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Digital Twin Technology in Water Treatment: Real-Time Process Optimization and Environmental Impact Reduction

Udu Chukwudi Emeka and Okpala Charles Chikwendu
Industrial/Production Engineering Department,
Nnamdi Azikiwe University, P.M.B. 5025 Awka,
Anambra State – Nigeria

Abstract
The growing demand for sustainable and efficient water treatment has accelerated the adoption of advanced technologies aimed at optimizing processes and reducing environmental impacts. This study focuses on the integration of Digital Twin (DT) technology into water treatment systems, emphasizing real-time process optimization and environmental impact reduction. Digital Twins, as virtual replicas of physical assets, enable continuous monitoring, simulation, and predictive analysis, offering valuable insights for process enhancement. This research develops and implements a DT framework specifically designed for water treatment facilities, combining real-time data acquisition, machine learning algorithms, and process simulation models. By synchronizing data between the physical system and its virtual counterpart, the DT facilitates proactive decision-making, predictive maintenance, and adaptive process control. The study assesses the technology's ability to optimize critical parameters such as energy consumption, chemical usage, and water recovery rates, while reducing waste generation and greenhouse gas emissions. Additionally, the research addresses challenges in DT integration, including data interoperability, computational demands, and cyber security risks, and suggests strategies to mitigate these issues. This study expands the understanding of Digital Twin applications in environmental engineering, showcasing their potential to transform water treatment by enabling real-time optimization and promoting sustainability. The findings offer valuable guidance for policymakers, industry leaders, and engineers in advancing water treatment practices towards long-term environmental goals.
Keywords*: digital twin technology, water treatment, process optimization, environmental sustainability, predictive maintenance, smart water management, AI*

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I. Introduction

The growing global demand for sustainable and efficient water treatment solutions has driven the integration of advanced technologies aimed at enhancing operational performance while reducing environmental impacts. Among these cutting-edge innovations, Digital Twin (DT) technology has emerged as a transformative force in the water treatment sector. DT is defined as the virtual representation of an existing physical entity, integrating mathematical models, real-time data, and cutting-edge analytics to monitor, predict and control the condition of the real-world part through the virtual model (Nwamekwe and Okpala, 2025a; Okpala et al., 2025; Nwamekwe et al., 2025). This integration allows for continuous monitoring, simulation, and predictive analysis, providing actionable insights that support process optimization and environmental stewardship.

In the context of water treatment, DT technology facilitates real-time process optimization, granting operators the ability to visualize and control treatment processes with unparalleled precision. By aggregating data from diverse sources, including IoT sensors, Supervisory Control and Data Acquisition (SCADA) systems, and historical datasets, a cohesive virtual model is created. This model enables the simulation of various scenarios, forecasting of outcomes, and proactive adjustments to the treatment process. As a result, operational efficiency improves, energy consumption decreases, and chemical usage is minimized, reducing the environmental footprint of water treatment facilities. Research indicates that implementing DT technology can achieve up to a 30% reduction in energy consumption in wastewater treatment plants (Li, 2025).

Beyond process optimization, DT technology significantly enhances predictive maintenance and asset management in water treatment infrastructures. Continuous monitoring of equipment conditions and performance indicators allows for the early detection of potential failures, preventing minor issues from escalating into major operational disruptions. This predictive approach reduces downtime and maintenance costs while extending asset lifespans. The virtual model offers comprehensive insights into asset lifecycles, facilitating optimized maintenance schedules and informed decisions regarding equipment upgrades or replacements (Nagpal et al., 2024). Such proactive maintenance strategies align with broader goals of sustainability and resource efficiency.

The environmental benefits of integrating DT technology into water treatment processes are extensive. By fine-tuning operational parameters, DTs contribute to lower greenhouse gas emissions and enhanced conservation of water resources. AI-driven DTs, for example, have demonstrated a 16% reduction in energy consumption, underscoring their potential in promoting more sustainable practices (Nagpal et al., 2024). Furthermore, the ability to simulate and predict treatment outcomes empowers operators to implement strategies that minimize waste production, improving the overall sustainability of water treatment operations.

