature, a critical factor for aquatic ecosystems and industrial processes.	Environmental monitoring, industrial processes, and aquaculture.	High-resolution thermistors and thermocouples; advanced ecosystem metabolism studies.	Accuracy is influenced by environmental fluctuations and periodic recalibration.	(Leal-Junior et al., 2022)
	Pressure	Measure hydrostatic pressure, indicating water depth. Essential for hydrology and reservoir management.	Flood risk assessment, irrigation, industrial applications.	Piezoresistive and capacitive sensors for precise depth measurements.	Susceptibility to sediment loads and biofouling.	(Leal-Junior et al., 2022)
	Flow Rate	Monitor water flow using ultrasonic and Electromagnetic flowmeters.	Irrigation systems, industrial water management.	Advanced transit-time Technologies for precise flow measurement.	Performance is affected by Sediment concentration and flow velocity variations.	(Han et al. 2024)
	Water Level	Measure water levels in reservoirs and rivers using ultrasonic and radar sensors.	Reservoir management, environmental monitoring, flood risk assessment.	Integration with IoT for real-time monitoring.	Decreased accuracy in highly dynamic or sediment-rich environments.	walpa.org
Chemical Sensors	pH	Measure the acidity or alkalinity of water. Affect the solubility of Chemicals and microbial growth.	Wastewater treatment, aquaculture, and drinking water treatment.	ISFET-based pH meters for enhanced Adaptability in field conditions.	Cross-sensitivity in complex Matrices, drift over time.	(Zainurin et al., 2022)

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	Dissolved Oxygen	Measure oxygen concentration in water, a critical parameter for aquatic ecosystems and industrial applications.	Environmental monitoring, aquaculture, wastewater treatment.	Amperometric sensors with high sensitivity for real-time monitoring.	Decreased accuracy in low-oxygen environments.	(Zainurin et al., 2022)
	Residual Chlorine	Detect chlorine levels after disinfection to ensure water safety.	Drinking water treatment, wastewater treatment.	Miniaturized sensors for portable applications.	Sensitivity to chemical interferences.	Zainurin et al., 2022)
	Total Organic Carbon (TOC)	Quantify organic carbon in water as an indicator of pollution.	Environmental monitoring, pharmaceutical industries, and drinking water quality control.	TOC analyzers with integrated data processing for real-time monitoring.	Maintenance requirements for continuous operation.	Zainurin et al., 2022)
Biological Sensors	Biochemical Oxygen Demand (BOD)	Measure oxygen consumed by microorganisms, indicating organic pollution levels.	Wastewater treatment, environmental monitoring.	Enzyme-based biosensors for real-time analysis.	Sensitivity to environmental conditions.	(Zainurin et al., 2022)
	Cell-based Biosensors	Detect pharmaceuticals, pesticides, and other pollutants using living cells with high sensitivity and selectivity.	Environmental monitoring, water quality assessment.	Integration with nanomaterials for improved performance; microfluidic platforms for miniaturization.	Stability of living cells, non-specific adsorption.	(Zainurin et al., 2022)

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Multi-Sensor Platforms and Their Applications
Modern water quality monitoring has advanced significantly with the development of multi-sensor platforms that integrate optical, chemical, biological, and physical sensors, offering a dynamic and comprehensive understanding of water systems. These platforms enable real-time, multi-parameter monitoring through modular arrays tailored to specific needs, facilitating unified data collection and processing (Shi et al., 2024). Synchronizing data from diverse sensor types provides a holistic perspective that is critical for effective water management and decision-making. (Xavier et al., 2022; Eggimann et al., 2017). Smart calibration mechanisms and sensor cross-validation enhance data accuracy and reliability, minimizing manual intervention and enabling timely responses to changes in water quality. These features are particularly valuable in wastewater treatment facilities, where continuous monitoring of nutrient levels, chemical concentrations, and effluent quality optimizes process control and ensures compliance with environmental regulations (Coughlan et al., 2023; Yang et al., 2024).
Multi-sensor platforms (Figure 2) typically include a Sample and Cleaning Module for automated water sampling and cleaning, a water quality monitoring module with specialized electrodes, and a Control Circuit Module that processes and transmits data to a Wireless Transmitter Module for cloud-based analysis (Yu et al., 2019). These systems are widely applied in drinking water quality monitoring, tracking parameters like turbidity, pH, and microbial contamination to protect public health (Wang et al., 2018). They are equally critical for environmental monitoring in natural water bodies, providing insights into long-term ecosystem health (Alzahrani et al., 2023). Although the integration and maintenance of these platforms require significant investment and technical expertise (Kinar & Brinkmann, 2021), their ability to enhance monitoring and enable proactive water management solidifies their role as essential tools for modern water quality analysis (Yang, 2024; Eggimann et al., 2017).

