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(Review Article)

Short review on Integration of Industry 4.0 Technologies in Water Treatment: Innovations, Challenges, and Future Perspectives

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Abstract

The growing demand for sustainable, efficient, and resilient water treatment systems has driven increasing interest in the integration of Industry 4.0 technologies. This review explores the practical applications of key digital innovations including the Internet of Things (IoT), artificial intelligence (AI) and machine learning, big data analytics, and automation with cyber-physical systems in modern water treatment. These technologies enable real-time monitoring, predictive maintenance, process optimization, and data-driven decision-making, transforming conventional facilities into adaptive, smart systems. A literature search was conducted across peer-reviewed publications and technical reports from 2015 to 2025, with data extracted on study areas, methodologies, outcomes, and practical implications. The analysis highlights successful case applications in water quality monitoring, wastewater treatment, and infrastructure management, while also identifying challenges related to cost, interoperability, and regulatory frameworks. Future perspectives emphasize the need for low-cost and scalable solutions, seamless integration with existing infrastructure, supportive policies, and collaborative partnerships across research, industry, and governance. Emerging opportunities include the convergence of Industry 4.0 with advanced biosensors, blockchain, and autonomous robotics, paving the way for fully automated and self-optimizing treatment plants.

Keywords: Industry 4.0; Water Treatment; Internet of Things (IOT); Artificial Intelligence; Smart Systems

1. Introduction

Water is an essential resource for human survival, ecosystem functioning, and economic development (Goswami and Bisht, 2017). However, the growing global population, rapid urbanization, industrial expansion, and the impacts of climate change are exerting unprecedented pressure on water resources (Saxena, 2025). These challenges are compounded by the increasing prevalence of water contamination from emerging pollutants, including pharmaceuticals, personal care products, microplastics, and industrial chemicals, which are often not fully removed by conventional water treatment systems. Consequently, ensuring safe, reliable, and sustainable water supply has become a critical global priority (Morin-Crini et al., 2022).

Traditional water treatment methods, such as coagulation, sedimentation, filtration, and disinfection, have been the backbone of water purification for decades (Ogwu et al., 2024). While these approaches are effective for many conventional contaminants, they often exhibit limitations in addressing complex or emerging pollutants, optimizing

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energy use, and enabling real-time monitoring and control. Additionally, traditional systems are typically reactive rather than proactive, responding to water quality issues after they arise, which can compromise public health and environmental safety. The need for more adaptive, efficient, and intelligent water treatment systems has therefore become increasingly evident (Hofman-Caris and Hofman, 2017).

The emergence of Industry 4.0, also known as the Fourth Industrial Revolution, provides promising solutions to these challenges. Industry 4.0 encompasses a suite of advanced technologies, including the Internet of Things (IoT), artificial intelligence (AI) and machine learning, big data analytics, cloud computing, and cyber-physical systems. These technologies enable real-time monitoring, predictive maintenance, process optimization, and data-driven decision-making, thereby transforming traditional water treatment plants into smart, adaptive, and resilient systems. The integration of Industry 4.0 in the water sector can enhance water quality management, reduce operational costs, improve energy efficiency, and enable rapid response to contamination events or system failures (Guth and Herák, 2025, Uwamungu et al., 2022; Guajardo et al., 2023).

Recent studies have demonstrated the potential of IoT-enabled sensors to provide continuous, real-time data on water quality parameters such as pH, turbidity, dissolved oxygen, and microbial contamination (Mandal et al., 2025). Similarly, AI and machine learning algorithms have been applied to predict contamination events, optimize chemical dosing, and improve process efficiency (Lowe et al., 2022). Big data analytics facilitate the interpretation of large and complex datasets generated by sensor networks, supporting informed decision-making and long-term planning (Kamyab et al., 2023). Despite these advancements, the adoption of Industry 4.0 technologies in water treatment also presents challenges, including high initial investment costs, technical complexity, cybersecurity risks, and the need for skilled personnel (Guth and Herák, 2025).

