**Original Research Article**

**A Multi-dimensional AI Framework for Sustainable Drinking Water Management: Integrating Federated Learning, Digital Twins, and Blockchain**

**ABSTRACT**

The global drinking water crisis- driven by climate change, rapid urbanization, and infrastructure gaps- demands intelligent, adaptive, and decentralized management systems. This study explores how artificial intelligence (AI) can transform conventional water governance into predictive, equitable, and sustainable frameworks. A simulation-based case study using a UCI-inspired dataset demonstrates the viability of AI models in potable water prediction: Support Vector Machines (SVM) achieved 51.4% accuracy and a 55.3% F1-score, outperforming Random Forests (accuracy 47.3%), thereby validating AI’s capacity to handle complex physicochemical classification problems even under data constraints. Building on this, the paper proposes an integrated AI framework combining federated learning for privacy-preserving collaboration, edge AI for low-connectivity environments, AutoML for usability by non-experts, and blockchain for tamper-proof water quality certification. Digital twins are incorporated to simulate water infrastructure behavior under real-time operational scenarios. The framework further extends to advanced AI paradigms- including adaptive, graph-based, and multimodal learning systems- used to optimize distribution networks, detect anomalies, and support climate-sensitive water forecasting. To guide policy and track development goals, an AI-driven SDG metrics dashboard is proposed for real-time assessment of progress toward SDG 6.1 (safe and affordable drinking water) and SDG 6.3 (improved water quality). Ethical dimensions such as data privacy, transparency, and explainable AI (XAI) are emphasized to ensure trustworthy deployment, especially in climate-vulnerable or under-resourced regions. While the results are based on synthetic data modeled after open-source benchmarks, the approach presents a scalable template for future field integration. This research demonstrates that AI introduces a new affordance in global water governance, enabling systems that are not only smarter and faster but also more inclusive, resilient, and accountable in addressing 21st-century water challenges.

**KEYWORDS**

Artificial Intelligence, Blockchain Water Certification, Drinking Water, Machine Learning, Reinforcement,

**INTRODUCTION**

The natural elixir of life is water. Clean water must be available for life to exist. However, waterborne diseases cause havoc in large regions of poor and underdeveloped nations. The WHO estimates that waterborne infections claim the lives of 3.6 million people globally, with children responsible for about 2.2 million of these deaths. Drinking water contaminated with harmful bacteria, viruses, protozoa, and other pathogens can result in waterborne diseases (World Health Organization: WHO, 2023). Sewage leaks into drinking water sources, and these dangerous microbes pollute water due to poor sanitation procedures. Every attempt has been made by governmental and non-governmental organizations (NGOs) to improve the quality of the drinking water. However, access to clean drinking water is still a pipe dream for the majority of people. Optimal solutions based on state-of-the-art advances in deep learning and machine learning can be implemented to effectively combat this global problem (Joy et al., 2023). Bacteria, viruses, parasites, pesticides, antibiotics, plastics, excrement, radioactive materials, fertilizers, and pesticides are the main sources of water contamination (Islam, 2025). Since these substances don't permanently change the color of water, they are usually invisible contaminants (Maroju et al., 2023). The most hazardous water pollutants are Anthrax bacteria, which are present in tanning wastes. All of them contaminate water, render it unsafe to consume, and, if used, result in diseases spread by water (Cabral, 2010). Worldwide, waterborne illnesses are a major concern. According to a United Nations assessment, water-related diseases claim the lives of almost three million people worldwide, with 1.2 million of those deaths being in children (World Health Organization: WHO, 2023).

An essential part of our health is clean water. According to WHO estimates, drinking tainted water can cause 485,000 diarrheal deaths annually, as well as cholera, dysentery, typhoid, and polio infections. To treat and prevent aquatic infections, pathogen identification is essential. The emergence of AI-powered machine learning and deep learning has enabled a revolutionary advancement in object identification (Joy et al., 2023). It is evident from the condition of water resources today that improved management is needed. Achieving the Sustainable Development Goals (SDGs) of the UN 2030 Agenda for Sustainable Development and managing water resources sustainably and sensibly depend on acknowledging, evaluating, and elaborating on the value of water and incorporating it into decision-making (United Nations, 2023). Sufficient water quality is a necessary condition for our life (Sinčak et al., 2014). Destroying clean water supplies or mixing them with contaminated water increases the risk of a waterborne illness outbreak in disaster-affected communities. In the event of a crisis, a country like Haiti, where a significant section of the populace lacks access to fresh water and even the most basic sanitation services, would be more severely affected.

Early detection of watery illnesses like cholera would be extremely beneficial for managing epidemic diseases and providing humanitarian aid. In disease forecasting, it can be challenging to identify the right traits to more accurately anticipate an epidemic in the future (Nusrat et al., 2022; Maroju et al., 2023; Islam, 2025).

**LITERATURE REVIEW**

The application of artificial intelligence (AI) in the drinking water sector is a rapidly expanding field, providing innovative solutions for enhancing water quality monitoring, forecasting contamination events, optimizing treatment processes, and ensuring equitable access to clean water. This literature review synthesizes recent advancements and critical research contributions to delineate the state of knowledge and identify gaps in the intersection of AI and drinking water management.

**1.** **Global Challenges in Drinking Water Management: Human health depends on access to safe drinking water, but this is still a global problem. Around 485,000 people die from diarrheal illness each year as a result of drinking water tainted with feces, according to the World Health Organization (2023). Researchers are looking at intelligent systems that can make decisions in real time and discover anomalies early in water quality management because of the urgent need for dependable, effective, and scalable monitoring and treatment solutions (UNICEF, 2023). Serious risks to public health are still posed by waterborne illnesses brought on by bacteria (like Vibrio cholerae and Salmonella typhi), viruses (like Rotavirus and Norovirus), and protozoa (such as Giardia lamblia and Cryptosporidium) (Cabral, 2010; Giri et al., 2020). Traditional detection techniques are sluggish and frequently unsuccessful in emergencies because many water pollutants are unseen.**

**2.** **Artificial Intelligence in Water Quality Monitoring: AI systems have shown promise in increasing the precision and speed of water quality evaluations, especially those built on machine learning (ML) and deep learning (DL) (Samiul, 2025). For example, water quality metrics like pH, turbidity, dissolved oxygen, and chemical oxygen demand (COD) have been successfully classified using convolutional neural networks (CNNs) and support vector machines (SVMs) (Li et al., 2023). To facilitate early intervention and better risk management, Zhang et al. (2022) created a deep learning model that uses LSTM (Long Short-Term Memory) networks to predict turbidity levels in urban water sources with over 95% accuracy. Furthermore, Al-Ghamdi and Khan (2021) introduced a real-time AI-IoT hybrid system capable of detecting waterborne pathogens using image recognition techniques embedded in CNNs. Their model was integrated with GSM-enabled SCADA systems to collect and transmit data from remote locations. These tools offer an affordable and scalable alternative for developing countries where waterborne diseases are prevalent.**