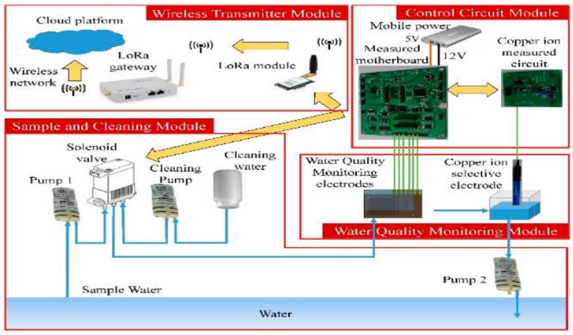

Figure 2: A block diagram of the multi-sensor platform for water quality monitoring (Yu et al., 2019)

Emerging and Advanced Sensor Technologies
Nano-sensors have revolutionized water quality monitoring with their exceptional sensitivity and specificity, enabling the detection of contaminants at trace levels. Utilizing advanced materials like carbon nanotubes and quantum dots, these sensors can identify pollutants such as heavy metals, pharmaceuticals, and microplastics (Hou et al., 2013; Garcia et al., 2012). Their unique properties, including a high surface-area-to-volume ratio and distinct electronic characteristics, facilitate ultra-sensitive detection capabilities. Nanostructured surfaces enhance signal amplification while minimizing noise, improving measurement reliability (Shang et al., 2017). Notably, plasmonic nanosensors extend these capabilities to molecular-level detection, enabling innovative applications in early warning systems and advanced monitoring of water treatment processes (Hong et al., 2019).
Nano-sensors, advanced bio-sensors, and smart sensors are transforming water quality assessments. Innovations such as CRISPR-based and aptamer-based detection systems offer high specificity for identifying pathogens, toxins, and genetic markers, while lab-on-a-chip devices and microfluidic platforms improve portability and field usability. Smart sensors integrate intelligence and connectivity features like self-calibration and IoT-enabled networks, facilitating real-time monitoring and machine learning-driven data analysis in dynamic environments (Bharani Baanu & Jinesh Babu, 2022). Efforts to enhance sensor performance focus on signal amplification, noise reduction, and multi-point calibration to improve sensitivity and accuracy (Shang et al., 2017; Gautam et al., 2020). Additionally, advancements in durability, such as anti-fouling coatings and self-cleaning mechanisms, ensure reliable operation in harsh conditions (Cedillo-Alcantar et al., 2019). Together, these innovations bolster the effectiveness of water quality monitoring systems, enabling proactive responses to contamination and advancing sustainable water management practices (Rakers et al., 2018).

IoT for Water Quality Monitoring
The IoT has revolutionized various sectors, with water quality monitoring standing out as one of its transformative applications. IoT systems integrate sensors, communication networks, cloud computing, and data analytics to enable real-time, continuous monitoring and management of water resources (Ighalo et al., 2021). This innovation overcomes the limitations of traditional methods, such as manual sampling and laboratory analysis, by providing automated, efficient, and effective solutions ; Jamal et al., 2021). First conceptualized by Kevin Ashton in 1999 as a vision of interconnected devices, IoT now delivers actionable insights that optimize water resource management and enhance sustainability practices (Garrido-Momparler & Peris, 2022).
Modern IoT systems for water quality monitoring are structured on a multi-layered architecture to ensure seamless data flow, as shown inFigure 3. At the core is the Perception Layer, which uses sensors and actuators to capture critical water quality parameters like pH, turbidity, temperature, and dissolved oxygen (Sugiharto et al., 2023; Pattnaik et al., 2021). These data points are transmitted through the Network Layer, employing communication technologies such as LoRaWAN, NB-IoT, or Wi-Fi. Gateways aggregate this data and transfer it to the Data Processing Layer, where it is cleaned, aggregated, and analyzed locally or remotely on cloud platforms (Pattnaik et al., 2021; Shahra et al., 2024). Finally, the Application Layer delivers insights through dashboards, real-time alerts, and APIs, empowering stakeholders to make informed decisions (Vijayakumar & Ramya, 2015; Pattnaik et al., 2021). This structured, scalable architecture, illustrated in Figure 3, adapts to diverse water quality monitoring needs while ensuring flexibility and reliability.
The integration of IoT with cloud computing has further revolutionized water quality monitoring by enabling advanced data storage and processing capabilities. Cloud platforms support the massive datasets generated by IoT sensors, facilitating predictive maintenance models powered by machine learning algorithms (Shahra, 2024; Pattnaik et al., 2021). These models detect abnormalities and forecast potential failures in