Despite the clear advantages, the widespread adoption of DT technology in water treatment faces several challenges. Data interoperability, computational demands, and cybersecurity concerns are among the primary obstacles. Integrating diverse data sources necessitates robust data management frameworks and standardized communication protocols. Real-time simulations require scalable infrastructure and advanced algorithms capable of efficiently processing large datasets. Additionally, ensuring cybersecurity is critical to safeguarding the integrity and reliability of both the virtual and physical components of the DT ecosystem (Mohsin et al., 2023).

II. Overview of Digital Twin Technology Applications in Water Treatment

Digital Twin Technology has become an innovative tool in water treatment, offering real-time monitoring, process optimization, and enhanced environmental sustainability. By creating virtual replicas of physical water treatment systems, DT allow operators to simulate, analyze, and optimize processes without disrupting actual operations. This integration enhances efficiency in resource consumption, pollutant management, predictive maintenance, and system performance. Table 1 provides an overview of key applications of DT Technology within water treatment processes, highlighting their functions, benefits, and real-world examples that demonstrate the transformative potential of this technology.

Table 1: Overview of Digital Twin Applications in Water Treatment

Application	Function	Benefits	Examples
Real-Time Process Monitoring	Continuous data collection from sensors to track system performance.	Improved operational control, early fault detection.	Syed et al. (2024) – Municipal plants.
Predictive Maintenance	Uses data analytics to forecast equipment failures and maintenance needs.	Reduced downtime, extended equipment lifespan.	Fantozzi et al. (2025) – Filtration units.
Resource Optimization	Optimizes chemical dosing, energy usage, and water flow.	Lower resource consumption, cost savings.	Hartmann et al. (2025) – Energy savings.
Pollutant Management	Simulates contaminant removal processes to improve efficiency.	Enhanced effluent quality, reduced pollutant discharge.	Lumley et al. (2024) – Industrial plants.
Emergency Response Planning	Models extreme scenarios (e.g., floods) to prepare for operational risks.	Increased resilience, improved crisis management.	Sánchez (2020) – Flood risk simulation.
Wastewater Reclamation and Reuse	Simulates treatment processes for water reuse in circular economy models.	Supports sustainability goals, resource recovery.	Chouraik et al. (2024) – Reuse projects.
Energy Efficiency Analysis	Tracks and optimizes energy consumption throughout the treatment process.	Reduced energy costs, lower carbon footprint.	Oliha et al. (2024) – Plant energy audits.
Regulatory Compliance Monitoring	Ensures treatment processes meet environmental and safety standards.	Improved compliance, reduced legal risks.	Janisar et al. (2024) – Effluent control

Digital Twin Technology in Water Treatment

Digital Twin Technology in water treatment offers transformative capabilities by creating real-time virtual replicas of physical treatment systems. This integration enables continuous monitoring, simulation, and optimization, enhancing operational efficiency and supporting sustainable practices. Through the combination of IoT sensors, AI-driven analytics, and cloud computing, Digital Twins optimize resource utilization, reduce environmental impact, and ensure high-quality water treatment.

Concept and Components of Digital Twins

A Digital Twin is a dynamic virtual representation that mirrors a physical water treatment system in real time. This sophisticated model integrates data from IoT sensors, AI-driven analytics, and cloud computing to process and analyze operational data continuously. The seamless interaction between the physical infrastructure and its digital counterpart enables real-time monitoring, simulation, and optimization of water treatment processes, thereby improving decision-making and operational efficiency (Kumar et al., 2024, Igbokwe et al., 2024).

