World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

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Review of smart water management: IoT and AI in water and wastewater treatment

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World Journal of Advanced Research and Reviews, 2024, 21(01), 1373–1382

Publication history: Received on 05 December 2023; revised on 12 January 2024; accepted on 15 January 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.21.1.0171

Abstract

Integrating the Internet of Things (IoT) and Artificial Intelligence (AI) in smart water management revolutionizes sustainable water resource utilization. This comprehensive review explores these technologies' benefits, challenges, regulatory implications, and future trends. Smart water management enhances operational efficiency, predictive maintenance, and resource conservation while addressing data security and infrastructure investment challenges. Regulatory frameworks play a pivotal role in shaping the responsible deployment of AI and IoT, ensuring data privacy and ethical use. Future trends include advanced sensors, decentralized systems, quantum computing, and blockchain for enhanced water data security. The alignment with Sustainable Development Goals (SDGs) underscores the transformative potential of smart water management in achieving universal access to clean water, climate resilience, and inclusive, sustainable development. As we embrace these technologies, collaboration, public awareness, and ethical considerations will guide the evolution of intelligent and equitable water management systems.

Keywords: Smart Water Management; Internet of Things; Artificial Intelligence; SDGs; Water Resource Optimization

1. Introduction

Water is indispensable for sustaining life and supporting various human activities, from agriculture and industry to domestic use (Gleick, 1996, 1998). As the global population continues to grow and the effects of climate change become more pronounced, the demand for efficient and sustainable water management practices intensifies. Traditional water treatment and distribution methods face increasing challenges in meeting the demands of growing urbanization, pollution, and climate variability (Cosgrove & Loucks, 2015; Larsen, Hoffmann, Lüthi, Truffer, & Maurer, 2016).

In response to these challenges, integrating advanced technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) has emerged as a promising solution for optimizing water and wastewater treatment processes (Lowe, Qin, & Mao, 2022; Rane, 2023; Rane, Choudhary, & Rane, 2023). Smart water management, empowered by the seamless interaction between IoT devices and AI algorithms, can revolutionize monitoring, analyzing, and managing water resources. This review explores and examines the current state of smart water management, focusing on integrating IoT and AI in water and wastewater treatment.

Historically, water management relied heavily on conventional methods that often lacked real-time monitoring and control capabilities (Eggimann et al., 2017; Sun & Scanlon, 2019). This resulted in inefficiencies, increased water

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wastage, and compromised water quality. With the advent of IoT, a paradigm shift occurred in how water systems are monitored and managed. IoT devices, equipped with sensors and communication capabilities, enable the collection of vast amounts of real-time data from water treatment plants, distribution networks, and even individual households. This data forms the foundation for informed decision-making and proactive interventions in water management (Jan, Min-Allah, & Düştegör, 2021; Oberascher, Rauch, & Sitzenfrei, 2022).

The integration of AI complements the capabilities of IoT by providing advanced data analytics, predictive modeling, and decision-making algorithms. AI algorithms can analyze complex datasets, identify patterns, and predict system behavior, allowing more efficient and responsive water management. The synergistic combination of IoT and AI enhances the monitoring and control of water treatment processes. It enables the development of intelligent, adaptive systems capable of learning and optimizing performance over time (Kamyab et al., 2023; Venkateswaran, Kumar, Diwakar, Gnanasangeetha, & Boopathi, 2023).

This review examines the current literature on smart water management, specifically focusing on integrating IoT and AI technologies. The paper aims to identify key trends, challenges, and opportunities in the field by synthesizing existing knowledge. Furthermore, it intends to shed light on the potential benefits of smart water management regarding resource efficiency, environmental sustainability, and resilience to emerging water-related challenges. As water scarcity and quality issues become increasingly prevalent, understanding and harnessing the potential of IoT and AI in water and wastewater treatment is crucial for developing effective and sustainable water management strategies. This review aims to contribute to the broader conversation on smart water management, providing insights that can inform future research, policy-making, and practical implementations.

2. Smart Water Management Technologies

In the quest for sustainable and efficient water management, the Internet of Things and artificial intelligence convergence have emerged as transformative forces. When integrated seamlessly, these cutting-edge technologies form the backbone of smart water management systems. The synergy between IoT and AI enhances the monitoring and control of water infrastructure. It empowers decision-makers with advanced analytics and predictive capabilities. This paper explores the intricate workings of smart water management technologies, shedding light on how they revolutionize water governance.

At the heart of smart water management is the integration of two pivotal technologies: the Internet of Things (IoT) and Artificial Intelligence (AI). IoT refers to the network of interconnected physical devices equipped with sensors, actuators, and communication capabilities. These IoT devices span the entire water supply chain in water management, from extraction sources to distribution networks and consumer endpoints. They collect real-time data on water quality, quantity, pressure, and other relevant parameters, forming the foundation for informed decision-making (Esmaeilian, Sarkis, Lewis, & Behdad, 2020; Simmhan, Ravindra, Chaturvedi, Hegde, & Ballamajalu, 2018).