This review aims to provide a comprehensive overview of the current state of Industry 4.0 applications in water treatment. Specifically, it will examine the key technologies involved, their practical applications, advantages, limitations, and potential for future development.

2. Methodology

This review was conducted to identify and analyze studies related to the integration of Industry 4.0 technologies in water treatment. A comprehensive literature search was carried out covering the period from 2015 to 2025 across major scientific databases, including Scopus, Web of Science, PubMed, ScienceDirect, and SpringerLink, as well as grey literature from international organizations such as UNESCO, OECD, EPA, and the World Bank. The search strategy combined keywords such as “Industry 4.0,” “water treatment,” “digital technologies,” “IoT in water management,” “artificial intelligence,” “automation,” and “cyber-physical systems.”

Studies were included if they focused on practical applications of Industry 4.0 technologies such as IoT, artificial intelligence, big data analytics, robotics, or smart sensors in water treatment. Conceptual papers without application evidence were excluded. Titles, abstracts, and keywords were screened for relevance, and potentially eligible articles were assessed in full. In total, the final selection comprised a set of peer-reviewed articles, reviews, and technical reports that provided concrete insights into the use of Industry 4.0 in the sector.

For each study, data were extracted on the country or region of application, the specific technology employed, the methodological approach, and the main findings with respect to efficiency, sustainability, and innovation in water treatment. The extracted information was then categorized according to the dominant Industry 4.0 technologies and mapped to their practical applications, such as wastewater management, desalination, water quality monitoring, and pumping system optimization. This process allowed for a comparative analysis to identify common patterns, emerging trends, and critical challenges. To ensure reliability, all references were cross-verified, and grey literature was only considered when published by internationally recognized organizations.