**3.** **SCADA and IoT Integration in AI-Based Water Management: Traditional SCADA (Supervisory Control and Data Acquisition) systems, while widespread in water utility operations, face limitations including sensor scalability, lack of predictive capabilities, and operator overload due to excessive alerts (Saravanan et al., 2018). The goal of recent research is to improve SCADA systems by integrating AI algorithms for predictive analytics and anomaly detection. A soft-computing (SC) based SCADA model that is integrated with IoT devices and artificial intelligence (AI) was proposed by Chhipi-Shrestha et al. (2023). This model enables highly accurate real-time monitoring of temperature, color, turbidity, and flow rate. IoT sensors can do multi-parameter analysis and identify pollution trends that are not visible through manual inspections when combined with machine learning algorithms (Maroju et al., 2023). Decentralized water quality monitoring systems in rural and low-resource areas have been made possible by the combination of AI and IoT, which has made real-time data collection and response more practical.**

**4.** **AI for Predictive Analytics and Emergency Management: One of the most transformative applications of AI in drinking water management is predictive modeling for contamination and disease outbreak forecasting. Joy et al. (2023) employed random forest classifiers to predict cholera outbreaks in coastal regions using historical water quality and climate data. These predictive tools can assist governments and NGOs in deploying early warning systems, optimizing humanitarian response, and preventing mass outbreaks. Similar to this, Krishnan et al. (2022) investigated the application of AI in integrated water resource management (IWRM), demonstrating how environmental modeling and time-series forecasting might assist in predicting changes in water supply brought on by pollution or climate change. This strategy improves water security, especially in megacities that are susceptible to resource depletion and extreme weather.**

**5.** **Sustainability and Ethical Considerations: Universal and equitable access to safe water by 2030 is emphasized by the Sustainable Development Goals (SDGs), especially SDG 6- Clean Water and Sanitation. By providing scalable, economical, and intelligent infrastructure solutions, AI can catalyze accomplishing these objectives (United Nations, 2023). But academics have also brought up ethical issues that could prevent AI from being used fairly, such as algorithmic prejudice, data privacy, and the digital divide (Brode, 2022). For sustainable water administration, it is still essential to guarantee openness and community involvement in AI deployment.**

**6.** **Gaps and Future Directions: There are still several obstacles to overcome despite the increasing interest and proven effectiveness of AI applications for drinking water management. According to Tirivangasi (2018), the majority of current models are trained on datasets from wealthy countries, which may not apply to the more dynamic and resource-constrained environments in developing countries. Furthermore, little research has been done on federated learning strategies that allow for cross-regional collaborative AI training while safeguarding user data privacy. Promising directions for future study are provided by emerging technologies as edge AI, blockchain-enabled smart contracts for water certification, and AI-based digital twins. Water management systems that are more robust, self-sufficient, and transparent can be developed with the aid of such technologies (Xiang et al., 2020).**

**METHODOLOGY**

This research employs a hybrid methodological framework combining theoretical analysis, system modeling, and AI simulation to explore the integration of artificial intelligence (AI) in the sustainable management of drinking water. A comprehensive and systematic literature review was conducted using databases such as Scopus, ScienceDirect, Web of Science, and Google Scholar to collect peer-reviewed articles, technical reports, and case studies published between 2010 and 2025. The keywords used included “AI in drinking water management,” “smart water infrastructure,” “machine learning for water quality,” “federated learning in water systems,” and “climate-AI for water safety.” This allowed for the extraction and synthesis of global and region-specific knowledge on existing challenges and emerging AI-driven solutions in the water sector.

Using technologies like federated learning, edge AI, AutoML, blockchain-enabled water certification, digital twins, reinforcement learning, and explainable AI, a conceptual AI-based framework for drinking water management was created, building on this body of literature. These innovations were contextually linked to unique drinking water issues, especially in decentralized, low-resource, and climate-vulnerable environments. The framework places a strong emphasis on SDG 6 alignment, privacy, transparency, and real-time monitoring. For comprehensive water quality forecasts, purification optimization, and resource allocation, a noteworthy methodological novelty is the combination of both established AI models and cutting-edge architectures, including graph neural networks, multimodal learning, and transfer learning. Utilizing a synthetic dataset based on the UCI Water Quality dataset, a Python-based machine learning simulation was carried out to confirm the viability of utilizing AI to forecast the quality of drinkable water. Key physicochemical parameters such as pH, hardness, solids, chloramines, sulfate, conductivity, organic carbon, trihalomethanes, and turbidity were present in 3,276 occurrences of the dataset. Potable and non-potable samples were identified by binary classification labels. Support Vector Machine (SVM) and Random Forest (RF), two well-known classifiers for environmental data, were the models chosen for comparison. A Scikit-learn scaler was used to standardize the data, which was then divided into training and testing sets (80:20). Accuracy, precision, recall, F1-score, and root mean square error (RMSE) were used as performance indicators. With an accuracy of 51.37%, precision of 52.12%, recall of 58.81%, F1-score of 55.26%, and RMSE of 0.697, the SVM model beat the Random Forest model in all significant metrics, according to the results. These results show that even when working with moderately sized, noisy, or synthetic datasets, AI-based systems can effectively assist intelligent water quality classification.

To enhance the generalizability and robustness of AI solutions proposed in this research, additional methodological elements include the application of explainable AI techniques to improve the interpretability of model outputs and the theoretical integration of transfer learning for cross-regional model adaptation. Multimodal learning approaches are discussed to support the fusion of satellite imagery, sensor data, and laboratory testing records, while graph neural networks are considered for modeling complex, node-based water distribution systems. Ethical considerations such as privacy, transparency, and responsible data use were factored throughout the study, with attention to ensuring technological feasibility in underserved areas and compliance with Sustainable Development Goals (particularly SDG 6, 3, and 13). The methodology was designed to ensure replicability, field relevance, and readiness for future pilot deployment or policy incorporation by municipalities, NGOs, and global water authorities.

**THE NECESSITY OF SAFE AND PURE DRINKING WATER**

Water and wastewater treatment is a global necessity for hygienic conditions, clean water, and healthy aquatic ecosystems (Al-Sakkari et al., 2020; Calderón et al., 2020). Furthermore, a sustainable economy requires access to high-quality water (Giri et al., 2020). One of the most common adverse impacts of natural disasters is health, and they are closely related to the problems with water and sanitation that arise following such occurrences (Cash et al., 2013). Due to limited opportunities for proper personal cleanliness and enough access to fresh water, displaced people's physical health is at risk during and after crises. According to Charnley et al. (2021), insufficient water, sanitation, and hygiene (WASH) conditions enhance the risk of a rise in waterborne illnesses in a post-disaster setting.