AI, on the other hand, endows smart water systems with advanced analytics and decision-making capabilities. Within AI systems, machine learning algorithms analyze the massive datasets IoT devices generate (Himeur et al., 2023; Lowe et al., 2022). They discern patterns, make predictions, and, in essence, transform raw data into actionable insights. This synergy enables smart water management systems to optimize operations, predict potential issues, and adapt to dynamic environmental conditions.

IoT technologies play a pivotal role in enhancing the monitoring and control of water infrastructure. In water treatment plants, smart sensors continuously monitor crucial parameters such as turbidity, pH levels, and chemical concentrations (Cloete, Malekian, & Nair, 2016; Park, Kim, & Lee, 2020). Throughout the distribution network, IoT-enabled devices provide real-time data on water flow, pressure, and leak detection. At the consumer end, smart meters equipped with IoT capabilities enable precise monitoring of water consumption, facilitating efficient billing and encouraging water conservation. The seamless integration of IoT in water infrastructure improves the accuracy and timeliness of data collection and enables remote monitoring and control. This capability is particularly valuable for early detection of anomalies, preventive maintenance, and rapid response to emergencies, contributing to the overall resilience of the water management system (Cloete et al., 2016; Koo, Piratla, & Matthews, 2015; Syrmos et al., 2023).

AI technologies bring intelligence to smart water management systems, particularly in optimizing water treatment processes. Machine learning algorithms within AI systems can analyze historical data to identify trends, recognize patterns, and predict future water quality fluctuations. In water treatment, AI assists in optimizing chemical dosages, energy consumption, and operational efficiency. Adaptive learning algorithms enable the system to continuously improve its performance based on real-time feedback, ensuring a more sustainable and adaptive approach to water treatment (Yang, Cao, Meng, & Si, 2021; Zhang, Tooker, & Mueller, 2020). Moreover, AI-driven predictive modeling can anticipate equipment failures, reducing downtime and maintenance costs. Through anomaly detection, AI algorithms can identify irregular water quality or system behavior irregularities, alerting operators to potential issues before they escalate. This proactive approach enhances the reliability and effectiveness of water treatment processes (Nong & Tarek, 2023; Sahu, Kaur, Singh, & Arya, 2023).

The true potential of smart water management emerges when IoT and AI technologies are seamlessly integrated, creating a holistic and adaptive system. The continuous data streams from IoT devices serve as inputs for AI algorithms, generating insights and actionable recommendations. This closed-loop integration enables real-time decision-making, allowing water management systems to respond to changing conditions dynamically. For instance, in the event of a water quality anomaly detected by IoT sensors, AI algorithms can trigger automated responses, such as adjusting treatment processes or alerting operators for manual intervention (Adeyemi, Grove, Peets, & Norton, 2017; Jansen et al., 2009). This synergy between IoT and AI transforms water management into a proactive, data-driven, and intelligent process capable of addressing challenges with agility and precision.

In conclusion, integrating IoT and AI technologies heralds a new era in water governance. Smart water management systems, fortified by the seamless collaboration of these transformative technologies, transcend traditional approaches, offering a proactive and adaptive model. By providing real-time insights, optimizing operations, and predicting potential issues, these technologies empower decision-makers to navigate the complexities of water management with unprecedented efficiency. As we embrace the digital age, the convergence of IoT and AI is a beacon, guiding the way towards a more sustainable and resilient water future.

3. Benefits and Challenges

3.1. Benefits of Smart Water Management Technologies

The fusion of the Internet of Things and Artificial Intelligence has ushered in a transformative era in water management, offering myriad benefits that contribute to operational efficiency, sustainability, and resilience. This technological synergy harnesses real-time data from IoT sensors. It employs AI-driven analytics to revolutionize the monitoring and control of water treatment processes. The result is improved operational performance and a cascade of advantages, including reduced energy consumption, minimized chemical usage, and a significant leap forward in resource conservation.

Central to the advantages of smart water management technologies is the substantial enhancement of operational efficiency. The marriage of IoT and AI allows for real-time monitoring and control of water treatment processes. This optimization is pivotal in reducing energy consumption, a critical factor in the sustainable operation of water treatment facilities. By leveraging AI-driven analytics, water utilities can fine-tune their processes, ensuring the right amount of resources is utilized precisely when needed (Vaughan, 2020). Consequently, this improves the economic viability of water treatment operations and contributes to a reduced carbon footprint, aligning with global sustainability objectives.

The integration of AI introduces predictive capabilities that redefine maintenance strategies within water management systems. Fueled by historical data, machine learning algorithms can accurately predict potential equipment failures (Sun & Scanlon, 2019; Xiang, Li, Khan, & Khalaf, 2021). This foresight empowers water utilities to implement preventive maintenance measures, addressing issues before they escalate. The ripple effect of proactive maintenance is substantial; it minimizes downtime, ensures uninterrupted water supply to communities, and extends the lifespan of critical infrastructure components (Itzwerth, 2013). These preventive measures translate into significant cost savings for water utilities, underlining the economic advantages of incorporating smart technologies.