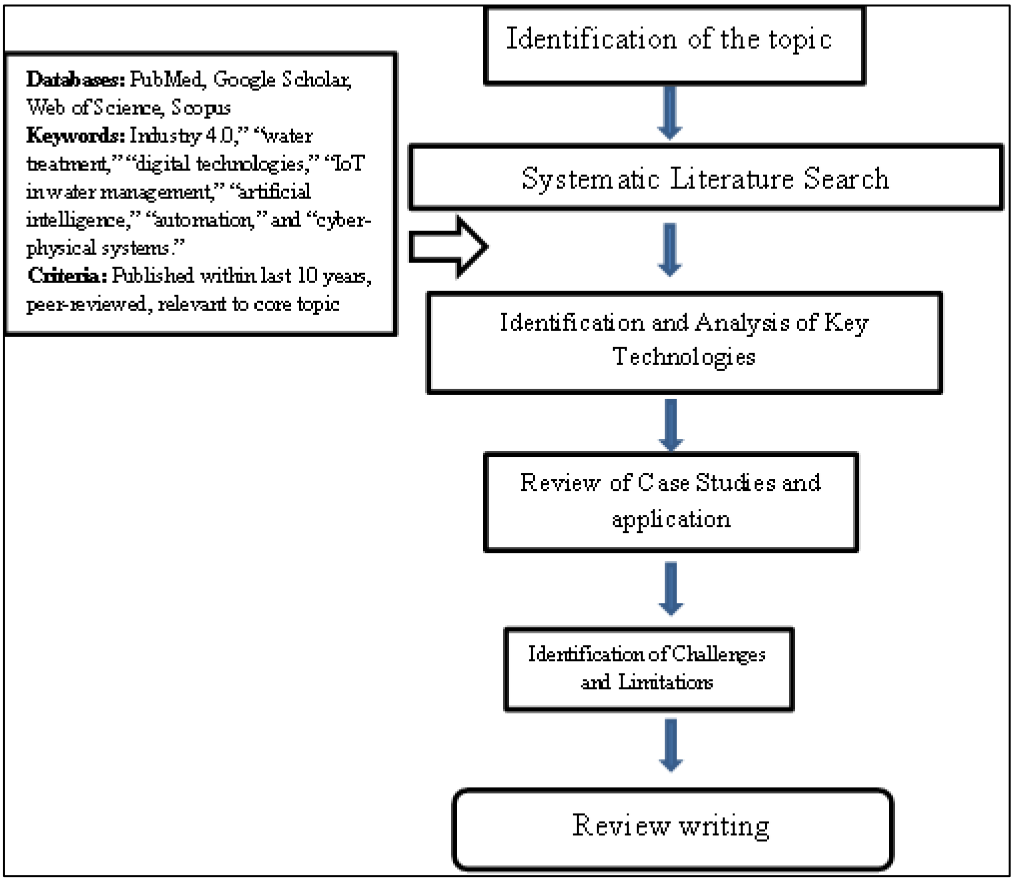

Figure 1 Systematic Review Process

3. Industry 4.0 technologies applied to water treatment

3.1. Internet of Things (IoT)

The Internet of Things (IoT) refers to a network of interconnected devices capable of collecting, transmitting, and analyzing data in real time. In the context of water treatment, IoT enables continuous monitoring of water quality, operational parameters, and infrastructure performance, allowing for timely interventions and improved management efficiency (Abdul-Qawy et al., 2015).

Smart sensors are at the core of IoT-enabled water treatment systems. These devices can measure a wide range of physicochemical parameters, including pH, turbidity, dissolved oxygen, conductivity, and total dissolved solids, as well as biological parameters such as microbial load. The real-time data generated by these sensors can be transmitted to centralized platforms for processing and analysis, enabling early detection of contamination events and proactive maintenance of treatment facilities (Solano et al., 2022; Skirvin, and Roseth, 2015).

Moreover, IoT systems facilitate automated control of treatment processes. For example, sensor data can trigger adjustments in chemical dosing, filtration rates, or disinfection procedures, optimizing water quality while minimizing operational costs and chemical usage. The integration of IoT with cloud computing and big data analytics further enhances the capacity to manage large datasets, identify trends, and predict potential system failures (Zhang et al, (2020; Martínez et al., 2020).

3.2. Artificial Intelligence (AI) and Machine Learning

Artificial Intelligence (AI) and machine learning technologies play a central role in modern water treatment systems by enabling intelligent data processing, decision-making, and process optimization (Kono, et al., 2023). These technologies can analyze complex datasets generated by IoT sensors and other monitoring devices to optimize operational parameters, such as filtration rates, chemical dosing, and disinfection processes, improving water quality while reducing energy consumption and operational costs (Mazhar et al., 2023).

AI algorithms can identify patterns and correlations in historical and real-time data, allowing for predictive maintenance of equipment and early detection of potential failures. This proactive approach minimizes system downtime and prevents disruptions in water supply. Additionally, machine learning models can forecast contamination events by analyzing trends in water quality parameters, environmental conditions, and operational factors, enabling timely intervention to mitigate risks (Paramesha et al., 2024; Goel et al., 2023).

3.3. Big Data and Data Analytics

Big data and data analytics are critical components of Industry 4.0 applications in water treatment, enabling the management and interpretation of large volumes of data generated by IoT sensors and other monitoring devices. These technologies allow water treatment operators to process complex datasets in real time, extracting actionable insights to optimize operational efficiency and improve water quality (Earnout et al., 2028).

Advanced analytics techniques can identify patterns, correlations, and trends in the data, supporting informed, data-driven decision-making. For instance, sudden deviations in sensor readings can be detected quickly, allowing operators to respond to potential contamination events before they escalate. Furthermore, predictive models can forecast water demand, contamination risks, or equipment malfunctions, facilitating proactive management and maintenance strategies (Ghinea et al., 2023;).