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water systems, enabling proactive quality management. Additionally, Big Data analytics within IoT frameworks enhances decision-making by enabling trend analysis, anomaly detection, and resource optimization—key elements for sustainable water management (Jamal et al., 2024). This integration ensures real-time, scalable, and efficient solutions to global water quality challenges, showcasing the transformative potential of IoT in addressing environmental sustainability.

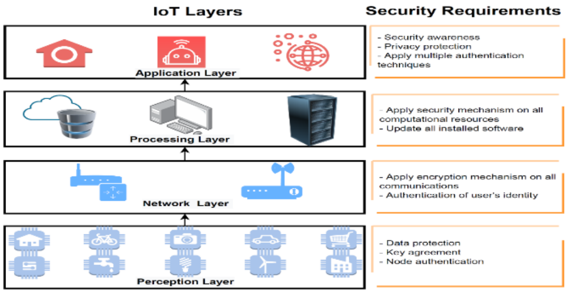

Figure 3: IoT Architecture (Alshahrani, 2021)

IoT Protocols and Data Analytics

Efficient data transmission within Internet of Things (IoT) systems hinges on the selection of robust communication protocols tailored to specific monitoring needs. Among these, LoRaWAN excels due to its low-power, long-range connectivity, making it ideal for remote water quality monitoring in areas with limited power sources. This ensures sustained operations without frequent battery replacements (Di Gennaro et al., 2019). Similarly, Narrowband IoT (NB-IoT), leveraging existing 4G and 5G networks, offers cost-effective and reliable data transfer, enhancing scalability for IoT-based water management applications (Shafique et al., 2020). For scenarios requiring higher data rates or shorter communication ranges, protocols such as Wi-Fi, Bluetooth, and Zigbee provide flexibility. The choice of protocol depends on factors like distance, power consumption, and cost, enabling IoT systems to address diverse operational requirements effectively (Skarga-Bandurova et al., 2020).

Beyond communication protocols, advanced data analytics is integral to IoT-based water quality monitoring, transforming raw sensor data into actionable insights. Machine learning algorithms identify trends, anomalies, and contamination events, allowing for timely interventions (Stojanovic & Chaudhary, 2023). Predictive models, utilizing historical data and environmental factors, forecast water quality trends and support proactive resource management (Radhakrishnan & Wu, 2018). These analytics optimize water usage, enhance leak detection, and ensure regulatory compliance. Cloud-based analytics further augment these capabilities, enabling real-time monitoring and swift responses to anomalies (Miry & Aramice, 2020). Together, tailored communication protocols and advanced analytics form the backbone of IoT systems, driving efficient and reliable water quality monitoring.

Applications, Benefits, and Challenges of IoT in Water Quality Monitoring

The implementation of IoT in water quality monitoring has revolutionized various sectors by enhancing efficiency, enabling real-time decision-making, and promoting sustainability. From municipal water supplies to aquaculture and smart water networks, IoT systems have demonstrated their ability to monitor critical parameters, ensure compliance with regulations, and optimize resource use. However, the adoption of IoT comes with challenges such as cybersecurity risks, high infrastructure costs, and data management complexities. Table 2 summarizes the key applications, benefits, and limitations of IoT in water quality monitoring, providing an overview of its transformative potential and associated challenges.

Table 2: Applications, Benefits, and Challenges of IoT in Water Quality Monitoring Systems