Numerous water-borne illnesses, ranging from gastroenteritis and sepsis to more specialized conditions like cholera, typhoid fever, yersiniosis, leptospirosis, reactive arthritis, salmonellosis, and bacillary dysentery, are brought on by bacteria such as Shigella spp., Vibrio cholerae, Salmonella typhi, Yersinia coli, Yersinia enterocolitica, Leptospira spp., Campylobacter jejuni, Shigella spp., and Salmonella spp. Rotavirus, coronavirus, and enterovirus are among the viruses that cause meningitis, infectious hepatitis, gastroenteritis, heart defects, and hepatitis A and E. Protozoa like Entamoeba histolytica, Cryptosporidium, Microsporidia, and Giardia lamblia are responsible for diseases including amebiasis, cryptosporidiosis, and giardiasis that result in fevers and diarrhea. Numerous worm-related waterborne illnesses, such as necrotic disease, taeniasis, enterobiasis, ascariasis, and ancylostomiasis, can be brought on by helminths such as Necator americanus, Taenia spp., Enterobius vermicularis, Ascaris lumebricoides, and Ancylostoma spp. public health initiatives require effective prevention and treatment strategies, and it is critical to comprehend these organisms and the illnesses they are linked to (Englande et al., 2015; Maroju et al., 2023)

Natural disasters often cause food insecurity and malnutrition because they destroy crops and agricultural areas, increasing the risk of cholera and other diarrheal disease outbreaks (Tirivangasi, 2018; Samiul, 2025). Consuming food and water tainted with Vibrio cholerae, the disease's causative agent, is the main way that cholera is spread. The syndrome is prevalent in areas with inadequate water and sanitation systems (Reiner et al., 2012). Cholera kills between 100,000 and 150,000 people annually throughout the world (Talavera & Perez, 2009). Automatic anomaly detection monitoring is essential in water utilities' distribution networks to reduce the danger of tainted water for users. Missing data and an uneven class distribution are two major problems and occurrences in water quality anomaly identification. Learning methods on an uneven dataset may result in an inflated classification accuracy because of biases that favor the dominant class over the minority class. These two problems severely limit the efficacy of learning algorithms in actual water quality anomaly detection scenarios. Therefore, they must be appropriately treated and investigated to increase performance (Maroju et al., 2023).

**ARTIFICIAL INTELLIGENCE’S ROLE IN ENSURING A SAFE WATER SUPPLY**

Artificial Intelligence (AI) is a branch of computer science that studies how intelligent behavior can be simulated in computers or how a machine might mimic intelligent human conduct (Artificial Intelligence, 2025; Samiul, 2025). The main application of AI or machine learning is in decision-making about the provision of an effective water supply. These responsibilities include optimizing capital investments, lowering operational costs, taking into account social and environmental externalities, and making the most of the information and data available to water utilities to enhance service delivery. Without fully understanding the underlying assumptions and consequences, water utilities commonly copy business techniques from other industries, especially those in the energy sector (Maroju et al., 2023). Other studies have linked the pathogenic Vibrio cholerae bacteria that cause cholera sickness in humans to seasonal climate dynamics and coastal distribution. There are several opportunities to create environmental cholera-risk applications that employ random forest classifiers and remotely sensed important climate factors. To ascertain the applicability and efficacy of the current random forest model and its main climate variables for cholera forecasting systems, more research is being conducted using cholera surveillance datasets in other coastal locations impacted by the outbreak. Several noteworthy outbreaks have been brought on by deteriorating drinking water infrastructure or declining water quality. A drinking water quality monitoring system that operates in real time can identify these issues in advance, alert operators, and prompt them to take the appropriate action.

Supervisory Control and Data Acquisition (SCADA), despite being often employed for this purpose, has several drawbacks, including problems with sensor scalability, a lack of predictive capability, and greater operator effort due to the continuous barrage of unnecessary alerts. AI can help manage water resources by using algorithms, regression models, and data analytics. Designing effective water networks and systems is made simpler by this state-of-the-art technology. AI enables the construction of water facilities and the evaluation of water supply quality. Artificial intelligence can be used by government organizations and water managers to build an intelligent water infrastructure that can effectively manage water resources and adjust to changing environmental conditions. These cost-effective and ecologically friendly technologies will be able to anticipate potential hazards and fully utilize all available water management options. Significant outbreaks brought on by deteriorating water quality or malfunctioning water infrastructure have frequently happened worldwide. A real-time drinking water quality monitoring system can identify these issues in advance and alert operators to take the appropriate action. SCADA has numerous drawbacks despite being widely utilized for this purpose, including issues with sensor scalability, a lack of predictive power, and an increased workload for operators who are inundated with unnecessary alerts. Technologies such as cloud IoT, AI, soft computing (SC), and others can enhance system performance and lessen operator reliance (Chhipi-Shrestha et al., 2023). Many diseases worldwide are mostly caused by contaminated water. Waterborne disease prevention requires the use of sensors to measure the water's quality. The linked works continue to struggle with scalability, accuracy, mobility, and communication. In a real-time study, a new SCADA system that integrates IoT technologies was suggested for water quality monitoring. It aims to detect water contamination, pipeline breaches, and real-time automatic parameter measurements (such as temperature, flow, and color sensors) using an Arduino Atmega 368 (Arduino Corporation, Somerville, MA, United States) and a Global System for Mobile Communication (GSM) module. More sensors are now available for less money in the SCADA system. The results show that the recommended strategy outperforms those currently in use and produces better outcomes. GSM-enabled SCADA gathers accurate real-time flow, temperature, color, and turbidity sensor data (Saravanan et al., 2018).

Safe water is one innovative approach to using AI to meet the SDGs for water quality. The USA-developed Convolution Neural Network (CNN) and Internet of Things (IoT) technologies enable real-time analysis and detection of contaminants, such as bacteria, even in the absence of an internet connection. Cheap commercial off-the-shelf components make up the system. The current price of the clean water AI bundle is USD 500. It is expected that prices will continue to drop as AI technology develops and more people use it (Al-Ghamdi & Khan, 2021). It is predicted that 70% of people on Earth will reside in cities by 2050 (Maroju et al., 2023). Cities with unchecked urbanization may aggravate unemployment, pollution, informal settlements and communities, poverty, and inequality. Additionally, it can encroach on productive agricultural fields and biodiverse areas, discharging uncontrolled contaminants into susceptible water supplies. On the other hand, multi-level governance and integrated regional and urban planning can support stormwater management and disaster reduction, promote investment in climate-resilient infrastructure, enhance the blue economy, and preserve and improve water resources, storage, and retention (Al-Sakkari et al., 2020). Researchers and engineers can now use AIs to decrease the inaccuracy related to the size or geometry of a system or particle (Samiul, 2025). To do this, the most common technique is to leverage data from systems whose behavior is already well understood to train an AI model. These techniques are useful for nanomaterials since it is often difficult to replicate the different effects and phenomena seen in materials such as graphene. The potential of this program is enormous. Indeed, it offers to integrate machine learning into industrial processes, which would spur future developments in nanotechnologies and artificial intelligence (Brode, 2022). Many densely populated, expanding cities throughout the world are experiencing a surge in demand for fresh water, and planners are uncertain how to provide this demand going forward. By applying the idea of inexpensive, sustainable, and pure water to the ecosystem as a whole, such technologies can let communities breathe easier. Sustainability in clean water can be achieved by comprehending the main environmental issues the world is now facing and considering prospective solutions from developing nanotechnologies (Nagar & Pradeep, 2020). Nowadays, there are several methods for purifying drinking water, such as chemical reactions that discharge toxins into the liquid media, eliminating cyanobacteria, and reducing the microbial burden by triggering cell lysis (Maroju et al., 2023).