Real-Time Process Optimization

The implementation of Digital Twin technology in water treatment facilities enables real-time process optimization by analyzing operational parameters to enhance efficiency. AI-powered simulations help to identify optimal settings for chemical dosing, filtration rates, and energy consumption, leading to improved treatment performance and resource utilization. Predictive analytics play a crucial role in identifying potential system failures, allowing for proactive interventions that prevent unplanned downtime and maintain continuous operations (Cairone et al., 2024). By leveraging data-driven insights, wastewater treatment facilities can sustain continuous operations and enhance overall system resilience (Quattrociocchi et al., 2023).

Predictive Maintenance and System Reliability

Digital Twins significantly contribute to predictive maintenance and system reliability in water treatment facilities. Utilizing Machine Learning (ML) algorithms, these systems can forecast equipment malfunctions before they occur, enabling maintenance teams to address issues proactively. Advanced AI algorithms detect patterns, predict outcomes, and uncover inefficiencies in manufacturing processes, while ML models are particularly valuable for predictive maintenance, the optimization of production schedules, and enhancing quality control (Okpala and Udu, 2025).

This approach reduces repair costs, extends asset lifespans, and improves overall system reliability. Automated alerts generated by the DT provide timely notifications for necessary interventions, minimizing operational disruptions and ensuring the consistent delivery of treated water. According to Homaei et al., (2024), DTs support real-time monitoring and predictive maintenance, allowing for automated alerts that notify operators of required actions. This proactive strategy minimizes operational disruptions and ensures the continuous delivery of high-quality treated water.

The integration of DT technology into water treatment processes marks a significant advancement towards achieving real-time process optimization and environmental sustainability. By leveraging continuous data integration and advanced analytics, water treatment facilities can improve operational efficiency, minimize environmental impacts, and guarantee reliable provision of safe water.

III. Conceptual Model of Digital Twin Technology in Water Treatment

Figure 1 presents a conceptual model illustrating the integration of Digital Twin Technology (DTT) within water treatment processes. The model highlights the dynamic interaction between physical water treatment infrastructure and its virtual counterpart, driven by real-time data exchange. IoT sensors embedded in treatment facilities continuously collect operational data, which is transmitted to the DT platform through cloud computing. Advanced analytics, including AI and ML algorithms, process this data to optimize treatment operations, predict maintenance needs, and improve resource efficiency. The model also emphasizes feedback loops where insights from the DT inform real-time adjustments in the physical system, enhancing process control and minimizing environmental impacts. Key elements such as data acquisition, simulation, process optimization, and system monitoring are visually represented, providing a holistic view of how DT Technology enhances water treatment efficiency and sustainability.

This conceptual framework serves as a foundation for understanding the core components and interactions that enable real-time process optimization and environmental impact reduction through Digital Twin Technology in water treatment.

Figure 1: Conceptual model of DT technology in water treatment

The Conceptual Model of DTT in water treatment represents the dynamic interaction between physical water treatment systems and their virtual counterparts. It involves real-time data collection through IoT sensors, feeding into a digital replica that simulates, monitors, and optimizes treatment processes. This virtual model enables predictive analysis, performance monitoring, and scenario testing without disrupting actual operations. By integrating AI and machine learning, the system can identify inefficiencies, forecast equipment failures, and suggest process improvements. This approach enhances operational efficiency, reduces costs, and minimizes environmental impact, thus supporting smarter, more sustainable water treatment practices.

Architecture of a Digital Twin Framework for Water Treatment Plants

Figure 2 illustrates the architecture of a DT framework for water treatment plants, highlighting the core components and data flows that enable real-time process optimization. The architecture integrates physical water treatment systems with digital models through IoT sensors and data acquisition tools. Real-time data from processes like filtration, chemical dosing, and sludge management is transmitted to cloud platforms for storage and advanced analytics. The DT Layer uses AI and machine learning algorithms to simulate plant operations, optimize workflows, and predict system failures. A feedback loop sends optimized parameters back to the physical plant, ensuring continuous improvement. The architecture also includes user interfaces for operators to monitor and control processes remotely, enhancing decision-making and sustainability efforts.