3.4. Automation and Cyber-Physical Systems

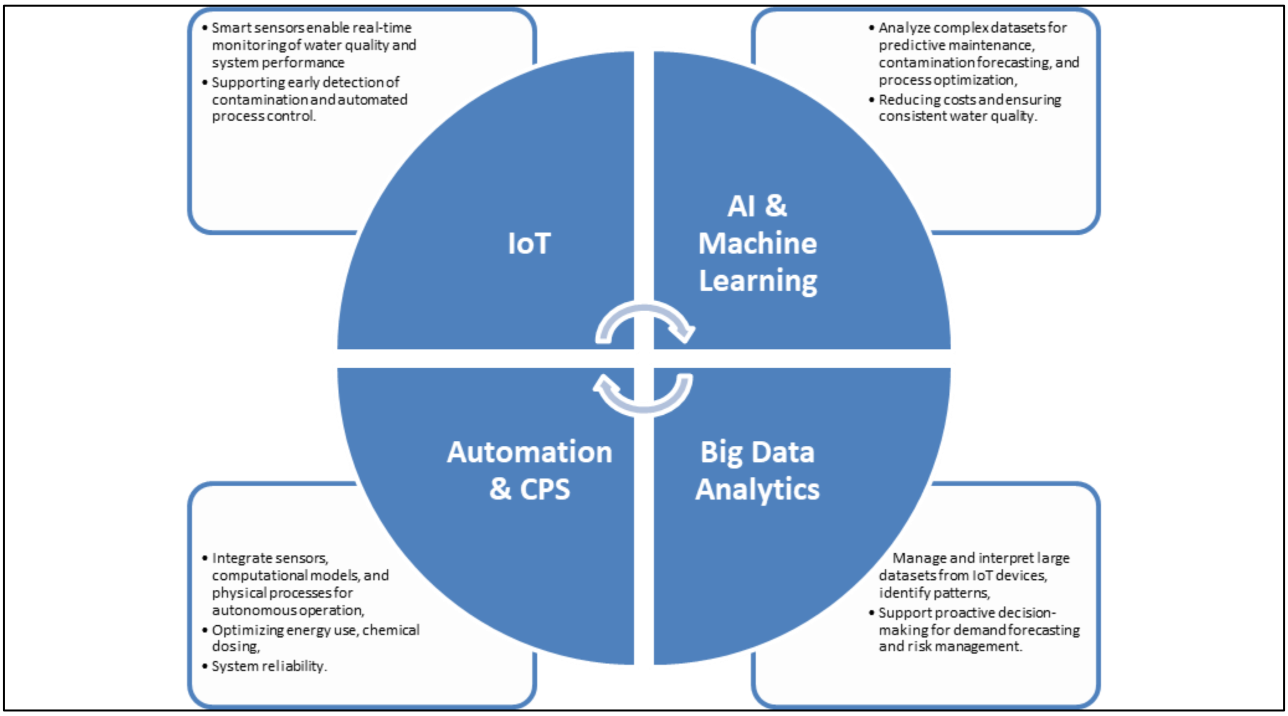

Figure 2 Industry 4.0 technologies applied to water treatment

Automation and cyber-physical systems (CPS) are essential for enhancing the efficiency and reliability of modern water treatment facilities. Cyber-physical systems integrate computational algorithms, networked sensors, and physical processes to enable real-time monitoring and intelligent control of water treatment operations. This integration allows treatment plants to operate autonomously or semi-autonomously, adjusting processes based on continuous data feedback from sensors and analytical models (Seshia et al., 2016; Leitão et al., 2016).

Through intelligent control, automation reduces the need for constant human supervision, minimizing the risk of operational errors and improving overall system reliability. It also enhances operational efficiency by optimizing energy consumption, chemical usage, and treatment performance. For example, automated control systems can regulate filtration rates, chemical dosing, and disinfection schedules dynamically in response to fluctuations in water quality and demand (Nikolakis et al., 2019; Seshia et al., 2016).