Smart water management plays a pivotal role in conserving precious water resources. IoT-enabled devices, such as smart meters, empower consumers to monitor and manage their water usage actively. This transparency fosters a sense of responsibility among consumers, encouraging water conservation at the individual level. Furthermore, AI-driven optimization within water treatment processes minimizes water wastage, ensuring that resources are utilized efficiently (Gaudio et al., 2021; Gunasekaran & Boopathi, 2023). This dual focus on consumer-level monitoring and treatment process optimization aligns seamlessly with broader sustainability goals, addressing challenges posed by water scarcity and emphasizing responsible water consumption practices.

The amalgamation of IoT and AI significantly enhances the resilience of water systems through early anomaly detection and swift response mechanisms. Automated responses triggered by AI algorithms enable rapid adjustments to treatment processes or immediate alerts to operators in the face of potential issues (Chatterjee & Ahmed, 2022; Rane et al., 2023). This capability proves critical in addressing emergencies, preventing water contamination, and ensuring the continuous supply of clean water to communities. By identifying anomalies in real-time, smart water management technologies empower water utilities to intervene promptly, mitigating risks and safeguarding public health.

3.2. Challenges of Smart Water Management Technologies

Integrating the IoT devices into water infrastructure represents a significant leap towards achieving more efficient and sustainable water management. However, as the proliferation of these technologies grows, it brings forth a myriad of challenges that need careful consideration to ensure the security, affordability, interoperability, and ethical deployment of smart water management systems.

One of the foremost challenges arises from the increased volume of sensitive data collected by IoT devices in water infrastructure (Kimani, Oduol, & Langat, 2019). The very nature of these devices, designed to monitor and optimize water management systems, means they amass critical data. The challenge lies in safeguarding this data against unauthorized access or manipulation. A breach in security could have severe consequences, compromising the integrity of water management systems. The potential risks range from tampering with water quality data to causing service disruptions. As smart water technologies become more integral to our water infrastructure, finding robust solutions to protect against cyber threats becomes imperative (Djenna, Harous, & Saidouni, 2021; Khang, Gupta, Rani, & Karras, 2023).

The implementation of smart water management technologies involves substantial upfront costs, creating a financial barrier that many water utilities, especially those in resource-constrained regions, may find challenging to overcome. Deploying IoT devices, sensors, and AI infrastructure requires significant initial investments. Balancing these costs with the anticipated long-term benefits poses a complex challenge for the widespread adoption of smart water technologies. Innovations in funding models and collaborations between public and private entities may offer potential solutions to overcome these financial barriers, ensuring that the benefits of these technologies are accessible to a broader range of communities (Dahan, Doh, Oetzel, & Yaziji, 2010; Ndou, 2004).

Technological integration and interoperability present another hurdle to the seamless implementation of smart water management systems (Ahmad, Cuomo, Wu, & Jeon, 2019; Mounce, 2021). The market offers diverse IoT devices and AI solutions with unique specifications and functionalities. Standardization efforts ensure that these devices and solutions can communicate seamlessly. Lack of standardization may hinder the scalability and compatibility of smart water technologies across various water infrastructure setups (Overmars & Venkatraman, 2020). Establishing common protocols and frameworks becomes essential to unlock the full potential of these technologies and promote widespread adoption.

One often overlooked challenge in adopting smart water technologies is the need for specialized knowledge and skills. Water utilities are tasked with recruiting and retaining personnel proficient in water management and advanced technologies such as IoT, AI, and data analytics (Geetha & Bhanu, 2018). Bridging the knowledge gap between traditional water management practices and cutting-edge technologies is essential for successfully implementing and maintaining smart water systems. Furthermore, fostering interdisciplinary collaboration is crucial to creating a workforce that effectively navigates water management and technological innovation complexities.

As smart water technologies evolve, they bring forth regulatory and ethical considerations that demand careful attention. Clear guidelines and regulations must be established to address data ownership, consent, and the responsible use of AI in decision-making processes. The evolving nature of these technologies requires a regulatory framework that is flexible enough to adapt to future advancements while maintaining ethical standards. Striking a balance between fostering innovation and upholding ethical principles is crucial for building public trust and ensuring the responsible deployment of smart water management technologies.

4. Regulatory and Policy Implications

As smart water management technologies, leveraging IoT and AI, become integral components of modern water infrastructure, the regulatory landscape must evolve to address emerging challenges and opportunities. Existing regulations primarily focus on ensuring water quality, safety, and accessibility. Regulatory bodies worldwide set standards for water treatment processes, permissible contaminant levels, and distribution system integrity. However, these regulations often lack specific provisions for incorporating advanced technologies like IoT and AI.

Integrating smart water management technologies into existing policies requires carefully examining how these innovations align with current regulatory frameworks. Policies related to water quality standards, environmental protection, and public health may need updates to account for the dynamic nature of IoT data and the decision-making processes facilitated by AI. The adaptability of regulations to technological advancements is crucial to fostering innovation while ensuring the continued protection of water resources. The vast amount of data generated by IoT devices in smart water systems raises questions about data ownership and privacy. Regulations must define clear guidelines on who owns the data, how it can be used, and under what circumstances it can be shared. Protecting consumer privacy and ensuring secure data handling practices are paramount to building public trust in smart water management technologies (de Almeida, dos Santos, & Farias, 2021).