Figure 2: Architecture of a digital twin framework for water treatment plants

The Architecture of a DT framework for water treatment plants integrates physical systems with virtual models to optimize operations. It starts with IoT sensors that collect real-time data on flow rates, chemical levels, and equipment performance. This data is transmitted to a cloud-based platform where AI and ML analyze and simulate treatment processes. The framework includes visualization tools for monitoring and control, enabling predictive maintenance and process optimization. Feedback loops ensure continuous system updates, enhancing decision-making and efficiency. This architecture supports proactive management, reduces downtime, and promotes sustainable water treatment by improving resource utilization and thus minimizing environmental impacts.

Comparison of Traditional Water Treatment and Digital Twin-Enabled Systems

Water treatment processes have traditionally relied on manual monitoring, static process controls, and reactive maintenance approaches, often resulting in inefficiencies, higher resource consumption, and delayed responses to operational issues. The integration of DT technology has revolutionized this sector by enabling real-time data analysis, predictive maintenance, and optimized resource management. By creating virtual replicas of physical treatment plants, digital twins allow continuous monitoring, simulation, and optimization of operations, leading to improved efficiency and reduced environmental impacts.

Table 2 presents a detailed comparison between traditional water treatment methods and DT-enabled systems, highlighting the key differences in process control, resource utilization, maintenance strategies, and overall operational performance. This comparison underscores the transformative potential of DT technology in achieving more sustainable, efficient, and resilient water treatment processes.

Table 2: Comparison of traditional water treatment and digital twin-enabled systems

Aspect	Traditional Water Treatment	Digital Twin-Enabled Systems
Process Monitoring	Periodic manual checks and offline data analysis.	Continuous real-time monitoring using IoT sensors and cloud analytics.
Process Control	Static control based on predefined parameters.	Dynamic control with AI-driven adjustments for optimal performance.
Resource Utilization	Higher water, energy, and chemical consumption due to inefficiencies.	Optimized resource usage with reduced energy and chemical consumption.
Maintenance Approach	Reactive maintenance after system failures or breakdowns.	Predictive maintenance based on data analytics to prevent failures.
Operational Efficiency	Prone to inefficiencies and delayed responses to issues.	Enhanced efficiency with real-time issue detection and resolution.
Pollutant Management	Variable effluent quality with higher pollutant discharge risks.	Improved pollutant removal through continuous process optimization.
Environmental Impact	Higher carbon footprint and resource wastage.	Reduced environmental footprint due to optimized operations.
Cost-Effectiveness	Higher operational costs due to inefficiencies and frequent repairs.	Lower costs through resource optimization and predictive maintenance.

Data Utilization	Limited data use with minimal real-time insights.	Advanced data analytics for real-time decision-making and process control.
Regulatory Compliance	Compliance achieved through periodic testing and adjustments.	Continuous monitoring ensures consistent compliance with regulations

IV. Environmental Impact Reduction Through Digital Twins

Digital twin technology is transforming environmental management by providing real-time, virtual representations of physical systems, enabling more efficient and sustainable operations. In water treatment, Digital twins optimize resource consumption, reduce pollutant discharge, and support Circular Economy (CE) practices. Nwamekwe and Okpala (2025b) pointed out that the circular economy paradigm is increasingly recognized as a crucial framework for sustainable industrial engineering, as it emphasizes on resource efficiency through reuse, recycling, and remanufacturing.

By simulating processes and analyzing data, these systems help in the minimization of energy use, chemical inputs, and water wastage while improving effluent quality. This proactive approach not only enhances operational efficiency, but also significantly lowers the environmental footprint, aligning with global sustainability goals and advancing eco-friendly practices across industries.

DTT for Sustainable Water Treatment

DTT has become a vital tool in minimizing the environmental impacts of water treatment processes. By creating dynamic, real-time virtual models of treatment plants, Digital Twins enhance resource utilization, pollutant management, and the integration of circular economy principles.