The adoption of automation and CPS, in combination with IoT, AI, and big data analytics, transforms conventional water treatment plants into smart, adaptive systems. These systems are capable of responding in real time to changing conditions, maintaining consistent water quality, and supporting sustainable and resilient water management strategies (Figure 2).

4. Practical applications in water treatment

The integration of Industry 4.0 technologies in water treatment has led to several practical applications that enhance efficiency, safety, and sustainability (Table 1). One of the primary applications is the real-time monitoring of drinking water and wastewater quality. IoT-enabled sensors continuously collect data on physicochemical and biological parameters, providing instantaneous insights into water conditions. This enables operators to detect deviations or contamination events promptly, allowing for immediate corrective actions and ensuring the safety of water for human consumption and environmental release (Alshami et al., 2024; Essam Lali et al., Essam Lali et al., 2024). Another critical application is energy optimization within treatment plants. Advanced data analytics and AI-driven models allow operators to identify inefficiencies in energy use and optimize processes such as pumping, aeration, and filtration (Adekunle et al., 2021). Industry 4.0 technologies also support proactive management of pollution and environmental incidents. Predictive analytics and machine learning models can forecast potential contamination events or equipment failures based on historical and real-time data. This predictive capability enables preventive maintenance and timely interventions, minimizing environmental impact and reducing the risk of service disruptions (Ayoub et al., 2024, Cruz et al., 2021).

Table 1 Practical applications of industry 4.0 technologies in water treatment

No.	Study Area	Country / Region	Methodology / Design	Main Results (Scientific Summary)	Reference
1	Cyber-attacks in communication networks of water purification and distribution plants	International (review of studies and real cases)	Technical review / systematic synthesis covering attack models, case reports, and mitigation solutions	Mapped attack vectors and IIoT/SCADA vulnerabilities in water sector; documented several real-world incidents; proposed defense framework (prevention, detection, resilience) and future directions for improving water utilities' cybersecurity.	Aslam et al., 2023
2	Organic contaminants in sewage sludge: comparative meta-analysis	USA and China	Comparative meta-analysis (binational database, statistical synthesis)	Compiled 105 US and 159 Chinese studies; among 1175 compounds tracked, only 23% assessed in both countries; mean OC concentrations ≈ 4× higher in US; identified priority groups (e.g., alkylphenol ethoxylates) and monitoring/management gaps.	Steele et al., 2022
3	AI in electrochemical processes for water treatment	International (empirical studies and experiments)	Systematic review / synthesis of AI applications (ANN, SVM, ANFIS, GA, PSO)	ANN models dominate for modeling and optimization of electrochemical processes (electrooxidation, electrocoagulation, electro-Fenton, electrodialysis); limitation: most datasets <150 samples; recommends strengthening robustness and reliability of black-box models.	Shirkoohi et al., 2022
4	AI for water treatment optimization	International	Systematic review and bibliometric analysis	AI/ML techniques improve prediction, supervision, and optimization of water treatment systems; gaps remain in industrial-scale validation, data quality, and replicability.	Mathaba Banza, 2023
5	Advanced technologies and AI for pollution control and river revitalization	Ghana (Pra river basin)	Targeted review + policy/technology roadmap	Identified advanced technologies (AI, sensors, adsorption, membranes, electrokinetics) for revitalization; AI supports decision-making and optimization; provided policy roadmap for local implementation.	Nti et al., 2023
6	"Minus Approach" in drinking water treatment (reduced chemical input)	International (conceptual + case analysis)	Conceptual review and comparative analysis of practices (Plus vs Minus)	Proposed alternatives (bank filtration, biofiltration, adsorption, membranes) to minimize chemical inputs and disinfection byproducts (DBPs); suggested integrating AI tools to optimize performance and microbial safety.	Reid et al., 2023
7	AI for chemical analysis and monitoring of pharmaceuticals and	International	Review of AI + HRMS/CCS applications	AI enhances prediction of chromatographic retention times and collision cross sections (CCS) for suspect/non-target screening; promising for wastewater-based	Kavianpour et al., 2024