Applications	Benefits	Limitations/Challenges	References
Municipal Water Supply Monitoring	Ensures safe drinking water by monitoring critical parameters like chlorine levels and turbidity in real-time; facilitates compliance with regulatory standards.	Cybersecurity risks and data privacy concerns; high initial setup and maintenance costs.	(Ashtikar 2019; Zakaria & Michael 2017)
Industrial Wastewater Management	Tracks pH, dissolved oxygen, and chemical pollutants to minimize environmental pollution; enables compliance with discharge regulations and enhances sustainability.	Infrastructure costs for large-scale implementation; complexities in integrating diverse sensor technologies.	(Zakaria & Michael 2017; Salem et al. 2022)
Agriculture (Smart Irrigation)	Improves crop yield and conserves water by monitoring soil moisture, temperature, and humidity; promotes sustainable farming	Limited connectivity in remote areas; technical expertise required for system operation.	(Madushanki et al., 2019; Pantha & Koju, 2023; Jesi et al., 2022)

	practices.		
Aquaculture	Maintains optimal conditions for fish and shellfish by monitoring dissolved oxygen and temperature; enhances productivity and sustainability.	Power consumption in remote deployments; regular sensor calibration and maintenance.	(Kamienski et al., 2019; Ashtikar, 2019)
Environmental Monitoring	Tracks ecosystem health and pollution sources in natural water bodies; informs conservation strategies and supports regulatory compliance.	Challenges in managing and analyzing large datasets; cost-intensive infrastructure for long-term deployments.	Perumal et al. (2015)
Smart Water Networks	Facilitates leak detection, predictive maintenance, and efficient infrastructure management.	Integration complexities with existing infrastructure.	Kovalenko (2024)

Drones for Water Quality Monitoring
TheddroneDrone technology has revolutionized water quality monitoring, offering a cost-effective and efficient alternative to traditional methods. Unmanned aerial vehicles (UAVs) equipped with advanced sensors and imaging systems enable real-time data collection in challenging terrains and remote locations, significantly enhancing the accuracy and timeliness of assessments. These drones are particularly valuable in accessing hard-to-reach areas, such as remote lakes and rivers, where ground-based sampling would be labour-intensive and time-consuming. For instance, UAVs have proven effective in topo-bathymetric monitoring, providing critical insights into water bodies' physical and chemical properties (Erena et al., 2019). By streamlining data collection processes, drones facilitate the generation of comprehensive datasets, informing environmental management practices and improving decision-making efficiency (Park et al., 2020).
Technological advancements in drones have further enhanced their capabilities through the integration of sophisticated sensor networks and IoT methodologies. These interconnected systems allow for simultaneous monitoring of multiple water quality parameters, with real-time data transmission for immediate analysis (Olatinwo, 2023). This approach not only reduces costs compared to traditional monitoring methods but also increases accessibility for widespread environmental applications (Anifatul Faricha et al., 2020). Moreover, the application of machine learning algorithms to drone-collected data has introduced new opportunities for proactive environmental management. These algorithms analyze large datasets to identify patterns and predict changes in water quality, enabling precise and timely interventions (Y et al., 2024; Thai-Nghe et al., 2020).

Drone Types
Different types of drones cater to specific monitoring objectives, the nature of the water body, and the desired data resolution. The primary categories include fixed-wing drones, rotary-wing drones, and hybrid drones. Each type has unique capabilities suited to various monitoring scenarios, ranging from large-scale surveys to targeted sampling. Table 3 compares all three types of drones used for water quality monitoring.

Fixed-Wing Drones
Fixed-wing drones, resembling traditional airplanes, are distinguished by their ability to generate lift through their wings, enabling extended flight times, high-speed operations, and long-range capabilities. These attributes make them ideal for large-scale environmental monitoring tasks, such as surveying lakes, rivers, and coastal areas (Fernández-Guisuraga et al., 2018). Equipped with advanced imaging technologies like multispectral and hyperspectral cameras, fixed-wing drones efficiently capture comprehensive data on environmental parameters such as turbidity, chlorophyll levels, and temperature. Notable examples include the senseFly eBee X, which offers precision mapping and is equipped with versatile payload options for assessing vegetation health and water quality (Lee et al., 2016). Similarly, the JOUAV CW-25E (Figure 4), a fixed-wing vertical take-off and landing (VTOL) drone, excels in long-range missions, providing detailed mapping of wetlands and coastal ecosystems, making it invaluable for extensive environmental studies (Román et al., 2021; Rossi et al., 2020).
The integration of multispectral and hyperspectral imaging technologies enhances the utility of fixed-wing drones in environmental monitoring. These imaging systems enable the collection of detailed spectral data, facilitating the assessment of ecological metrics like vegetation health and marine macrophyte distribution (Vanegas et al., 2018). Studies highlight the effectiveness of UAV-mounted cameras in monitoring coastal vegetation and other critical ecological parameters. Additionally, these drones' real-time data acquisition capabilities are invaluable for environmental management, allowing timely and informed decision-making (Alevizos & Alexakis, 2022).

