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Recent Survey on Applications of IoT in Water Treatment Processes

MuthuPandi R
Department of CSE, University College of Engineering Dindigul, India
Email: muthupandi234@gmail.com

Abstract

The escalating global water crisis, driven by population growth, industrialization, and climate change, necessitates the adoption of advanced technologies for sustainable water management. The Internet of Things (IoT) has emerged as a transformative force in the water treatment sector, facilitating a transition from traditional, manual operations to smart, automated, and data-driven systems. This report provides a comprehensive survey of recent advancements (2023–2026) in IoT applications for water and wastewater treatment. It explores the integration of diverse sensor networks, communication protocols (e.g., LoRaWAN, MQTT), and artificial intelligence (AI) frameworks including Machine Learning (ML) and Deep Learning (DL) for real-time monitoring and process optimization. Key applications such as automated water quality sensing, leak detection, predictive maintenance, and smart desalination are analyzed. The report further discusses the methodologies employed in current research, ranging from physical sensor deployment to cloud-based analytics. Significant findings, such as a 25% increase in operational efficiency and up to 88.8% reduction in optical density through IoT-enabled biological treatment, are highlighted. Finally, future research directions—including cybersecurity, scalability, and the integration of blockchain and 5G—are outlined to guide the next generation of smart water management systems.

Keywords: IoT, Water Treatment, Smart Water Management, AI, Real-time Monitoring, Wastewater, Industry 4.0, Sensors.

1. Introduction

The management of water resources has become one of the most critical challenges of the 21st century. Traditional water treatment facilities often rely on periodic manual sampling and offline laboratory analysis, leading to significant delays in responding to contamination events or operational failures. The integration of Internet of Things (IoT) technologies into water treatment processes, often referred to as "Smart Water Management," offers a solution by providing continuous, real-time data acquisition and autonomous control capabilities [2], [5].

IoT in water treatment involves a network of interconnected devices—sensors, actuators, and microcontrollers—that collect and transmit data regarding various water quality parameters such as pH, turbidity, dissolved oxygen, and chemical concentrations [4], [6]. This data is subsequently processed using advanced analytics and artificial intelligence to optimize treatment efficiency, reduce energy consumption, and ensure compliance with environmental standards [1], [11].

The emergence of Industry 4.0 has further accelerated this digital transformation. Technologies like big data analytics, cloud computing, and digital twins are being combined with IoT to create resilient and efficient water treatment infrastructures [15], [17]. For instance, smart water grids (SWGs) are being implemented in regions like India to advance purification and conservation efforts [9]. This survey examines the recent literature to categorize the applications, methodologies, and outcomes of IoT integration in this vital sector.

2. Recent Works and Applications

Recent literature highlights the diverse applications of IoT across the entire water treatment cycle, from source water monitoring to distribution and wastewater reclamation.

2.1 Water Quality Monitoring and Distribution

A primary application of IoT is the real-time monitoring of water quality indices. Forhad et al. reviewed systems that monitor parameters across multiple stages of water treatment plants (WTPs), ensuring that drinking water meets safety standards before distribution [4]. Similarly, Addow et al. demonstrated a low-cost, easy-to-deploy IoT system in Somalia that collects essential water parameters, communicates with a central database, and provides real-time alerts via SMS and web applications [20].

In the context of smart cities, IoT-enabled solutions are used for consumption analysis and leak detection. Kukadiya et al. highlighted the use of IoT for flood management and infrastructure maintenance, which improves the overall sustainability of urban water systems [12]. Slany et al. further discussed the concept of "Smart Water-IoT" (SW-IoT), which integrates AI with smart distribution grids to detect leaks and manage rising consumption [18].

2.2 Wastewater and Effluent Treatment

Wastewater management has seen significant advancements through IoT. Alprol et al. discussed how IoT automates monitoring in natural systems and wastewater applications, particularly in aquaculture where it automates effluent treatment [1]. Das et al. implemented an IoT platform for the physico-biological treatment of wastewater, using sensors for pH and ultrasound-based flow monitoring. Their prototype demonstrated high reliability in optimizing treatment analytics and significant reductions in pollutants [19].