	personal care products (PPCPs)			epidemiology; gaps: long-term time series and methodological comparisons.	
8	Deep learning in wastewater treatment	International (methodological review)	Critical review comparing semi-mechanistic vs data-driven approaches	Highlighted opportunities and limitations of deep learning in wastewater treatment (prediction, soft-sensing, control); advocated hybrid models (mechanistic + data-driven) for robust solutions.	Alvi et al., 2023
9	Microbial drinking water monitoring	International (prospective review)	Review and foresight synthesis (flow cytometry, sequencing, AI)	Emerging techniques (flow cytometry, fingerprinting, 3rd-gen sequencing) combined with AI will enable holistic monitoring of distribution networks; call to shift from point sampling to systemic surveillance.	Pluym et al., 2024
10	AI and water treatment (2010–2020)	International	Systematic review (92 articles)	AI supports prediction of water quality and automation of processes; growing number of studies but still limited industrial-scale applications and standardized datasets.	Ismail et al., 2023
11	AI in drinking water treatment processes (coagulation, filtration, DBP control)	International	Review (historical + recent publications)	ML models improve prediction of coagulant dose, membrane flux, DBP formation; deep learning and hybrid approaches show promise for image-based floc recognition and operational optimization.	Chowdhury et al., 2024
12	AI/ML for microalgal wastewater treatment and biorefinery	International (critical review)	Critical review of ML in microalgal cultivation and analysis	ML algorithms (ANN, SVM, GA, etc.) can optimize productivity and robustness of algal systems; IoT-AI integration promising, but industrial adoption still limited.	Oruganti et al., 2023
13	AI/ML for biological wastewater treatment monitoring and design	International	Review (bibliometric + synthesis of models: ANN, FL, RF, LSTM)	Predictive models (ANN, RF, LSTM) effective for effluent parameter prediction (BOD, COD, N, P) and predictive control; recommended using RMSE, MSE, R^2 as performance indicators with proper validation practices.	Singh et al., 2023
14	AI in water disinfection and DBP management	International	Thematic review (CiteSpace + synthesis)	AI methods (esp. neuro-fuzzy systems) perform well in disinfection control and DBP prediction; hybrid approaches recommended for full-scale applications.	Ding et al., 2024
15	AI optimization of wastewater treatment plants	International	Review (pilot/demo cases, performance metrics)	Reported pilot studies and demos showing improved predictive accuracy (R^2 0.64–1.00), fault detection, and resource optimization; discussed cost-benefit and ethical concerns.	Nagpal et al., 2024

5. Advantages and limitations of industry 4.0 integration in water treatment

The adoption of Industry 4.0 technologies in water treatment systems represents a paradigm shift from conventional, reactive approaches to intelligent, data-driven, and adaptive management. These technologies encompassing the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, and Cyber-Physical Systems (CPS) offer transformative advantages, but also present notable limitations that require careful consideration for practical implementation.

5.1. Advantages

5.1.1. Enhanced water quality and safety

IoT-enabled sensors and automated control systems enable real-time monitoring and rapid intervention to maintain water quality within regulatory and safety standards. Continuous surveillance of physicochemical and microbiological parameters allows for early detection of contaminants, including emerging pollutants that conventional methods might miss. Consequently, water treatment systems become more resilient to episodic pollution events, ensuring safe drinking water and reducing public health risks (Ikonen et al., 2025; Verma et al., 2025).

5.1.2. Optimized operational efficiency

AI algorithms and predictive models allow dynamic optimization of treatment processes, including filtration, chemical dosing, aeration, and disinfection. By adjusting operational parameters in response to real-time data, treatment plants can minimize energy consumption, reduce chemical use, and maintain optimal performance under fluctuating input water quality. Such optimization translates into significant cost savings and improved sustainability of treatment operations (Lekkala, 2024; Rokaya et al., 2025).