Regulatory bodies are crucial in driving standardization efforts for smart water management technologies. Establishing industry-wide standards ensures interoperability among different devices and systems. Regulatory guidelines should encourage developing and adopting open standards to facilitate seamless integration, reduce technological barriers, and promote a competitive market for innovative solutions. Given the critical nature of water infrastructure, regulatory frameworks should include specific standards addressing the cybersecurity and resilience of smart water management systems. Requirements for encryption, secure communication protocols, and measures to safeguard against cyber threats are essential components of regulatory frameworks. Standards for ensuring the resilience of systems to natural disasters and other emergencies should also be considered (Loukas, Gan, & Vuong, 2013; Markopoulou & Papakonstantinou, 2021).

Regulatory guidelines must address the ethical considerations associated with AI in water management. Transparent decision-making processes, accountability mechanisms, and safeguards against biased algorithms are crucial aspects that should be incorporated into regulations (Zerilli, Knott, Maclaurin, & Gavaghan, 2019). Ethical guidelines can help prevent the misuse of AI and foster responsible innovation in smart water technologies. Regulations should encourage public engagement and awareness regarding deploying smart water management technologies. Clear communication on these technologies' benefits, risks, and ethical considerations is essential for gaining public trust. Informed public participation can also shape regulatory frameworks that reflect societal values and priorities (Goldenfein, 2019).

Given the global nature of water challenges, international collaboration is crucial for developing consistent regulatory frameworks. Collaborative efforts can facilitate information sharing, harmonize standards, and ensure a coordinated approach to addressing cross-border water issues. International organizations and agreements can be pivotal in promoting best practices and fostering a unified regulatory environment.

5. Future Trends and Emerging Technologies

The future of smart water management will witness the integration of advanced sensors capable of providing more granular and diverse data. Miniaturized, low-cost sensors can monitor a broader range of water parameters with increased sensitivity. These sensors may include emerging technologies such as biosensors and nanosensors, enabling real-time detection of contaminants at extremely low concentrations. A shift towards decentralized water treatment systems is anticipated, driven by advancements in modular and scalable technologies. Decentralized systems leverage IoT and AI to enable local water treatment at the community or individual level, reducing the need for large, centralized treatment plants. This trend aligns with the principles of resilience and adaptability, offering solutions for urban and remote areas (Daigger, Voutchkov, Lall, & Sarni; Huang et al., 2023).

The advent of quantum computing holds promise for revolutionizing water modeling and simulation. Quantum algorithms can handle complex computations required for modeling water systems with unprecedented speed and efficiency. This can lead to more accurate predictions, optimization of treatment processes, and enhanced understanding of the interconnected factors influencing water quality. Blockchain technology will likely play a significant role in ensuring the security and integrity of water-related data. Blockchain's decentralized and immutable ledger system can enhance transparency, traceability, and data integrity. This is particularly important in IoT-generated data, where secure and tamper-proof records are essential for maintaining public trust and regulatory compliance (Mohammed et al., 2023; Silva, 2018).

The integration of augmented reality (AR) in water infrastructure maintenance and training is an emerging trend. AR applications can provide real-time data visualization, facilitating maintenance tasks and aiding operators in decision-making. Additionally, AR can be utilized for training, offering immersive simulations for water treatment plant operators to enhance their skills and responsiveness. The concept of digital twins, virtual replicas of physical water systems, is evolving with the incorporation of AI. AI-powered digital twins leverage machine learning algorithms to learn and adapt continuously based on real-world data. This technology enables more accurate modeling, predictive analytics, and scenario testing, supporting dynamic decision-making for optimizing water treatment processes and system performance (Hou et al., 2017; Radhakrishnan, Koumaditis, & Chinello, 2021).

Energy harvesting technologies are emerging to address the challenge of powering remote or inaccessible IoT devices. These technologies, including solar, kinetic, and thermal energy harvesting, can generate power for sensors and devices, reducing the reliance on traditional batteries. This advancement contributes to sustainable and self-sufficient IoT deployments in water management. The integration of citizen science initiatives and crowdsourced data collection is gaining prominence. Mobile apps and community engagement platforms allow individuals to contribute data on water quality, leaks, or other relevant parameters. This collaborative approach enhances data's spatial and temporal coverage, providing valuable insights for water management authorities (Walker, Smigaj, & Tani, 2021).

Given the increasing impacts of climate change on water availability and quality, future trends in smart water management will emphasize climate-responsive strategies. AI algorithms will be employed to analyze climate data, predict extreme weather events, and dynamically adjust water treatment processes to mitigate the impacts of climate-related challenges. Future trends in smart water management will see increased collaboration between the water sector and other industries. Integration with smart city initiatives, agriculture, and industrial processes will lead to holistic approaches to water resource management. Cross-sector collaboration can result in more comprehensive data sets and innovative solutions to address water challenges. As smart water management continues to evolve, staying abreast of these future trends and emerging technologies will be crucial for researchers, policymakers, and industry professionals. The proactive adoption of these innovations has the potential to enhance the efficiency, resilience, and sustainability of water systems globally.