Figure 4: JOUAV CW-25E Drone

Rotary-Wing Drones
Rotary-wing drones, or multirotor drones (Figure 5), are highly manoeuvrable thanks to their vertical take-off and landing (VTOL) capabilities, allowing them to hover in place and navigate complex terrains (Song et al., 2017). These features make them particularly effective for close-up inspections and targeted water sampling in smaller, challenging environments such as ponds, reservoirs, and wetlands. Their agility enables them to access difficult or unsafe areas for traditional methods, facilitating water quality monitoring and ecosystem studies with greater precision and efficiency (Hanlon et al., 2022). Equipped with advanced water sampling mechanisms, rotary-wing drones can collect physical samples for laboratory analysis, providing critical data for assessing aquatic ecosystems. Some models are even designed to land on water, simplifying sample retrieval and drone recovery, which is especially useful in remote or hard-to-reach aquatic environments (Song et al., 2017). These capabilities enhance the frequency and volume of water sampling, improving the accuracy of environmental data collection.

Hybrid Drones
Hybrid drones represent a significant innovation in UAV technology, combining the long-range efficiency of fixed-wing designs with the precise VTOL capabilities of rotary-wing drones (Hu et al., 2024). This dual functionality enables hybrid drones to excel in applications requiring extensive coverage and detailed inspections, such as environmental monitoring and agricultural assessments (Alhammadi et al., 2022). Their versatility allows for seamless adaptation to varied terrains and monitoring needs, providing a flexible solution for complex operational requirements. A prime example is the TJ-FlyingFish (Figure 6), a hybrid drone capable of operating in both aerial and underwater environments. This ground breaking drone can transition effortlessly between air and water, collecting comprehensive data above and below the surface. This feature is particularly valuable for monitoring aquatic environments such as wetlands, coastal areas, and inland water bodies, where traditional methods often fall short (Qin, 2024). The advanced capabilities of hybrid drones are underpinned by ongoing research in hybrid energy systems and enhanced control mechanisms. Integrating multiple energy sources, such as lithium batteries and supercapacitors, these drones achieve improved flight endurance and operational efficiency (Kang et al., 2023; Li et al., 2023). Moreover, developments in aerodynamic design and sophisticated control systems enable hybrid drones to execute complex manoeuvres and maintain stability in diverse environmental conditions (Hyun et al., 2023; Hu et al., 2024). The TJ-FlyingFish exemplifies these advancements, featuring a dual-mode hover system that ensures stability and precision during data collection, making it a versatile tool for environmental and water quality monitoring. As research continues to refine these technologies, hybrid drones are poised to play an increasingly pivotal role in addressing the challenges of modern monitoring and assessment tasks.


Figure 5: A Rotary-Wing Drone

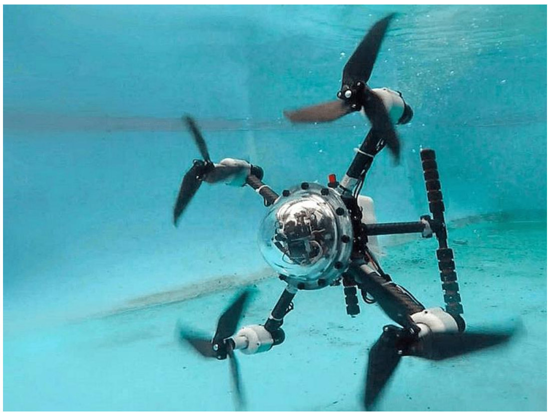
Figure 6: The TJ-FlyingFish Drone

Table 3: Comparison of Drone Types for Water Quality Monitoring

Feature	Fixed-Wing Drones	Rotary-Wing Drones	Hybrid Drones
Flight range	Long	Short	Long
Flight time	Long	Short	Moderate
Maneuverability	Limited	High	Moderate
VTOL capability	No	Yes	Yes
Payload capacity	High	Moderate	Moderate
Cost	High	Moderate	High
Ideal for	Large-scale surveys, remote locations	Close-up inspections, targeted sampling	Both large-scale surveys and close-up inspections

Drone Sensors for Water Quality Monitoring
The integration of advanced sensors with drone technology has transformed water quality monitoring by enabling the real-time collection of accurate and comprehensive data. Multispectral sensors like the Parrot Sequoia and MicaSense RedEdge capture imagery across multiple wavelengths, identifying indicators such as chlorophyll-a concentrations and turbidity levels, with aerial views proving superior to traditional sampling

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methods in cases like dredge-induced turbidity monitoring (Chang & Juang, 2024; Hayes et al., 2022). These sensors also enhance environmental assessments by distinguishing between land and water classes in complex ecosystems (Sarira et al., 2020). Hyperspectral sensors further extend capabilities, capturing broader wavelengths for detailed analysis of water constituents and quality changes (Rossi et al., 2020). Additionally, thermal sensors reveal temperature variations critical to aquatic habitats (Kumarasan et al., 2023), while LiDAR technology maps waterbody topographies, providing spatial context for assessments (Casana et al., 2020).