5.1.3. Proactive and predictive management

Machine learning and big data analytics facilitate predictive maintenance and contamination forecasting. Instead of reacting to system failures or contamination after occurrence, water utilities can anticipate equipment malfunctions, chemical imbalances, or pollution events. This proactive management reduces downtime, prevents environmental incidents, and enhances the reliability of water services (Sun and Scanlon, 2019).

5.1.4. Data-Driven decision making and strategic planning

The integration of big data analytics allows the aggregation and interpretation of vast datasets from multiple sensors, treatment units, and historical records. This capability supports informed, evidence-based decision-making, identifies long-term trends in water quality, and aids in infrastructure planning. Utilities can thus implement targeted interventions and optimize resource allocation more effectively than with conventional monitoring systems (Boubiche et al., 2028; Sun and Scanlon, 2019).

5.1.5. Improved System Resilience and Adaptability

Industry 4.0 technologies enable adaptive control of treatment processes, allowing water systems to respond in real time to sudden changes in water quality, flow rates, or environmental conditions. Such flexibility enhances system resilience against both predictable and unforeseen challenges, including extreme weather events, pollution incidents, or seasonal fluctuations in water demand (Guth and Herák, 2025).

5.2. Limitations

Despite the significant potential of Industry 4.0 technologies in advancing water treatment, several limitations constrain their widespread adoption. One of the foremost challenges is the high capital and maintenance costs. Establishing IoT networks, automated control systems, and computational infrastructure requires substantial initial investment, while the ongoing maintenance of sensors, software platforms, and data storage solutions further increases operational expenses, posing difficulties for resource-constrained regions (Konfo et al., 2023).

Technical complexity and integration challenges also hinder implementation. Retrofitting existing treatment plants with multiple Industry 4.0 technologies demands sophisticated system engineering and careful planning to ensure compatibility, data interoperability, and minimal service disruptions. Such processes are often disruptive and may delay adoption (Herrera-Vidal et al., 2025; Okwu et al., 2022).

Another limitation arises from the strong dependence on data quality. AI and predictive models can only perform effectively when supplied with reliable, accurate, and continuous datasets. Sensor malfunctions, calibration issues, or missing data can result in flawed predictions and suboptimal decisions, underlining the need for robust data management strategies (Yang, 2022; Bauskar, 2024).

Cybersecurity and privacy risks further complicate deployment. The growing reliance on connectivity and remote monitoring exposes systems to potential cyber-attacks, which may compromise operational integrity or allow unauthorized access to sensitive information. While encryption, access control, and real-time threat detection are crucial safeguards, their implementation adds extra technical and financial burdens (Boeckl et al., 2019; Wylde et al., 2022).

Human resource and skills requirements also represent a critical barrier. The operation and maintenance of Industry 4.0-enabled water treatment systems demand expertise in AI, big data analytics, IoT management, and cyber-physical systems engineering. However, training, recruiting, and retaining such specialized personnel is challenging, particularly in regions with limited technical capacity (Ochieng et al., 2015; Nnadi et al., 2025).

Finally, regulatory and standardization gaps remain unresolved. Current water treatment regulations were largely designed for conventional systems and often fail to address the unique features of smart, automated, and AI-driven technologies. To ensure safety, reliability, and public trust, policymakers must adapt regulatory frameworks, establish standardized protocols, and develop clear validation procedures for emerging technologies (Konfo et al., 2023).