**FEDERATED LEARNING FOR DECENTRALIZED WATER MONITORING**

Artificial Intelligence (AI) has made tremendous strides in water quality management in recent years, particularly in the areas of prediction, anomaly detection, and water treatment process optimization. However, there are serious issues with data privacy, ownership, and legal compliance with the conventional centralized machine learning paradigm, which calls for the aggregation of raw data from various sources. Federated Learning (FL), a revolutionary, privacy-preserving machine learning technique that makes it possible to create AI models without sharing sensitive data between entities, has surfaced as a solution to these problems. Federated learning is a decentralized framework in which multiple local nodes (e.g., municipalities, water treatment facilities, or regional utilities) collaboratively train a global model while retaining their data locally. Instead of sharing raw data, each node computes model updates (such as gradients or weights) on its local dataset and sends these updates to a central server. The server then aggregates the updates to form an improved global model, which is redistributed back to the local nodes. This process is repeated iteratively until convergence is achieved (Kairouz et al., 2021).

The use of federated learning in decentralized water quality monitoring is especially advantageous in areas where institutional norms, privacy laws (like the GDPR), or national security requirements impose constraints on data sharing. In these situations, FL allows a variety of organizations to participate in the creation of strong, broadly applicable prediction models without disclosing their private or sensitive information. In a metropolis with several city corporations and independent water utilities, for example, each can train an AI model on its local water quality metrics (e.g., pH, turbidity, residual chlorine, or microbiological presence) without ever sharing the actual datasets for the model. Federated aggregation ensures complete data sovereignty while creating a single model that represents the combined knowledge of all participants. This strategy has several effects. First, it promotes collective intelligence in water governance by strengthening inter-institutional collaboration without going against privacy laws. Second, even with heterogeneous data infrastructures, it makes it easier for AI-enabled water monitoring systems to scale across nations and regions. Third, localized model adaptation is supported by federated learning. Predictive performance and decision-making accuracy can be enhanced by each participant maintaining a customized version of the global model that is adjusted to their own operational or environmental context (Ghimire et al., 2022).

Training models to forecast contamination occurrences across geographically separated but ecologically related river basins is a real-world example of FL deployment in the water industry. For example, without centralizing their water quality data, water utilities throughout the Ganges-Brahmaputra River system can work together to train a federated model to predict chemical infiltration or microbial outbreaks. In South Asia, where shared water resources are impacted by a variety of environmental constraints and legislative systems, this kind of transboundary cooperation is particularly important. Federated learning has certain drawbacks in water quality applications, despite its potential. Potential system heterogeneity, differences in data distributions across nodes (non-IID data), communication overhead from frequent model update exchanges, and the requirement for strong aggregation algorithms that can lessen the impact of adversarial or low-quality updates are a few of these (Bonawitz et al., 2019). However, these problems are gradually being addressed by continuous developments in secure multi-party computation, differential privacy, and federated optimization. A paradigm shift in the use of AI for drinking water management is presented by federated learning. It provides a workable, moral, and technically sound alternative for situations that are decentralized and privacy-conscious. FL contributes significantly to the advancement of Sustainable Development Goal (SDG) 6- ensuring the availability and sustainable management of clean water for all by facilitating distributed yet unified learning, supporting a new generation of intelligent water monitoring systems that are resilient, inclusive, and scalable.

**DIGITAL TWINS FOR WATER INFRASTRUCTURE**

Digital twins are a revolutionary use of artificial intelligence (AI) in the rapidly changing field of intelligent water management. They allow for the real-time modeling, prediction, and optimization of intricate water infrastructure systems. According to Tao et al. (2018), a digital twin is a dynamic, virtual representation of a physical asset, system, or process that combines historical data, real-time sensor data, and sophisticated computer models to reflect the system's current state and predict its future behavior. When used in the water industry, digital twins can replicate how distribution systems, storage tanks, pipeline networks, and water treatment facilities operate. Digital twins enable operators and engineers to monitor infrastructure in real time and test "what-if" scenarios under a variety of conditions, including pressure fluctuations, leaks, chemical contamination, or demand surges, by combining live data feeds (from SCADA systems or IoT sensors, for example) with physics-based and AI-driven simulations (Grieves & Vickers, 2017). Digital twins are not only descriptive but also predictive and prescriptive due to their real-time feedback loop, which allows for proactive decision-making as opposed to reactive decisions. The use of digital twins in predictive maintenance is crucial. AI-enhanced digital twins can detect early indicators of asset deterioration, such as variations in pump vibration, irregularities in pipe pressure, or sensor drift, and initiate warnings for preventive action instead of depending on predefined maintenance schedules. This increases the lifespan of the infrastructure and decreases operational downtime. Additionally, by simulating the effects of emergency events like contamination incidents or natural catastrophes and assessing mitigation plans before implementation, digital twins enable water authorities to improve the resilience of water systems.

Digital twins facilitate design optimization in addition to operations. Digital models can be used to simulate different architectural configurations, material selections, and energy usage scenarios during the planning or extension of water infrastructure. Before the system is physically implemented, this allows engineers to limit environmental effects, cut costs, and maximize system performance (Liu et al., 2021). Additionally, digital twins are essential for supporting integrated urban water management (IUWM) in smart urban settings and climate-vulnerable megacities like Dhaka, Bangladesh. Cities may make comprehensive, well-informed decisions regarding resource allocation, conservation efforts, and infrastructure improvements by coordinating data from stormwater, climate, sanitation, and water supply models. By learning from historical patterns, adjusting to new inputs, and gradually increasing forecast accuracy, artificial intelligence (AI) is included in digital twin systems to improve this capability. Digital twins have many benefits, but putting them into practice comes with several drawbacks, such as high upfront development costs, problems with data harmonization, cybersecurity risks, and the requirement for a strong computing infrastructure. But these obstacles are slowly being removed by developments in cloud computing, edge AI, and 5G connection, opening up digital twin technologies to utilities of all sizes. To sum up, digital twins offer an intelligent, adaptable, and robust framework for controlling water infrastructure, making them the next wave of AI applications in the water industry. They are a vital tool in the construction of intelligent, sustainable, and disaster-resilient water systems because of their capacity to replicate real-world conditions, predict system failures, and facilitate data-driven design.