Table 4: Comparison of Drone Sensor Technologies for Water Quality Monitoring

Sensor Type	Functionality	Key Applications
Multispectral Sensors	Capture images across multiple spectral bands to analyze light reflectance from water.	Monitoring chlorophyll levels, turbidity, and suspended sediments; assessing water clarity and algal biomass.
Hyperspectral Sensors	Capture hundreds of narrow spectral bands for detailed analysis of water composition.	Measuring dissolved organic matter, nutrient concentrations (e.g., nitrates and phosphates), and detecting specific pollutants like heavy metals or chemicals.
Thermal Sensors	Measure water temperature to detect thermal pollution and changes in water circulation.	Identifying industrial discharges, monitoring aquatic life habitats, and assessing thermal impacts on ecosystems.
LiDAR Sensors	Use laser pulses to measure water depth and create 3D maps of water bodies.	Providing bathymetric data, sediment distribution analysis, and mapping habitats; understanding water flow and Sediment transport.

Cost-Benefit Analysis and Initial Investments of Sensors, IoT, and Drones

Cost-benefit analysis (CBA) is a critical tool in evaluating the economic viability of implementing advanced technologies for water quality monitoring, particularly in the context of the Internet of Things (IoT), drones, and sensor networks. The initial investment for these systems can vary widely based on the technology's scale and type. For IoT systems, costs for essential components such as pH, turbidity, and dissolved oxygen sensors range from approximately $6.90 to $500 per sensor (Adu-Manu et al., 2017). Drones, equipped with advanced imaging sensors and data analysis software, can incur costs between $30,000 and $200,000, while sensor systems also require investments in data loggers and communication infrastructure (Lariosa et al., 2024; Roy & J Kizhakkethottam, 2024). Despite these high upfront costs, the deployment of such technologies marks a significant advancement in water quality management, providing comprehensive datasets that were previously unattainable through conventional methods (Jagtap et al., 2021).

Operational Costs and Long-Term Savings

Operational costs and long-term savings are crucial considerations in the adoption of these advanced monitoring systems. The ongoing expenses associated with IoT systems include energy consumption, equipment calibration, and personnel training, which are essential for maintaining system efficiency and cybersecurity (Al Duhayyim et al., 2022; Ullo & Sinha, 2020). Drones, while facilitating access to challenging terrains, require regular maintenance, sensor calibration, and pilot training to ensure safe and effective operation (Ridolfi and Manciola, 2018). Sensor systems also demand frequent cleaning and calibration to maintain accuracy (Demetillo et al., 2019). Nonetheless, the long-term benefits of these technologies often outweigh their initial and operational costs. For example, IoT systems can automate data collection, thereby reducing labour costs, while drones can enhance operational efficiency by minimizing the need for manual inspections (Dawaliby et al., 2020; Samanta & Sarkar, 2023). Predictive maintenance, supported by advanced analytics, can optimize operational performance, extend equipment lifespan, and reduce water losses, leading to significant long-term savings (Krishnan et al., 2022). Case studies, such as IoT-enabled monitoring in India and drone-based assessments for wastewater discharge, have demonstrated cost savings exceeding 60%, highlighting the economic viability of these systems (Nmecha et al., 2024).

Future of Water Quality Monitoring

Artificial Intelligence (AI) in Water Quality Monitoring

Artificial Intelligence (AI) is significantly transforming water quality monitoring by facilitating a proactive approach to water resource management. AI algorithms, particularly Artificial Neural Networks (ANNs) and Long Short-Term Memory (LSTM) networks, are employed to analyze historical data, enabling the prediction of critical water quality parameters such as pH, dissolved oxygen, and turbidity (Fan and Zhao, 2023). This predictive capability is crucial for early detection of potential water quality issues, allowing for timely interventions that can prevent contamination and protect public health (P. Liu et al., 2019; Senhaji et al., 2021). The integration of advanced data processing techniques, including deep learning, enhances the analysis of extensive datasets collected through in situ monitoring, thereby improving the efficiency and effectiveness of water quality management systems (Michael et al., 2024).