Table 2 Applications, benefits, and limitations of industry 4.0 technologies in water treatment

Application	**Technology Used**	**Description**	**Benefits**	**Inconveniences / Limitations**	**References**
Real-time monitoring of water quality	IoT sensors	Continuous measurement of physicochemical and biological parameters in drinking water and wastewater	Early detection of contamination, improved safety, rapid decision-making	High installation and maintenance costs, sensor calibration requirements, potential network connectivity issues	Balaji et al., 2019
Energy optimization	AI and data analytics	Dynamic adjustment of pumping, aeration, and filtration processes based on real-time data	Reduced energy consumption, cost savings, enhanced efficiency	Requires accurate data inputs, complex implementation, potential errors in AI predictions	Gonçalves et al., 2025
Proactive pollution management	Machine learning and predictive analytics	Forecasting of contamination events and equipment failures	Preventive maintenance, reduced environmental impact, minimized service disruptions	Model accuracy depends on historical data quality, high computational requirements	Strielkowski et al., 2023
Automated control of treatment processes	Cyber-physical systems	Intelligent control of chemical dosing, filtration, and disinfection	Reduced human intervention, consistent water quality, improved operational reliability	High initial investment, integration challenges with existing systems, cybersecurity risks	Singh et al., 2023
Data-driven decision-making	Big data analytics	Integration and analysis of large datasets from IoT and CPS	Insightful decision-making, trend analysis, predictive planning	Requires skilled personnel, data privacy and security concerns, complex infrastructure	Kuznetsov et al., 2023

6. Future Perspectives and Recommendations

The integration of Industry 4.0 technologies into water treatment systems offers significant opportunities for enhancing innovation, sustainability, and resilience. To fully realize these benefits, however, future efforts must focus on advancing research and development, improving integration with existing infrastructure, strengthening regulatory frameworks, and fostering collaborative approaches across sectors (Thames and Schaefer, 2017; Rai et al., 2021).

A key priority is the development of cost-effective and accessible solutions. Future research should emphasize the design of low-cost sensors, modular automation systems, and lightweight analytical platforms that can function reliably in diverse contexts, including resource-constrained regions. Equally important is the development of energy-efficient AI algorithms and data-processing techniques that minimize operational demands while ensuring sustainability (Cacciuttolo et al., 2023; Mobaraki et al., 2021).

Another critical challenge lies in the seamless integration of Industry 4.0 technologies into legacy water treatment facilities. Retrofitting existing infrastructure requires modular and flexible designs, supported by standardized communication protocols, interoperability frameworks, and adaptive control systems. Such measures will enable smart technologies to complement rather than disrupt conventional treatment processes (Korodi et al., 2023; Burns, 2019).

Regulatory and policy support will also play a decisive role in shaping the future of intelligent water treatment. Policymakers must establish guidelines for technology validation, data governance, cybersecurity, and safety standards, while simultaneously providing incentives such as subsidies, tax benefits, and funding programs to encourage adoption by utilities, particularly in developing regions (Kuo et al., 2019; Teixeira et al., 2019).

The successful deployment of Industry 4.0 solutions further depends on collaborative approaches. Strong partnerships among researchers, engineers, technology providers, utilities, and policymakers are essential to ensure that innovations address practical challenges and support sustainable water management. Interdisciplinary cooperation will also facilitate pilot testing, demonstration projects, and the dissemination of best practices.

Looking ahead, emerging opportunities include the convergence of Industry 4.0 with complementary technologies such as advanced biosensors, blockchain for secure water data management, and autonomous robotics for inspection and maintenance (Bodkhe et al., 2020; Gadicha et al., 2025). When combined with AI-driven predictive models, these innovations could enable fully autonomous and self-optimizing treatment systems, delivering improved efficiency, reduced human intervention, and enhanced environmental sustainability.

7. Conclusion

Industry 4.0 technologies IoT, AI, big data analytics, and cyber-physical systems are transforming water treatment by enabling real-time monitoring, process optimization, and predictive management. These innovations improve water quality, operational efficiency, and system resilience while reducing energy use and environmental impact.

Despite challenges such as high costs, technical complexity, and cybersecurity risks, gradual adoption supported by research, policy incentives, and collaboration can maximize benefits. Future efforts should focus on low-cost, accessible solutions and integration with existing infrastructure. Overall, Industry 4.0 offers a pathway toward smarter, more sustainable, and resilient water treatment systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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