2.3 Advanced Purification and Desalination

IoT is also being applied to specialized treatment processes such as desalination and membrane filtration. Allaoui et al. conducted a bibliometric review showing how IoT sensors and AI can improve the efficiency and sustainability of desalination processes [7]. Cai et al. explored the use of smart sensing materials combined with AI-IoT platforms for drinking-water treatment, mapping applications from the water source to the point of distribution [3].

Summary of Recent Works

The following table summarizes key recent studies and their contributions to the field of IoT in water treatment.

Ref	Author(s) & Year	Application Area	Key Technologies	Major Findings/Impact
[1]	Alprol et al. (2024)	Wastewater & Aquaculture	AI, ML, Cloud Computing, ANN	Optimized chlorination and membrane filtration; automated effluent treatment.
[5]	Dada et al. (2024)	Smart Water Management	Advanced Sensors, AI, Blockchain	Enhanced operational efficiency and predictive maintenance.
[11]	Humnabadkar et al. (2024)	Resource Management	IoT, Predictive Analytics, ML	Significant progress in real-time resource monitoring and sustainability.
[12]	Kukadiya et al. (2025)	Smart Cities	Leak Detection, Consumption Analysis	Improved urban water sustainability and infrastructure maintenance.
[13]	Okoli et al. (2024)	Smart Water City	3D Printing, Solar Energy, IoT	Revolutionary integration of sustainable energy and manufacturing in IoT.
[14]	Anonymous (2024)	Wastewater Plants	AI Algorithms, IoT Sensors	25% efficiency increase; 40% reduction in emergency repairs via predictive maintenance.
[18]	Slany et al. (2025)	Distribution Grids	SW-IoT, AI Integration	Improved safety and leak detection in smart distribution grids.
[19]	Das et al. (2023)	Physico-biological Treatment	Open-source IoT, Adsorption, RBC	78.9% BOD and 91.6% TDS reduction; reliable automated monitoring.
[20]	Addow et al. (2023)	Regional Monitoring (Somalia)	Low-cost sensors, SMS Alerts	Enhanced decision-making and sustainable management in developing regions.

3. Methodology in IoT-Enabled Water Treatment

The implementation of IoT in water treatment follows a multi-layered architectural approach, integrating physical hardware with sophisticated software frameworks.

3.1 Physical and Sensing Layer

The foundation of any IoT system is the sensing layer. Recent works emphasize the use of physical sensors to measure chemical and physical properties of water. Common sensors include:

- **pH Sensors:** For monitoring acidity/alkalinity, crucial in both drinking water and wastewater treatment [14], [19].
- **Turbidity Sensors:** To detect the presence of suspended solids [14].
- **Conductivity and TDS Sensors:** For measuring total dissolved solids, used to evaluate filtration efficiency [19].
- **Flow Sensors:** Often utilizing ultrasound technology for real-time effluent flow measurement [19].

Microcontrollers such as Arduino or ESP32 are frequently used as edge devices to interface with these sensors, providing initial data processing before transmission [13].

3.2 Communication and Networking Layer

Reliable data transmission is vital for real-time monitoring. Researchers utilize various communication modules and protocols based on the scale of the application:

- **MQTT (Message Queuing Telemetry Transport):** A lightweight protocol ideal for low-bandwidth, high-latency environments [2], [4].
- **LoRaWAN:** Used for long-range, low-power communication, particularly in large-scale smart water grids [2].
- **Zigbee and Wi-Fi:** Common for localized treatment plant monitoring [13].
- **Cellular (4G/5G):** While 5G integration is highlighted as a future trend, many current systems utilize 4G or GSM for SMS alerts and cloud connectivity [20].