In addition to prediction, AI optimizes water treatment processes by minimizing resource consumption and enhancing operational efficiency. Techniques such as Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and various machine learning classifiers, including Random Forest and Gradient Boosting, are utilized to evaluate comprehensive measures like the Water Quality Index (WQI). These tools provide valuable insights for resource allocation and water condition classification, thereby supporting better decision-making in water management (Drogkoula et al., 2023). Moreover, real-time anomaly detection facilitated by deep learning algorithms allows for immediate responses to deviations from expected water quality conditions, significantly minimizing environmental damage (Qiu, 2023). AI enhances water treatment operations by analyzing datasets on water quality, plant performance, and energy use, enabling efficiency improvements and cost reductions while ensuring safe drinking water (Abba et al., 2023; Gaudio et al., 2021). However, its implementation faces challenges, including the need for high-quality datasets and ensuring transparency in decision-making to build stakeholder trust (Doorn, 2021). Despite these obstacles, advancements in AI hold significant promise for fostering more resilient and sustainable water systems.

Blockchain Technology: Ensuring Data Integrity

Blockchain technology has emerged as a transformative solution for managing water quality data, addressing challenges such as data integrity and transparency. Its immutable nature ensures that water quality records collected from various sources, including sensors and laboratories, remain tamper-proof and authentic (Herzog, 2024). This characteristic fosters trust among stakeholders, including regulatory authorities, water utilities, and the public, by providing a secure and transparent system for data management (Lin et al., 2020; Asgari & Nemati, 2022). Additionally, blockchain's transparency facilitates real-time monitoring and verification of water quality data, a critical aspect of effective water resource management (Samanta & Sarkar, 2023). This approach ensures that all stakeholders have access to accurate and reliable information, promoting accountability and informed decision-making.

The integration of smart contracts within blockchain frameworks further enhances water quality management by automating processes such as data validation and reporting (Samanta & Sarkar, 2023). This automation reduces administrative burdens and increases system efficiency. Blockchain-based peer-to-peer data-sharing systems enable seamless integration between urban and rural water monitoring frameworks, fostering coordinated efforts in resource management (Asgari & Nemati, 2022). Beyond securing data, blockchain also supports innovative applications, such as water quality trading and real-time monitoring in smart water systems. Transparent ledger systems allow for verifying and trading water quality credits, incentivizing pollution reduction and sustainable practices (Herzog, 2024; Asgari & Nemati, 2022). Moreover, integrating blockchain with IoT-enabled water meters provides stakeholders with real-time insights into water quality dynamics, enabling proactive measures to optimize resource allocation and address pollution issues effectively (Xie et al., 2019).

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Big Data Analytics
Big data analytics is emerging as a transformative tool in water quality monitoring, enabling the integration and analysis of vast datasets from various sources such as sensors, weather stations, and even social media. By uncovering patterns, trends, and anomalies, big data platforms provide critical insights into water quality dynamics and potential risks (Zhu, 2019). Predictive models, developed through big data analytics, allow for the forecasting of water quality trends and the identification of pollution hotspots, enhancing proactive decision-making in water resource management (Kim et al., 2022). For example, platforms like KETOS centralize data from multiple sources into real-time, user-friendly dashboards, enabling water operators to monitor over 30 water quality parameters and implement timely interventions that protect water resources and public health (Elhassan et al., 2020).
Moreover, big data analytics plays a pivotal role in optimizing water systems and agricultural practices. Tools that analyze data patterns from smart meters and soil sensors help detect leaks in urban water networks, reducing water loss, and improving irrigation efficiency in agriculture (AL-Madhrahi et al., 2021). Visualization platforms like NASA's STREAM and ArcGIS StoryMap make complex datasets accessible to a broader range of stakeholders, improving communication and collaborative decision-making in water management (Elhassan et al., 2020). As big data continues to evolve, its integration with cutting-edge technologies like artificial intelligence (AI), blockchain, and the Internet of Things (IoT) holds immense potential to innovate water quality monitoring further. These synergies are expected to enhance operational efficiencies in utilities, optimize water delivery systems, and equip communities to respond to the challenges posed by climate change and urbanization (Kim et al., 2022; Ping et al., 2019).