6. Integration with Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) outlined by the United Nations provide a comprehensive framework for addressing global challenges and fostering sustainable development. Water is a fundamental element underpinning several SDGs, notably SDG 6, which focuses on ensuring the availability and sustainable management of water and sanitation for all. The integration of smart water management technologies aligns closely with multiple SDGs, contributing to the broader agenda of promoting environmental sustainability, economic development, and social equity.

Smart water management directly addresses the objectives of SDG 6 by enhancing the efficiency and effectiveness of water resource utilization. The deployment of IoT and AI technologies in water treatment processes, distribution networks, and consumption monitoring contributes to achieving SDG 6 targets related to universal access to safe and affordable drinking water, adequate sanitation, and sustainable water management practices (Aivazidou et al., 2021; Liu, Yang, & Yang, 2021). The integration of smart water management technologies promotes resource efficiency, aligning with SDG 12, which focuses on responsible consumption and production. By optimizing water treatment processes, minimizing wastage, and enhancing distribution system efficiency, these technologies contribute to the sustainable use of water resources, reducing the environmental impact associated with water extraction and treatment (Bengtsson, Alfredsson, Cohen, Lorek, & Schroeder, 2018; Chan, Weitz, Persson, & Trimmer, 2018).

The impact of climate change on water availability and quality necessitates proactive measures, aligning with SDG 13 on climate action. Smart water management, with its predictive capabilities and adaptability to changing climate conditions, supports SDG 13 by enhancing resilience against climate-related challenges (Delany-Crowe, Marinova, Fisher, McGreevy, & Baum, 2019; Mthembu & Nhamo, 2022). The integration of climate-responsive strategies in water systems contributes to the broader goal of mitigating the impacts of climate change. SDG 9 emphasizes the development of resilient infrastructure, promoting inclusive and sustainable industrialization. Smart water management technologies are crucial in advancing this goal by providing innovative solutions for water infrastructure. Integrating IoT and AI fosters the development of intelligent, adaptable systems that contribute to the overall resilience and sustainability of water-related infrastructure (Bhaduri et al., 2016; Singh, 2023).

SDG 17 highlights the importance of partnerships for achieving sustainable development goals. Integrating smart water management requires collaboration among government agencies, private sectors, academia, and local communities. Cross-sectoral alliances can lead to sharing expertise, resources, and technology, fostering a collective effort toward achieving SDG 6 and other interconnected sustainability goals (Arbeiter & Bucar, 2021; Horan, 2022). Smart water management technologies can contribute to achieving SDG 5 (Gender Equality) and SDG 10 (Reduced Inequalities) by ensuring inclusive access to clean water and sanitation (Bachmann, Tripathi, Brunner, & Jodlbauer, 2022; Tang, 2022). IoT-enabled solutions, such as smart meters, empower individuals to monitor and manage their water consumption, providing equitable access to information and promoting responsible water use.

The data-driven nature of smart water management facilitates the monitoring and reporting progress towards SDG targets. Real-time data collection and analytics enable authorities to assess water quality, consumption patterns, and infrastructure performance. This information is vital for evidence-based decision-making, policy formulation, and measuring the impact of interventions to achieve SDG objectives (Agbozo, 2018; Mukonza & Chiang, 2023). While smart water management aligns with the SDGs, affordability, accessibility, and inclusivity must be addressed. Ensuring that the benefits of these technologies reach vulnerable and marginalized populations is essential for achieving the overarching goal of leaving no one behind.

7. Conclusion

The evolution of smart water management, driven by integrating IoT and AI technologies, represents a transformative shift in our approach to water resource sustainability. This review has explored the myriad facets of this dynamic field, analyzing the benefits, challenges, regulatory implications, future trends, and alignment with SDGs.

The benefits of smart water management technologies are evident in the improved operational efficiency, predictive maintenance, resource conservation, and enhanced resilience of water systems. These technologies optimize water treatment processes and contribute to a more sustainable and equitable distribution of water resources. As we navigate the challenges of data security, high initial costs, and technological integration, addressing these issues will be crucial to realizing the full potential of smart water management. Regulatory and policy frameworks play a pivotal role in shaping the trajectory of smart water management. Clear guidelines are necessary to address data security, privacy, standardization, and ethical considerations associated with AI and IoT technologies. As regulatory bodies adapt to the evolving landscape, collaborative efforts at national and international levels become imperative for ensuring a harmonized approach that fosters innovation while upholding ethical standards.