3.3 Data Processing and AI Integration

The data collected by IoT sensors is processed using cloud computing and AI algorithms to derive actionable insights.

- **Machine Learning (ML):** Used for predictive maintenance, allowing plants to anticipate equipment failures before they occur. For example, AI integration has been shown to reduce emergency repairs by 40% [14].
- **Artificial Neural Networks (ANN):** Employed for modeling complex water quality indices and optimizing chemical dosage in processes like chlorination [1].
- **Big Data Analytics:** Essential for managing the high volume and velocity of data generated by extensive sensor networks [17].

3.4 Sustainable Integration

Recent methodologies also incorporate sustainable practices, such as the use of solar energy to power remote IoT nodes and 3D printing for rapid prototyping of sensor housings and treatment components [13].

4. Comparative Analysis of Findings

The integration of IoT has yielded measurable improvements in water treatment performance and operational management.

4.1 Efficiency and Compliance

IoT-driven automation leads to significant gains in operational efficiency. One study reported a 25% increase in efficiency following the implementation of IoT-based training and monitoring systems [14]. Furthermore, the continuous nature of IoT monitoring helps in reducing compliance violations by approximately 10% [14].

4.2 Treatment Performance

The impact on actual treatment outcomes is profound. In the biological treatment of wastewater, an IoT platform was instrumental in achieving a 78.9% reduction in biological oxygen demand (BOD) and a 52.15% reduction in chemical oxygen demand (COD). Additionally, the system achieved a 91.6% reduction in total dissolved solids (TDS) and an 88.8% reduction in optical density [19]. These results underscore the precision that IoT brings to the control of biological and physical treatment processes.

4.3 Cost and Maintenance

Predictive maintenance, enabled by the fusion of IoT and AI, has transformed the economic landscape of water treatment. The ability to perform maintenance based on real-time sensor data rather than fixed schedules has led to a 40% reduction in emergency repairs [14]. This not only saves costs but also minimizes the downtime of critical infrastructure.

5. Future Research Direction

Despite the rapid advancements, several challenges and research gaps remain that define the future trajectory of the field.

5.1 Cybersecurity and Data Privacy

As water treatment plants become increasingly interconnected, they become vulnerable to cyber-attacks. Ensuring the security of data transmission and the integrity of control systems is a paramount concern [5], [12]. Future research must focus on robust encryption, anomaly detection for cyber-threats, and the integration of blockchain for secure, decentralized data management [16].

5.2 Interoperability and Standardization

The field currently suffers from a lack of standardized protocols, making it difficult to integrate devices from different manufacturers. Developing interoperable frameworks is essential for the scalability of smart water systems [11], [12].

5.3 Scalability and Implementation Costs

While IoT offers long-term savings, the initial investment in sensors and infrastructure can be high. Research into cost-effective sensors and low-power, wide-area network (LPWAN) technologies is needed to make these systems accessible for developing regions [11], [14], [20].

5.4 Advanced AI and 5G/6G Integration

The next generation of IoT in water treatment will likely leverage 5G and future 6G networks for ultra-low latency control. Furthermore, the use of quantum computing for complex water modeling and advanced deep learning for more accurate predictive analytics represents a significant frontier [5].

5.5 Hybrid and Decentralized Systems

There is a growing interest in decentralized water treatment systems. Future work should investigate the maintenance and scalability of these systems using IoT, particularly for rural or isolated communities [14].

6. Conclusion

The application of IoT in water treatment processes represents a paradigm shift toward more sustainable, efficient, and resilient water management. By enabling real-time monitoring and integrating artificial intelligence, IoT allows for precise control over purification and wastewater treatment, leading to significant improvements in water quality and operational costs. While challenges such as cybersecurity and high implementation costs persist, the continued advancement of Industry 4.0 technologies provides a clear path forward. The synergy of IoT, AI, and emerging communication standards will undoubtedly play a central role in addressing the global water challenge, ensuring the availability of clean water for future generations.

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