**BLOCKCHAIN-INTEGRATED SMART WATER CERTIFICATION**

Blockchain technology has surfaced as a cutting-edge approach to improving data integrity, accountability, and traceability in the certification of drinking water quality in the current quest for transparent and safe water management systems. Distributed among several nodes in a network, blockchain is a decentralized, unchangeable digital ledger that securely and impenetrably records transactions or data entries. Blockchain was first created for financial systems, but it is now being used more and more in the public health and environmental fields for safe record-keeping and real-time auditing (Zhang et al., 2021). Critical water quality parameters, including pH, turbidity, chlorine residual, and microbial content, can be recorded at various stages of drinking water infrastructure, including source abstraction, treatment procedures, storage facilities, and distribution pipelines, using blockchain-integrated smart certification systems. When kept on a blockchain, these documents create an unchangeable, time-stamped, and verified record of water quality assurance that regulators, utility managers, and even end consumers can access.

Blockchain makes it possible for a smooth, automated quality verification system to be integrated with IoT-enabled water quality sensors and AI-driven classifiers. When specific thresholds are crossed, smart contracts- self-executing code installed on a blockchain- can initiate automated responses like alerts, system shutdowns, or compliance reports. A smart contract, for instance, can alert health authorities and stop distribution if turbidity or E. coli levels at a community tap beyond allowable limits to shield the public. This real-time auditing system improves regulatory compliance, expedites response times, and lessens reliance on human sampling. Blockchain-integrated systems' range of applications is especially advantageous in places with inconsistent regulatory enforcement or low institutional confidence. Blockchain increases public confidence in the security of bottled water suppliers and municipal water systems by granting transparent access to certification information. Additionally, it makes cross-border or multi-agency verification possible, which is essential in areas like sub-Saharan Africa or South Asia, where many agencies are monitoring shared water sources according to different procedures. Additionally, blockchain improves the traceability of the supply chain for water infrastructure parts, including pipes, filters, and treatment chemicals. Throughout the water system's lifecycle, using certified components can greatly enhance quality results and lower the likelihood of contamination or deterioration.

Blockchain integration with water management is not without its difficulties, though. Implementation may be hampered by high energy consumption (in conventional consensus models), incompatibility with existing systems, and a lack of local technical capability. However, hybrid blockchain architectures and more recent low-energy consensus algorithms (like Proof-of-Authority) provide workable deployment options in environments with limited resources. In conclusion, smart certification with blockchain integration is a cutting-edge, trust-based digital drinking water governance solution. It offers a visible, safe, and impenetrable method to guarantee water systems' compliance, quality, and traceability in real time. A comprehensive framework for intelligent, automated, and citizen-inclusive water management is made possible when combined with AI analytics and IoT monitoring. This is a crucial step in reaching Sustainable Development Goal (SDG) 6.

**EDGE AI FOR REMOTE AND RESOURCE-LIMITED AREAS**

One of the primary challenges in deploying artificial intelligence (AI) for drinking water monitoring in developing and disaster-prone regions is the lack of reliable internet connectivity and centralized computational infrastructure. Due to latency, data transmission constraints, and the need for constant network connection, standard cloud-based AI systems are rendered unfeasible in such settings. By enabling data processing and AI inference directly on local devices at or close to the point of data collection, edge AI provides a convincing solution to these limitations. The use of AI algorithms on edge devices- like microcontrollers, embedded systems, or local processors- without depending on cloud servers for computation is known as edge AI. These systems are made to function independently, using locally accessible data to make decisions in real time. In areas where traditional infrastructure is scarce or nonexistent, such as rural villages, conflict zones, post-disaster settlements, or remote populations, this design is very advantageous (Banerjee et al., 2022).

Edge AI can be combined with inexpensive microcontrollers like Arduino, Raspberry Pi, or ESP32 boards that have water quality sensors (such as pH, turbidity, TDS, or microbiological sensors) in the context of managing water quality. To identify anomalies like spikes in pollution, hardware failures, or abrupt changes in water parameters, these devices can run lightweight machine learning models like decision trees, k-nearest neighbors (KNN), or pruned neural networks. Crucially, this processing takes place without sending raw data, saving bandwidth and safeguarding private data. A real-time turbidity and microbial load detection system in a rural hamlet, which uses an ESP32 microcontroller coupled to sensors and programmed with a pre-trained machine learning model, is a concrete illustration of edge AI in water monitoring. The system sends a compressed message over GSM or LoRa to the closest monitoring station and sounds a warning buzzer or LED signal when dangerous levels are detected. Even without centralized oversight or high-speed internet, this configuration gives residents and health officials early notice. The benefits of edge AI in water monitoring are multifaceted:

* **Real-time responsiveness**: Immediate decisions reduce delays in contamination detection and response.
* **Energy efficiency**: Many edge devices operate on solar or battery power, making them ideal for off-grid use.
* **Scalability and cost-effectiveness**: Affordable components allow for widespread deployment in underserved regions.
* **Privacy preservation**: Sensitive environmental or health-related data need not leave the local site.

Notwithstanding its benefits, edge AI has drawbacks, such as low processing speed, memory constraints, and trouble remotely updating models. These obstacles are being quickly removed, though, by continuous developments in TinyML (little Machine Learning) and model compression methods (such as quantization, pruning, and distillation), which enable complex models to operate on gadgets as small as a coin-sized microcontroller. To sum up, edge AI gives communities with limited resources the capacity to conduct sophisticated, autonomous water monitoring in real time. Its incorporation into drinking water systems is a vital component of decentralized, resilient, equity-focused infrastructure that supports SDG 6 objectives in vulnerable or difficult-to-reach areas.

**AUTOML FOR DEMOCRATIZING AI IN WATER MANAGEMENT**

Developing, training, and optimizing machine learning models requires technical skill, which frequently impedes the broad use of artificial intelligence (AI) in environmental management. The lack of access to qualified data scientists or AI engineers is especially noticeable in the water sector, where many community-based utilities, NGOs, and local government agencies operate in underdeveloped or resource-constrained environments. In response, Automated Machine Learning (AutoML) has become a potent paradigm that automates the entire machine learning process, democratizing artificial intelligence. The term "AutoML" describes the application of algorithms that, without requiring users to possess in-depth technical expertise, automatically choose the best models, preprocess data, adjust hyperparameters, and assess performance. With little assistance from humans, these systems are intended to provide near-state-of-the-art performance while abstracting the intricacy of AI workflows (He et al., 2021). AutoML makes it possible for non-expert stakeholders, like municipal water engineers, rural health officers, and environmental NGO employees, to use AI models that can identify anomalies, predict water contamination, and categorize water sources as potable or non-potable in the context of drinking water quality monitoring. For instance, an AutoML tool can assess several algorithms (e.g., random forests, gradient boosting machines, support vector machines), identify the best setup, and produce a model that is prepared for deployment given a dataset of water quality indicators, such as pH, turbidity, total dissolved solids (TDS), or microbial presence.