The exploration of future trends and emerging technologies has illuminated a path toward more advanced, decentralized, and climate-responsive water management systems. From quantum computing to augmented reality, the integration of cutting-edge technologies holds promise for further enhancing the efficiency, adaptability, and sustainability of water infrastructure. Finally, the alignment of smart water management with the Sustainable Development Goals underscores its significance in the broader context of global development. By contributing to SDG 6 and interconnected goals, these technologies offer a pathway towards universal access to clean water, climate resilience, and inclusive, sustainable development.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Adeyemi, O., Grove, I., Peets, S., & Norton, T. (2017). Advanced monitoring and management systems for improving sustainability in precision irrigation. *Sustainability, 9*(3), 353.

[2] Agbozo, E. (2018). The role of data-driven e-government in realizing the sustainable development goals in developing economies. *Journal of Information Systems & Operations Management, 12*(1), 70-77.

[3] Ahmad, A., Cuomo, S., Wu, W., & Jeon, G. (2019). Intelligent algorithms and standards for interoperability in Internet of Things. In (Vol. 92, pp. 1187-1191): Elsevier.

[4] Aivazidou, E., Banias, G., Lampridi, M., Vasileiadis, G., Anagnostis, A., Papageorgiou, E., & Bochtis, D. (2021). Smart technologies for sustainable water management: An urban analysis. *Sustainability, 13*(24), 13940.

[5] Arbeiter, J., & Bucar, M. (2021). Cross-sectoral cooperation. *Bridge: Los Angeles, CA, USA, 47*.

[6] Bachmann, N., Tripathi, S., Brunner, M., & Jodlbauer, H. (2022). The contribution of data-driven technologies in achieving the sustainable development goals. *Sustainability, 14*(5), 2497.

[7] Bengtsson, M., Alfredsson, E., Cohen, M., Lorek, S., & Schroeder, P. (2018). Transforming systems of consumption and production for achieving the sustainable development goals: Moving beyond efficiency. *Sustainability science, 13*, 1533-1547.

[8] Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., . . . Foster, S. (2016). Achieving sustainable development goals from a water perspective. *Frontiers in Environmental Science*, 64.

[9] Chan, S., Weitz, N., Persson, Å., & Trimmer, C. (2018). SDG 12: responsible consumption and production. *A Review of Research Needs. Technical annex to the Formas report Forskning för Agenda, 2030*.

[10] Chatterjee, A., & Ahmed, B. S. (2022). IoT anomaly detection methods and applications: A survey. *Internet of Things, 19*, 100568.

[11] Cloete, N. A., Malekian, R., & Nair, L. (2016). Design of smart sensors for real-time water quality monitoring. *IEEE access, 4*, 3975-3990.

[12] Cosgrove, W. J., & Loucks, D. P. (2015). Water management: Current and future challenges and research directions. *Water Resources Research, 51*(6), 4823-4839.

[13] Dahan, N. M., Doh, J. P., Oetzel, J., & Yaziji, M. (2010). Corporate-NGO collaboration: Co-creating new business models for developing markets. *Long range planning, 43*(2-3), 326-342.

[14] Daigger, G. T., Voutchkov, N., Lall, U., & Sarni, W. The Future of Water. *Water and Sanitation Division*.

[15] de Almeida, P. G. R., dos Santos, C. D., & Farias, J. S. (2021). Artificial intelligence regulation: a framework for governance. *Ethics and Information Technology, 23*(3), 505-525.

[16] Delany-Crowe, T., Marinova, D., Fisher, M., McGreevy, M., & Baum, F. (2019). Australian policies on water management and climate change: are they supporting the sustainable development goals and improved health and well-being? *Globalization and health, 15*, 1-15.

[17] Djenna, A., Harous, S., & Saidouni, D. E. (2021). Internet of things meet internet of threats: New concern cyber security issues of critical cyber infrastructure. *Applied Sciences, 11*(10), 4580.

[18] Eggimann, S., Mutzner, L., Wani, O., Schneider, M. Y., Spuhler, D., Moy de Vitry, M., . . . Maurer, M. (2017). The potential of knowing more: A review of data-driven urban water management. *Environmental science & technology, 51*(5), 2538-2553.

[19] Esmaeilian, B., Sarkis, J., Lewis, K., & Behdad, S. (2020). Blockchain for the future of sustainable supply chain management in Industry 4.0. *Resources, Conservation and Recycling, 163*, 105064.

[20] Gaudio, M. T., Coppola, G., Zangari, L., Curcio, S., Greco, S., & Chakraborty, S. (2021). Artificial intelligence-based optimization of industrial membrane processes. *Earth Systems and Environment, 5*(2), 385-398.

[21] Geetha, R., & Bhanu, S. R. D. (2018). Recruitment through artificial intelligence: a conceptual study. *International Journal of Mechanical Engineering and Technology, 9*(7), 63-70.

[22] Gleick, P. H. (1996). Basic water requirements for human activities: Meeting basic needs. *Water international, 21*, 83-92.

[23] Gleick, P. H. (1998). Water in crisis: paths to sustainable water use. *Ecological applications, 8*(3), 571-579.