Minimizing Resource Consumption

Digital Twins optimize resource use by continuously analyzing operational data to detect inefficiencies in treatment systems. AI-driven simulations adjust process parameters in real-time, ensuring chemical dosing and energy consumption are maintained at minimal yet effective levels. Syed et al. (2024), demonstrated that implementing DT frameworks reduced water wastage by up to 25% in municipal treatment plants through optimized resource management and advanced monitoring. Similarly, Fantozzi et al. (2025), reported significant reductions in chemical and energy usage due to simulations run within Digital Twin environments. These improvements not only lower operational costs but also contribute to a reduced environmental footprint, supporting broader sustainability goals.

Reduction of Pollutant Discharge

Real-time monitoring through digital twins allows precise control over effluent quality, ensuring compliance with environmental regulations. Continuous simulations and adjustments to operational parameters enhance contaminant removal efficiency. Hartmann et al. (2025), found that DT applications improved pollutant removal efficiency by 15%, resulting in lower discharge levels into natural water bodies. Lumley et al., (2024), highlighted that enhanced process control facilitated by digital twins helps in the mitigation of harmful pollutant releases and supports proactive wastewater system management, thereby reducing the risk of overflows during extreme weather events.

Integration with Circular Economy Practices

Digital twins also play a key role in circular economy practices by optimizing wastewater reclamation and reuse. By simulating recovery scenarios, they enable treatment facilities to effectively repurpose treated wastewater, closing the loop in water management. Sánchez (2020), illustrated that integrating DTs into closed-loop water systems boosted resource recovery rates and encouraged sustainable industrial practices, promoting a shift towards more circular and eco-friendly water management strategies.

V. Challenges and Future Directions in Adopting Digital Twin Technology for Water Treatment

The integration of Digital Twin Technology (DTT) in water treatment presents transformative opportunities but also faces significant challenges, including data security concerns, high implementation costs, and interoperability issues. Overcoming these barriers is essential for the broader adoption and optimization of DTT in sustainable water treatment. Future efforts must focus on strengthening cybersecurity, reducing costs, establishing standardized frameworks, and enhancing system integration.

Table 3 outlines some challenges, solutions, and future directions in adopting digital twin technology for water treatment.

Table 3: Challenges, solutions and future directions

Challenges	Solutions	Future Directions
High Implementation Costs	Development of cost-effective and modular digital twin models.	Increased funding, government incentives, and subsidies.
Data Quality and Availability	Use of IoT sensors and AI-driven analytics for real-time data collection.	Enhanced real-time data integration with AI optimization.
Complex System Integration	Standardized frameworks and interoperability protocols.	AI-powered automation for seamless system integration.
Cybersecurity and Data Privacy Concerns	Implementation of advanced encryption and blockchain security.	Development of water industry-specific cybersecurity standards.
Limited Technical Expertise	Training programs and workforce upskilling in digital twin technologies.	Integration of user-friendly interfaces and automated AI assistance.
Computational and Storage Requirements	Cloud computing and edge processing to optimize performance.	Next-gen quantum and distributed computing for better efficiency.
Regulatory and Compliance Issues	Collaboration with policymakers to create standardized regulations.	Global regulatory harmonization for digital twin adoption.
Scalability and Adaptability	Development of flexible and customizable digital twin solutions.	AI-driven self-learning models for adaptive performance.
Interoperability with Legacy Systems	Middleware and API-based integration for existing infrastructure.	Advanced digital twin frameworks supporting legacy systems.
Uncertainty in ROI and Performance Gains	Pilot projects and feasibility studies to demonstrate benefits.	Expansion of real-world case studies and industry benchmarks.

Data Security and Privacy Concerns

The adoption of DTT in water treatment requires robust cybersecurity strategies to protect sensitive operational data. The use of IoT sensors, AI analytics, and cloud computing increases exposure to potential cyber threats, making secure data transmission and storage critical. Implementing encryption and strong authentication protocols is vital to maintaining data integrity and confidentiality (Chouraik et al., 2024). Oliha et al. (2024), emphasized that robust access controls and network segmentation can further limit the impact of potential breaches. Additionally, compliance with data privacy regulations such as the GDPR adds complexity, necessitating continuous updates and rigorous security measures (Daneshgar et al., 2024). Future research should focus on advancing encryption technologies and developing resilient cybersecurity frameworks to mitigate these risks.