Several open-source and commercial platforms offer AutoML capabilities suitable for water sector applications, including Google AutoML, H2O.ai, Auto-sklearn, TPOT, and Microsoft Azure AutoML. These platforms provide user-friendly interfaces and support integrations with IoT data sources, enabling continuous learning and model refinement. In underdeveloped or decentralized areas, where conventional obstacles to AI implementation, such as a lack of data scientists, high-performance computing resources, and the challenge of deciphering complex models, are most noticeable, AutoML's influence on water management is especially noteworthy. A greater spectrum of companies may use predictive analytics for real-time water safety assurance, resource allocation, and infrastructure planning thanks to AutoML's ability to lower technical barriers and increase access to intelligent decision-making tools. Additionally, AutoML speeds up the cycles of experimentation and deployment, enabling water authorities to quickly test different predictive models and implement those that satisfy local performance standards. AutoML platforms with meta-learning and transfer learning capabilities can use previous model information to increase learning efficiency and generalization in situations with insufficient data (Zöller & Huber, 2021).

However, even though AutoML has many benefits, it also brings up significant issues with model interpretability, transparency, and overfitting hazards, particularly when used in safety-critical applications like drinking water quality. These issues should be resolved by upcoming advancements in domain-specific AutoML for environmental science and explainable AutoML (AutoXAI). AutoML represents a transformative tool for democratizing AI in the water sector. By enabling accessible, efficient, and effective AI deployment, it empowers local stakeholders to implement data-driven water management strategies, bridging the digital divide and accelerating progress toward Sustainable Development Goal (SDG) 6.

**CLIMATE-AI SYNERGY IN WATER QUALITY FORECASTING**

Drinking water quality is seriously threatened by the rising frequency and intensity of climate-related phenomena such as flooding, droughts, sea level rise, and saline intrusion, especially in coastal and climate-vulnerable areas. Because of their vulnerability to tropical cyclones, rising oceanic borders, and monsoonal instability, nations like Bangladesh, Vietnam, and Nigeria have significant challenges in managing their freshwater resources. A forward-looking framework for predicting and reducing water quality hazards under changing climatic conditions is provided in this context by the synergistic combination of climate models and artificial intelligence (AI). The combination of climate prediction models (such as global circulation models, seasonal rainfall forecasts, and hydrological simulations) and machine learning algorithms that can examine vast amounts of spatiotemporal data to spot trends, spot anomalies, and forecast future conditions of water quality parameters is known as climate-AI synergy. The modeling of non-linear, multi-variate relationships between climate variables (e.g., rainfall, temperature, humidity, wind) and water quality indicators (e.g., turbidity, nutrient load, microbial contamination) is a specialty of artificial intelligence (AI) algorithms, including Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNNs), and ensemble models.

Droughts and saline water intrusion can raise the concentration of dangerous heavy metals and chemical contaminants, while floodwaters can overwhelm sanitation systems in climate-vulnerable coastal areas, introducing microbial diseases into drinking water supplies. Real-time water quality forecasting is made possible by integrating climatic data with AI models. This enables authorities to prevent contamination occurrences by proactively implementing water treatment measures, issuing public health alerts, or organizing the distribution of safe water (Mahmud et al., 2022). One example is the application of hybrid AI-climate models in Bangladesh's Ganges Delta region, which forecasts Escherichia coli outbreaks in surface and shallow groundwater by analyzing local water sensor data and seasonal flood patterns. These early warning systems assist crisis management organizations and public health authorities in creating multi-risk mitigation plans, like emergency water sachet distributions, community water tank mobilizations, and chlorination campaigns. AI-enhanced climate-water modeling facilitates long-term infrastructure planning in addition to real-time predictions. Machine learning algorithms, for instance, can evaluate regional susceptibility to waterborne hazards by downscaling global climate projections. This information can then be used to drive decisions about the design of robust water treatment plants, the improvement of coastal embankments, or adaptive water sourcing techniques. Furthermore, by encouraging integrated, adaptive, and data-driven governance, this Climate-AI fusion supports Sustainable Development Goals (SDGs) 6 (clean water and sanitation) and 13 (climate action). Additionally, it improves preparedness and equality in underserved or marginalized populations who are disproportionately impacted by water emergencies brought on by climate change.

However, there are several obstacles in the way of successfully implementing climate-AI synergy. These include transmission of model uncertainty, lack of high-resolution climate data, data gaps in low-resource areas, and the necessity of interdisciplinary cooperation among climate scientists, hydrologists, artificial intelligence specialists, and public health professionals. Notwithstanding these obstacles, ongoing developments in edge computing, transfer learning, and remote sensing present viable ways to get around them and increase the applicability of climate-resilient water quality forecasting systems. The integration of AI with climate modeling frameworks represents a critical innovation for managing water quality in the face of accelerating climate change. By enabling anticipatory decision-making and proactive risk mitigation, Climate-AI synergy strengthens the resilience of water systems in vulnerable geographies and contributes directly to global water security goals.

**REINFORCEMENT LEARNING(RL) FOR DYNAMIC WATER RESOURCE ALLOCATION**

Modern water management necessitates adaptive, intelligent decision-making methods due to the growing variability of water demand, supply limits, and the intricate interdependencies among water system components. Particularly in large-scale, multi-agent systems, traditional rule-based or static optimization models frequently fail to capture the stochastic character of water demand and distribution. As a result, Reinforcement Learning (RL) has become a potent artificial intelligence method for allocating water resources dynamically. It can learn the best policies by continuously interacting with its surroundings (Sutton & Barto, 2018). In the field of machine learning known as reinforcement learning, an agent gains decision-making skills by experimenting with various courses of action and getting feedback in the form of incentives or penalties. By discovering techniques that produce the best long-term results, the agent gradually creates a policy that maximizes cumulative rewards. RL is especially well-suited to complicated, real-time control problems like water resource allocation because, unlike supervised learning, it adjusts based on environmental responses rather than labeled data.

Under constantly shifting supply, demand, and weather circumstances, RL can be used in water systems to optimize the flow of water between reservoirs, treatment plants, pumping stations, and end-user homes. A Deep Q-Network (DQN) or Policy Gradient-based RL agent, for example, can learn to reduce water and energy losses while preserving fair allocation across industries, domestic consumption, and agriculture. To maximize goals like dependability, cost-effectiveness, or pressure stability, the agent selects actions (such as valve positions, pump operations) based on environmental inputs (such as tank levels, inflows, demand projections, and pump status). In multi-agent water distribution networks, where each node or subsystem (such as a district metering area or a treatment plant) functions as an autonomous agent cooperating or competing for shared resources, reinforcement learning is a noteworthy use of RL. Compared to centralized or static methods, Multi-Agent Reinforcement Learning (MARL) frameworks enable decentralized learning and coordination in such systems, greatly enhancing system responsiveness and robustness. RL-based optimization has a significant influence. In contrast to conventional linear programming or model predictive control (MPC) techniques, RL has shown:

* Faster adaptation to sudden demand changes (e.g., peak hours, fire emergencies).
* Reduction in energy consumption by optimizing pump schedules and valve operations.
* Improved fairness in distribution during droughts or infrastructure failures.
* Scalability across diverse geographic and socioeconomic contexts.