[24] Goldenfein, J. (2019). Algorithmic transparency and decision-making accountability: Thoughts for buying machine learning algorithms. *Jake Goldenfein,'Algorithmic Transparency and Decision-Making Accountability: Thoughts for buying machine learning algorithms' in Office of the Victorian Information Commissioner (ed), Closer to the Machine: Technical, Social, and Legal aspects of AI (2019)*.

[25] Gunasekaran, K., & Boopathi, S. (2023). Artificial Intelligence in Water Treatments and Water Resource Assessments. In *Artificial Intelligence Applications in Water Treatment and Water Resource Management* (pp. 71-98): IGI Global.

[26] Himeur, Y., Elnour, M., Fadli, F., Meskin, N., Petri, I., Rezgui, Y., . . . Amira, A. (2023). AI-big data analytics for building automation and management systems: a survey, actual challenges and future perspectives. *Artificial Intelligence Review, 56*(6), 4929-5021.

[27] Horan, D. (2022). A framework to harness effective partnerships for the sustainable development goals. *Sustainability science, 17*(4), 1573-1587.

[28] Hou, L., Chi, H.-L., Tarng, W., Chai, J., Panuwatwanich, K., & Wang, X. (2017). A framework of innovative learning for skill development in complex operational tasks. *Automation in construction, 83*, 29-40.

[29] Huang, Y., Zhang, J., Ren, Z., Xiang, W., Sifat, I., Zhang, W., . . . Li, B. (2023). Next generation decentralized water systems: a water-energy-infrastructure-human nexus (WEIHN) approach. *Environmental Science: Water Research & Technology*.

[30] Itzwerth, R. (2013). *Critical infrastructure and preparedness-perspectives on pandemic influenza.* UNSW Sydney,

[31] Jan, F., Min-Allah, N., & Düştegör, D. (2021). Iot based smart water quality monitoring: Recent techniques, trends and challenges for domestic applications. *Water, 13*(13), 1729.

[32] Jansen, J.-D., Douma, S., Brouwer, D. R., Van den Hof, P., Bosgra, O., & Heemink, A. (2009). *Closed-loop reservoir management.* Paper presented at the SPE Reservoir Simulation Conference?

[33] Kamyab, H., Khademi, T., Chelliapan, S., SaberiKamarposhti, M., Rezania, S., Yusuf, M., . . . Ahn, Y. (2023). The latest innovative avenues for the utilization of artificial Intelligence and big data analytics in water resource management. *Results in Engineering*, 101566.

[34] Khang, A., Gupta, S. K., Rani, S., & Karras, D. A. (2023). *Smart Cities: IoT Technologies, big data solutions, cloud platforms, and cybersecurity techniques*: CRC Press.

[35] Kimani, K., Oduol, V., & Langat, K. (2019). Cyber security challenges for IoT-based smart grid networks. *International journal of critical infrastructure protection, 25*, 36-49.

[36] Koo, D., Piratla, K., & Matthews, C. J. (2015). Towards sustainable water supply: schematic development of big data collection using internet of things (IoT). *Procedia engineering, 118*, 489-497.

[37] Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B., & Maurer, M. (2016). Emerging solutions to the water challenges of an urbanizing world. *Science, 352*(6288), 928-933.

[38] Liu, Q., Yang, L., & Yang, M. (2021). Digitalisation for water sustainability: Barriers to implementing circular economy in smart water management. *Sustainability, 13*(21), 11868.

[39] Loukas, G., Gan, D., & Vuong, T. (2013). A review of cyber threats and defence approaches in emergency management. *Future Internet, 5*(2), 205-236.

[40] Lowe, M., Qin, R., & Mao, X. (2022). A review on machine learning, artificial intelligence, and smart technology in water treatment and monitoring. *Water, 14*(9), 1384.

[41] Markopoulou, D., & Papakonstantinou, V. (2021). The regulatory framework for the protection of critical infrastructures against cyberthreats: Identifying shortcomings and addressing future challenges: The case of the health sector in particular. *Computer law & security review, 41*, 105502.

[42] Mohammed, M. A., Lakhan, A., Abdulkareem, K. H., Abd Ghani, M. K., Marhoon, H. A., Kadry, S., . . . Zapirain, B. G. (2023). Industrial Internet of Water Things architecture for data standarization based on blockchain and digital twin technology☆. *Journal of Advanced Research*.

[43] Mounce, S. R. (2021). Data science trends and opportunities for smart water utilities. *ICT for Smart Water Systems: Measurements and Data Science*, 1-26.

[44] Mthembu, D. E., & Nhamo, G. (2022). Aligning SDG 13 with South Africa's development agenda: Adaptation policies and institutional frameworks. *Jàmbá-Journal of Disaster Risk Studies, 14*(1), 1155.

[45] Mukonza, S. S., & Chiang, J.-L. (2023). Meta-Analysis of Satellite Observations for United Nations Sustainable Development Goals: Exploring the Potential of Machine Learning for Water Quality Monitoring. *Environments, 10*(10), 170.

[46] Ndou, V. (2004). E-government for developing countries: Opportunities and challenges. *Electron. J. Inf. Syst. Dev. Ctries., 18*(1), 1-24.