High Implementation Costs and Technical Expertise

Deploying DTs involves significant financial investments in hardware, software, and specialized personnel. High-performance sensors, advanced computational infrastructure, and sophisticated AI models contribute to the elevated costs of DTT integration (Smith et al., 2022). Moreover, operating these systems effectively requires interdisciplinary expertise in process engineering, data analytics, and cybersecurity. Small and Medium Enterprises (SMEs) often struggle with these demands due to limited budgets and shortages of skilled talent (Syed, Khan, et al., 2024). Solutions such as scalable, modular systems and targeted training programs can help lower these barriers and make DTT adoption more feasible across various sectors.

Standardization and Interoperability Issues

A significant challenge to widespread DTT adoption is the lack of standardized frameworks and protocols. Diverse data formats and communication protocols across existing water treatment systems hinder seamless integration (Janisar et al., 2024; Vempati, 2024). Establishing universal standards for data exchange and system interoperability is crucial to ensure Digital Twins can integrate smoothly with legacy infrastructures. Collaborative efforts among industry stakeholders should focus on developing these standards to facilitate efficient and consistent DTT deployment. Addressing these challenges is critical for maximizing the potential of DTs in real-time water treatment optimization and reducing environmental impacts.

Future Roadmap for DT Integration in Sustainable Water Treatment

Figure 3 presents a future roadmap for DT integration in sustainable water treatment, outlining the strategic steps and advancements needed to fully leverage DTT for enhanced environmental sustainability and process optimization. This roadmap highlights the progressive stages, from initial adoption to advanced implementation, focusing on key areas such as enhanced data integration, AI-driven predictive analytics, improved interoperability, and stronger cybersecurity frameworks. It also emphasizes the role of continuous innovation, regulatory compliance, and industry collaboration in driving widespread adoption. The visual representation provides a structured timeline and key milestones that illustrate how DTT can evolve to support more efficient, resilient, and eco-friendly water treatment systems.

Figure 3: Future roadmap for digital twin integration in sustainable water treatment

The future roadmap for digital twin integration in sustainable water treatment outlines key stages for advancing the technology's adoption. It begins with enhancing data integration through IoT, AI, and real-time analytics to improve operational efficiency. The next phase focuses on addressing challenges like cybersecurity, standardization, and cost reduction. Collaborative efforts among stakeholders will drive the development of scalable, interoperable solutions. Long-term goals emphasize achieving full-scale implementation, enabling predictive maintenance, optimized resource management, and reduced environmental impacts. This roadmap aims to promote sustainable water treatment practices, ensuring efficient, resilient, and eco-friendly water management systems globally.

VI. Conclusion

Digital twin technology holds transformative potential for water treatment by enabling real-time process optimization and reducing environmental impacts. By integrating IoT sensors, AI-driven analytics, and cloud computing, this technology optimizes chemical dosing, energy consumption, and filtration processes, leading to reduced resource usage and lower pollutant discharge. Additionally, DTs support predictive maintenance, minimizing downtime and extending equipment lifespan.

However, several challenges hinder widespread adoption, including data security and privacy concerns, high implementation costs, and issues with standardization and interoperability. Recent studies emphasize the importance of robust cybersecurity protocols to safeguard sensitive data, while also advocating for scalable, cost-effective solutions and standardized frameworks for seamless integration with existing infrastructure.

In conclusion, despite existing challenges, DTT offers a promising approach to achieving more efficient, resilient, and eco-friendly water treatment. Continued research and development are therefore essential to refine these digital solutions and advance sustainable water management globally.