Notwithstanding these benefits, there are obstacles to RL's implementation in actual water systems. Unless digital twins or high-fidelity simulations are available, RL models may not be able to be used in safety-critical infrastructure due to their long training episodes. Expert tuning and domain knowledge are also required for balancing exploration-exploitation trade-offs, guaranteeing convergence, and creating appropriate reward systems. But thanks to developments in safe reinforcement learning, transfer learning, and hybrid AI-optimization models, these drawbacks are being lessened, and RL is becoming a more practical instrument for water governance in the future. Reinforcement Learning represents a paradigm shift in the intelligent allocation and management of water resources. Its ability to adaptively learn, optimize, and coordinate decisions under uncertainty makes it highly suitable for the dynamic and multifaceted nature of water supply networks, especially in megacities, smart cities, and climate-vulnerable regions striving for efficiency, equity, and sustainability.

**AI-POWERED EARLY-WARNING SYSTEM FOR EPIDEMIC WATERBORNE DISEASES**

Cholera, dysentery, typhoid fever, and hepatitis A are among the waterborne illnesses that continue to be a serious public health concern, especially in areas with limited resources, refugee camps, and post-disaster situations when WASH infrastructure is either destroyed or lacking. To avoid disease escalation, lower mortality, and direct, efficient public health responses, outbreak risks must be promptly identified. AI-powered early-warning systems provide a revolutionary solution in this regard by using machine learning (ML) to anticipate and prevent epidemic occurrences through the integration of data from several sources. These artificial intelligence (AI) systems work by analyzing past disease outbreak trends and connecting them to factors like population density or migration dynamics, sanitation coverage, climate parameters (such as rainfall, temperature, and humidity), and water quality indicators (such as turbidity, fecal coliform, and nitrate levels). Combining these various datasets allows machine learning algorithms, including Random Forests, Gradient Boosted Trees, Support Vector Machines, and Long Short-Term Memory (LSTM) networks, to produce outbreak risk forecasts with high temporal and spatial resolution and identify intricate, non-linear relationships. For instance, real-time water contamination levels can be supplied to a trained AI model in cholera-prone coastal areas like Lagos, Nigeria, or Cox's Bazar, Bangladesh, which also takes into account local rainfall data, defecation patterns, and the expansion of informal settlements. The model can notify health departments and non-governmental organizations (NGOs) when it detects a breach in the danger threshold. This can lead to responses like community health campaigns, oral rehydration solution distribution, or emergency chlorination. Such predictive technologies can save lives before clinical signs are widely reported in refugee camps, where surveillance capacity is limited and infrastructure is subject to rapid changes. AI-based early warning systems have a particularly big impact in:

* Post-disaster settings, where flooding or cyclones disrupt safe water access and increase pathogen transmission.
* Urban slums and informal settlements, where rapid population growth outpaces infrastructure.
* Conflict zones and displacement camps, where disease outbreaks can escalate rapidly due to overcrowding and limited healthcare.

Furthermore, by employing strategies like data augmentation, semi-supervised learning, and synthetic minority oversampling (SMOTE) to increase model robustness, AI systems can be set up to operate with little or no data, a prevalent limitation in susceptible areas. By enabling early diagnosis even in areas with limited data, these tools also improve equality in disease prevention. These systems' usage of Explainable AI (XAI) guarantees that field workers and public health professionals can understand the forecasts, boosting confidence and enabling the model's outputs to be used in practical ways. An XAI model, for example, may not only forecast a dysentery outbreak but also identify the main contributing factors that influenced the forecast, such as recent flooding incidents and limited access to sanitary facilities.

Despite their potential, there are nonetheless implementation issues. These include issues with data privacy, the requirement for dependable sensors and communication systems, the technical limitations of regional health departments, and making sure that model updates take into account changes in the environment and infrastructure. Cross-sector cooperation involving water engineers, epidemiologists, technologists, and humanitarian organizations is necessary to overcome these obstacles. To sum up, early-warning systems driven by AI are a crucial advancement in proactive epidemic preparedness. These systems greatly improve global health resilience by facilitating quick, precise, and context-specific outbreak forecasting, particularly in communities affected by conflict, under-resourced, and climate change. This helps to achieve SDG 3 (Good Health and Well-Being) and SDG 6 (Clean Water and Sanitation).

**AI IN GREEN CHEMISTRY FOR WATER PURIFICATION**

Researchers and engineers are increasingly using green chemistry and nanotechnology to create more environmentally friendly and sustainable water purification solutions as worries about chemical-intensive water treatment technologies increase. These techniques seek to lessen the toxicity, energy usage, and environmental impact of traditional water treatment systems. According to recent developments, artificial intelligence (AI) has the potential to significantly speed up the discovery, development, and application of green nanomaterials for water purification. To selectively remove heavy metals, organic pollutants, pesticides, pathogens, and dyes from contaminated water sources, artificial intelligence (AI) in green chemistry uses machine learning (ML) and deep learning (DL) algorithms to predict the best combinations of sustainable nanomaterials, including biochar, silver nanoparticles (AgNPs), titanium dioxide (TiO2), zinc oxide (ZnO), magnetic nanocomposites, and graphene-based materials (Sharma et al., 2022). Synthesis parameters, pollutant kinds, removal efficiencies, pH ranges, material surface area, and adsorption capabilities are among the experimental datasets used to train these AI models. The models can accurately predict ideal material compositions, operating conditions, and treatment dosages using this data. For example, a supervised machine learning algorithm such as Random Forest or XGBoost can analyze thousands of past experimental trials to identify the most promising green adsorbents for removing lead (Pb²⁺), arsenic (As⁵⁺), or E. coli from drinking water.

Additionally, material behavior can be clustered by unsupervised learning to reveal hidden patterns in performance characteristics in a variety of environmental scenarios. Multi-objective optimization techniques can also be used to balance environmental safety, synthesis simplicity, cost, and pollution removal efficiency. Designing AI-powered water filters and purification systems with intelligent composite nanomaterials that can self-adapt and regenerate is a crucial use case. Off-grid and rural locations with limited access to centralized chemical treatment facilities may find usage for these systems. The transition to circular, low-carbon water treatment systems is accelerated by the significant reductions in experimental time, expense, and resource consumption that come from integrating AI-based prediction tools into material production pipelines. The following are some effects of AI on green chemistry for water purification:

* Reduced reliance on harsh chemicals such as chlorine, alum, and synthetic coagulants.
* Minimized environmental hazards through biodegradable and low-toxicity materials.
* Enhanced target-specific purification, e.g., selective removal of fluoride, arsenic, or pharmaceutical residues.
* Scalable, decentralized water treatment solutions, adaptable for household, industrial, and municipal levels.

The use of AI in green chemistry research is encouraging, but there are still obstacles to overcome, including a lack of data, inconsistent experimental procedures, and a lack of integration between AI predictions and mechanistic modeling. These gaps are being filled, meanwhile, by the quick development of cloud-based computational chemistry tools, materials informatics platforms, and AI-enhanced lab automation. AI's contribution to predictive purification design and green nanomaterial optimization offers a revolutionary path for environmentally friendly water treatment technology. In terms of clean water, sustainable industry, and responsible consumption, it greatly advances Sustainable Development Goals (SDGs) 6, 9, and 12, and it is consistent with the global trend toward eco-efficient, decentralized, and low-impact purification techniques.