[47] Nong, N. B., & Tarek, M. (2023). Surveillance Approaches to Intrusion Detection, Crop Health, and Disease Prevention in Agriculture. *Quarterly Journal of Emerging Technologies and Innovations, 8*(3), 1-17.

[48] Oberascher, M., Rauch, W., & Sitzenfrei, R. (2022). Towards a smart water city: A comprehensive review of applications, data requirements, and communication technologies for integrated management. *Sustainable Cities and Society, 76*, 103442.

[49] Overmars, A., & Venkatraman, S. (2020). Towards a secure and scalable iot infrastructure: A pilot deployment for a smart water monitoring system. *Technologies, 8*(4), 50.

[50] Park, J., Kim, K. T., & Lee, W. H. (2020). Recent advances in information and communications technology (ICT) and sensor technology for monitoring water quality. *Water, 12*(2), 510.

[51] Radhakrishnan, U., Koumaditis, K., & Chinello, F. (2021). A systematic review of immersive virtual reality for industrial skills training. *Behaviour & Information Technology, 40*(12), 1310-1339.

[52] Rane, N. (2023). Integrating Leading-Edge Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Technologies for Smart and Sustainable Architecture, Engineering and Construction (AEC) Industry: Challenges and Future Directions. *Engineering and Construction (AEC) Industry: Challenges and Future Directions (September 24, 2023)*.

[53] Rane, N., Choudhary, S., & Rane, J. (2023). Leading-edge Artificial Intelligence (AI), Machine Learning (ML), Blockchain, and Internet of Things (IoT) technologies for enhanced wastewater treatment systems. *Machine Learning (ML), Blockchain, and Internet of Things (IoT) technologies for enhanced wastewater treatment systems (October 31, 2023)*.

[54] Sahu, S., Kaur, A., Singh, G., & Arya, S. K. (2023). Harnessing the potential of microalgae-bacteria interaction for eco-friendly wastewater treatment: A review on new strategies involving machine learning and artificial intelligence. *Journal of Environmental Management, 346*, 119004.

[55] Silva, D. M. M. L. S. d. (2018). *Blockchain as a service for bioeconomy agri-sector. An exploratory study of blockchain in the European bioeconomy.*

[56] Simmhan, Y., Ravindra, P., Chaturvedi, S., Hegde, M., & Ballamajalu, R. (2018). Towards a data-driven IoT software architecture for smart city utilities. *Software: Practice and Experience, 48*(7), 1390-1416.

[57] Singh, B. (2023). Federated learning for envision future trajectory smart transport system for climate preservation and smart green planet: Insights into global governance and SDG-9 (Industry, Innovation and Infrastructure). *National Journal of Environmental Law, 6*(2), 6-17.

[58] Sun, A. Y., & Scanlon, B. R. (2019). How can Big Data and machine learning benefit environment and water management: a survey of methods, applications, and future directions. *Environmental Research Letters, 14*(7), 073001.

[59] Syrmos, E., Sidiropoulos, V., Bechtsis, D., Stergiopoulos, F., Aivazidou, E., Vrakas, D., . . . Vlahavas, I. (2023). An intelligent modular water monitoring iot system for real-time quantitative and qualitative measurements. *Sustainability, 15*(3), 2127.

[60] Tang, C. S. (2022). Innovative technology and operations for alleviating poverty through women's economic empowerment. *Production and Operations Management, 31*(1), 32-45.

[61] Vaughan, D. (2020). *Analytical Skills for AI and Data Science: Building Skills for an AI-Driven Enterprise*: " O'Reilly Media, Inc.".

[62] Venkateswaran, N., Kumar, S. S., Diwakar, G., Gnanasangeetha, D., & Boopathi, S. (2023). Synthetic Biology for Waste Water to Energy Conversion: IoT and AI Approaches. *Applications of Synthetic Biology in Health, Energy, and Environment*, 360-384.

[63] Walker, D. W., Smigaj, M., & Tani, M. (2021). The benefits and negative impacts of citizen science applications to water as experienced by participants and communities. *Wiley Interdisciplinary Reviews: Water, 8*(1), e1488.

[64] Xiang, X., Li, Q., Khan, S., & Khalaf, O. I. (2021). Urban water resource management for sustainable environment planning using artificial intelligence techniques. *Environmental Impact Assessment Review, 86*, 106515.

[65] Yang, Q., Cao, W., Meng, W., & Si, J. (2021). Reinforcement-learning-based tracking control of waste water treatment process under realistic system conditions and control performance requirements. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 52*(8), 5284-5294.

[66] Zerilli, J., Knott, A., Maclaurin, J., & Gavaghan, C. (2019). Transparency in algorithmic and human decision-making: is there a double standard? *Philosophy & Technology, 32*, 661-683.

[67] Zhang, W., Tooker, N. B., & Mueller, A. V. (2020). Enabling wastewater treatment process automation: leveraging innovations in real-time sensing, data analysis, and online controls. *Environmental Science: Water Research & Technology, 6*(11), 2973-2992.