References

[1]. Cairone, S., Hasan, S. W., Choo, K., Lekkas, D. F., Fortunato, L., Zorpas, A. A., Korshin, G., Zarra, T., Belgiorno, V., and Naddeo, V. (2024). Revolutionizing wastewater treatment toward circular economy and carbon neutrality goals: Pioneering sustainable and efficient solutions for automation and advanced process control with smart and cutting-edge technologies. Journal of Water Process Engineering, 63, 105486. https://doi.org/10.1016/j.jwpe.2024.105486

[2]. Chouraik, N. C., El-Founir, N. R., and Taybi, N. K. (2024). Comprehensive review of smart city cybersecurity strategies. International Journal of Applied Research in Social Sciences, 6(9), 2112–2120. https://doi.org/10.51594/ijarss.v6i9.1560

[3]. Daneshgar, S., Polesel, F., Borzooei, S., Sørensen, H. R., Peeters, R., Weijers, S., Nopens, I., and Torfs, E. (2024). A full- scale operational digital twin for a water resource recovery facility—A case study of Eindhoven Water Resource Recovery Facility. Water Environment Research, 96(3). https://doi.org/10.1002/wer.11016

[4]. Fantozzi, I. C., Santolamazza, A., Loy, G., and Schiraldi, M. M. (2025). Digital Twins: Strategic Guide to utilize Digital Twins to improve operational efficiency in industry 4.0. Future Internet, 17(1), 41. https://doi.org/10.3390/fi17010041

[5]. Hartmann, S., Valles, R., Schmitt, A., Al-Zuriqat, T., Dragos, K., Gölzhäuser, P., Jung, J. T., Villinger, G., Rojas, D. V., Bergmann, M., Pullmann, T., Heimer, D., Stahl, C., Stollewerk, A., Hilgers, M., Jansen, E., Schoenebeck, B., Buchholz, O., Papadakis, I., . . . Smarsly, K. (2025). Digital Twin-Based Management of Sewer Systems: Research Strategy for Kasytwin Project. Water, 17(3), 299. https://doi.org/10.3390/w17030299

[6]. Homaei, M., Di Bartolo, A. J., Ávila, M., Gutiérrez, Ó. M., and Caro, A. (2024). Digital transformation in the water distribution system based on the Digital Twins concept. Computers and Society (cs.CY); Artificial Intelligence (cs.AI). https://doi.org/10.20944/preprints202412.0756.v1

[7]. Igbokwe, N. C., Okpala, C. C. and Nwamekwe, C. O. (2024). The Implementation of Internet of Things in the Manufacturing Industry: An Appraisal. International Journal of Engineering Research and Development, vol. 20, iss. 7, https://www.ijerd.com/paper/vol20-issue7/2007510516.pdf

[8]. Janisar, A. A., Kalid, K. S., Sarlan, A. B., Iqbal, M. A., and Khan, M. A. (2024). Comprehensive review of security requirements for mitigating threats and attacks on IoT assets. JOIV International Journal on Informatics Visualization, 8(3–2), 1827. https://doi.org/10.62527/joiv.8.3-2.3084

[9]. Kumar, V., Kumar, A., and Singh, S. (2024). Smart grids for wastewater treatment plants: automation and energy management. Conference: International Conference on Cutting-Edge Developments in Engineering Technology and Science. https://doi.org/10.62919/dftc5661

[10]. Li, Y. (2025). AI-Enhanced digital twins for energy efficiency and carbon footprint reduction in smart city infrastructure. Applied and Computational Engineering, 118(1), 42–47. https://doi.org/10.54254/2755-2721/2025.20569

[11]. Lumley, D. J., Polesel, F., Sørensen, H. R., and Gustafsson, L. (2024). Connecting digital twins to control collections systems and water resource recovery facilities: From siloed to integrated urban (waste)water management. Water Practice and Technology, 19(6), 2267–2278. https://doi.org/10.2166/wpt.2024.128

[12]. Mohsin, A., Janicke, H., Nepal, S., and Holmes, D. (2023). Digital Twins and the Future of their Use Enabling Shift Left and Shift Right Cybersecurity Operations. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2309.13612