Challenges in the Integration of Emerging Technologies in Water Quality Monitoring
Data Management
The integration of advanced technologies generates vast amounts of data, which poses substantial data management challenges. Efficiently storing, processing, and analyzing this continuous stream of information from various sources necessitates a robust data infrastructure and advanced analytics capabilities. The development of smart water quality monitoring systems (SWQMSs) has been facilitated by advancements in IoT and cloud computing technologies, which allow for real-time data collection and analysis (Martínez et al., 2020). However, the sheer volume of data collected from multiple sensors can overwhelm traditional data management systems, necessitating more sophisticated data processing techniques (De Camargo et al., 2023). Moreover, the integration of low-cost sensors with IoT can enhance real-time monitoring capabilities, but it also requires careful consideration of data reliability and accuracy (Alam et al., 2020). The challenge lies in ensuring that the data collected is voluminous and actionable, which requires advanced data analytics and machine learning techniques to derive meaningful insights from the data (Lou et al., 2022).

Standardization
Standardization of data formats and communication protocols is crucial for seamless integration and interoperability between different components of water quality monitoring systems. The lack of standardization can lead to data silos, which hinder comprehensive analysis and informed decision-making. The integration of various sensor types and communication technologies, such as ZigBee and LoRaWAN, can create compatibility issues if standard protocols are not established. Furthermore, the absence of standardized data formats can complicate data sharing and collaboration among different stakeholders, including researchers, policymakers, and water management authorities (Bohara et al., 2024). The development of a unified framework for data exchange and communication is essential to facilitate interoperability and enhance the overall effectiveness of water quality monitoring systems (Lakshmikantha et al., 2021)

Cybersecurity
As water quality monitoring systems increasingly rely on digital technologies and IoT platforms, the importance of cybersecurity cannot be overstated. Protecting water quality data and infrastructure from cyberattacks is paramount to ensure data integrity and maintain the reliability of the monitoring system. Implementing robust cybersecurity measures is essential to prevent unauthorized access and data breaches (Yaroshenko et al., 2020). The integration of drones and IoT devices into water quality monitoring introduces additional vulnerabilities, as these technologies can be susceptible to hacking and other cyber threats (Nmecha, 2024). Therefore, it is critical to adopt comprehensive cybersecurity strategies that encompass not only the protection of data but also the security of the underlying infrastructure and communication networks (Lou et al., 2022). This includes regular security assessments, encryption of data transmissions, and the establishment of protocols for responding to potential cyber incidents.

Conclusion
This review has provided an in-depth examination of recent advancements in sensor technologies, Internet of Things (IoT) systems, and drone applications for water quality monitoring. The integration of these cutting-edge technologies holds great promise for transforming the way we monitor, analyze, and manage water resources. Sensors, ranging from nano-sensors to bio-sensors, offer precise detection capabilities at trace levels, while IoT systems enable real-time data transmission, analysis, and decision-making. Drones, equipped with advanced sensor payloads, provide high-resolution, spatially comprehensive data, particularly in remote and inaccessible locations. Together, these technologies form a powerful framework for proactive and efficient water quality management, supporting sustainability and environmental protection.
Despite these promising advancements, several weaknesses and challenges persist within the existing literature and technological landscape. Firstly, there is a significant gap in scalability and interoperability among the technologies discussed. While sensors, IoT systems, and drones have demonstrated their capabilities in controlled environments or specific case studies, there is limited research on their large-scale deployment, especially in regions with limited infrastructure. Many studies focus on single-technology applications, and integrated systems that combine sensors, IoT, and drones remain underexplored in practical contexts. Additionally, the high costs associated with implementing these technologies, including the deployment of sensor networks, drone operations, and data management, present significant barriers to their widespread adoption.
Furthermore, data management and cybersecurity remain ongoing

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concerns, with few studies addressing how to protect and securely transmit the massive volumes of data generated by IoT-enabled water quality monitoring systems. Standardization of protocols for sensor calibration, data exchange, and communication is another area where current research falls short. This lack of uniformity hinders system integration and limits the broader applicability of these technologies. Lastly, the long-term reliability and maintenance of these systems, especially in harsh environmental conditions, are not thoroughly addressed in the literature. Many sensor technologies and drones require frequent recalibration and regular maintenance, which can limit their sustainability in real-world applications.

Hence, Future research should focus on developing cost-effective solutions, enhancing system integration, and creating standardized protocols that ensure the widespread adoption and successful deployment of these technologies. Interdisciplinary collaboration and continued innovation will be key to overcoming these challenges and paving the way for more sustainable and resilient water quality management systems.

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