[13]. Nagpal, M., Siddique, M. A., Sharma, K., Sharma, N., and Mittal, A. (2024). Optimizing wastewater treatment through artificial intelligence: recent advances and future prospects. Water Science and Technology, 90(3), 731–757. https://doi.org/10.2166/wst.2024.259

[14]. Nwamekwe, C. O. and Okpala, C. C. (2025a). Machine Learning-Augmented Digital Twin Systems for Predictive Maintenance in High-Speed Rail Networks. International Journal of Multidisciplinary Research and Growth Evaluation, vol. 6, iss. 1, https://www.allmultidisciplinaryjournal.com/uploads/archives/ 20250212104201_MGE-2025-1-306.1.pdf

[15]. Nwamekwe, C. O. and Okpala, C. C. (2025b) Circular Economy Strategies in Industrial Engineering: From Theory to Practice. International Journal of Multidisciplinary Research and Growth Evaluation, vol. 6, iss. 1, https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212103754_MGE-2025-1-288.1.pdf

[16]. Nwamekwe, C. O., Okpala, C. C. and Okpala, S. C. (2024). Machine Learning-Based Prediction Algorithms for the Mitigation of Maternal and Fetal Mortality in the Nigerian Tertiary Hospitals. International Journal of Engineering Inventions, vol. 13, iss. 7, http://www.ijeijournal.com/papers/Vol13-Issue7/1307132138.pdf

[17]. Oliha, N. J., Biu, N. P. and Obi, N. O. (2024). Securing The Smart City: A Review Of Cybersecurity Challenges And Strategies. Engineering Science and Technology Journal, 5(2), 496–506. https://doi.org/10.51594/estj.v5i2.827

[18]. Okpala, C. C. and Udu, C. E. (2025). Big Data Applications in Manufacturing Process Optimization. International Journal of Multidisciplinary Research and Growth Evaluation, vol. 6, iss. 1, https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212105349_MGE-2025-1-308.1.pdf

[19]. Okpala, C. C., Udu, C. E. and Nwankwo, C. O. (2025). Digital Twin Applications for Predicting and Controlling Vibrations in Manufacturing Systems. World Journal of Advanced Research and Reviews, vol. 25, iss. 01, https://doi.org/10.30574/wjarr.2025.25.1.3821

[20]. Quattrociocchi, A., Subroto, R. K., Oppedijk, W. M., and Dragičević, T. (2023). Energy efficiency optimization of a wastewater pumping station through IoT and AI: a Real-World application of Digital twins. IECON 2020 the 46th Annual Conference of the IEEE Industrial Electronics Society, 1–6. https://doi.org/10.1109/iecon51785.2023.10312592

[21]. Sánchez, A. S. (2020). Toward "Zero Liquid Discharge" industrial facilities: Reducing the impact on freshwater resources by reusing industrial and urban wastewaters. In Elsevier eBooks (pp. 215–246). https://doi.org/10.1016/b978-0-12-822183-9.00009-x

[22]. Syed, T. A., Khan, M. Y., Jan, S., Albouq, S., Alqahtany, S. S., and Naqash, M. T. (2024). Integrating Digital Twins and Artificial Intelligence Multi-Modal Transformers into Water Resource Management: Overview and Advanced Predictive Framework. AI, 5(4), 1977–2017. https://doi.org/10.3390/ai5040098

[23]. Syed, T. A., Muhammad, M. A., AlShahrani, A. A., Hammad, M., and Naqash, M. T. (2024). Smart Water Management with Digital Twins and Multimodal Transformers: A Predictive Approach to Usage and Leakage Detection. Water, 16(23), 3410. https://doi.org/10.3390/w16233410

[24]. Vempati, N. S. (2024). Securing Smart Cities: A Cybersecurity perspective on integrating IoT, AI, and machine learning for digital twin creation. Deleted Journal, 20(3), 1420–1429. https://doi.org/10.52783/jes.3548