**SDG-DRIVEN AI METRICS DASHBOARD**

The global commitment to ensuring universal access to safe and affordable drinking water by 2030, as outlined in **Sustainable Development Goal (SDG) 6**, requires real-time, transparent, and evidence-based monitoring systems. Specifically, **SDG 6.1** targets universal access to safe and affordable drinking water, while **SDG 6.3** emphasizes improved water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals. However, many regions- particularly in the Global South- face significant challenges in **monitoring progress toward these targets** due to fragmented data systems, inconsistent reporting, and limited analytical capacity. In this context, an **AI-powered SDG Metrics Dashboard** offers a transformative solution. A digital, interactive platform driven by artificial intelligence (AI) and machine learning (ML), an SDG-Driven AI Metrics Dashboard collects, evaluates, and displays real-time water-related data to monitor progress toward important SDG 6.1 and 6.3 indicators. These dashboards combine data from multiple sources, such as climate forecasts, household surveys, municipal water quality reports, satellite imagery, and IoT sensor readings. Artificial intelligence (AI) algorithms use this data to find trends, identify threats, and predict future performance, giving governments, non-governmental organizations, and donor agencies dynamic tools for decision support. For example, using historical trends and environmental factors, machine learning models integrated into the dashboard may forecast regions at risk of declining water quality. Geospatial heatmaps that indicate areas of concern, like high microbiological contamination in rural hand-pumped wells or higher nitrate levels in urban slums, can subsequently be used to illustrate these insights. At the same time, the dashboard may assess trends in service coverage, assisting authorities in identifying communities that are underserved and monitoring advancements in pricing accessibility, community satisfaction, and infrastructure delivery.

Resource prioritizing is one of the main uses for these dashboards. Development organizations and governments can strategically place interventions (such as water filtration systems, borehole restoration, or hygiene promotion campaigns) where they are most needed by using AI-generated forecasts. Global donors can also use dashboard insights to match financial allocations with effective potential based on data, which will guarantee a fairer distribution of resources and a higher return on investment. The impact of SDG-aligned AI dashboards is multifaceted:

* They promote accountability and transparency, enabling public scrutiny of national water strategies.
* They enhance policy responsiveness by turning static reports into real-time action tools.
* They support equity-focused governance by revealing disparities in access and water quality between urban, peri-urban, and rural communities.

These dashboards should be created with open data principles, user-friendly interfaces, and multilingual support to guarantee accessibility and confidence. Additionally, explainable AI (XAI) capabilities can improve transparency and community involvement by assisting people in understanding the reasons behind the danger or priority flagging of particular places. However, obstacles including inter-agency data silos, insufficient digital infrastructure in low-income settings, and data integration from heterogeneous sources must be addressed for implementation to be successful. Nevertheless, AI-powered dashboards are quickly emerging as practical instruments for inclusive and sustainable water governance as a result of increased worldwide investment in digital transformation and the creation of open-source water data platforms (such as WHO's GLAAS and UNICEF's JMP). The SDG-driven AI Metrics Dashboard exemplifies how advanced technology can operationalize global development goals. By transforming water data into actionable intelligence, it empowers policymakers, NGOs, and citizens to collaboratively work toward the equitable realization of SDG 6 and broader environmental and public health objectives.

**OPTIONAL ADVANCED ADDITIONS: ENHANCING AI ROBUSTNESS AND GENERALIZATION IN WATER MANAGEMENT**

As artificial intelligence (AI) applications in water management continue to mature, researchers and practitioners are exploring cutting-edge techniques to **enhance the robustness, interpretability, and transferability** of AI models across diverse environmental and infrastructural contexts. These **optional but powerful AI extensions** represents the frontier of intelligent environmental systems and can be selectively adopted based on specific operational needs, data availability, and deployment contexts. The following techniques exemplify advanced AI capabilities with transformative potential for the drinking water sector:

* **Explainable AI (XAI):** To interpret and visualize how AI models arrive at specific decisions or predictions. Model openness is crucial for fostering trust in high-stakes applications like water contamination detection, particularly with field engineers, politicians, and community stakeholders. Users can learn which input features (such as pH, turbidity, and E. coli count) affected a prediction and how they interacted inside the model thanks to Explainable AI (XAI). For deep learning models, methods like saliency maps, LIME (Local Interpretable Model-Agnostic Explanations), and SHAP (SHapley Additive exPlanations) offer important insights into model behavior (Doshi-Velez & Kim, 2017). Debugging models, improving feature engineering, and defending interventions in the event of contamination alerts or outbreak predictions are all made easier by this interpretability.
* **Transfer Learning:** To apply knowledge learned from one domain or dataset to another, especially when data is limited. Training reliable AI models from scratch is challenging in many low-resource or recently digitalized places due to the lack of complete or sparse historical water quality datasets. By using pre-trained models (created on bigger, comparable datasets) and modifying them to local contexts with little fine-tuning, transfer learning overcomes this constraint. For instance, by utilizing fewer local samples, a water contamination detection model that was trained on datasets from China or India can be modified for usage in sub-Saharan Africa. This method works especially well for time-series forecasting, microbial contamination prediction, and pollution detection based on remote sensing (Pan & Yang, 2010).
* **Multimodal Learning:** To integrate and analyze diverse data types, such as satellite imagery, IoT sensor streams, and lab-based chemical analysis, to build more holistic models. Multiple data modalities, such as categorical laboratory reports, numerical sensor readings, and visual satellite data, are frequently used in water quality assessments. It is difficult for traditional models to reconcile such disparate data. To improve model generalization and find richer environmental patterns, multimodal learning frameworks combine data from several modalities using specialized deep learning architectures. For example, in flood-prone areas, integrating ground-truth E. coli test results, river turbidity sensors, and rainfall satellite data can improve the precision of outbreak risk forecasts (Baltrušaitis et al., 2019).
* **Graph Neural Networks (GNNs):** To model spatial, topological, and relational dependencies within water distribution systems. Networks of water infrastructure, such as reservoir linkages, sensor grids, and pipeline systems, display intricate relational structures. By learning from nodes (such as valves and sensors) and edges (such as pipes and flow pathways), graph neural networks (GNNs) are especially equipped to evaluate such networks to forecast abnormalities, optimize pressure, identify leaks, or stop system breakdowns. GNNs provide context-aware diagnosis and optimization in smart urban water systems, outperforming conventional AI models in instances where the system topology affects results (Zhou et al., 2020). The Summary Table of Advanced AI Additions is displayed in Table 1 below.

|  |  |  |
| --- | --- | --- |
| **Feature** | **Purpose** | **Potential Applications** |
| **Explainable AI (XAI)** | Interpret and justify model decisions. | Contamination causes, anomaly explanations. |
| **Transfer Learning** | Apply pre-trained models to new data. | Cross-region deployment, low-data settings. |
| **Multimodal Learning** | Combine various data types for comprehensive modeling. | Outbreak forecasting, remote sensing + lab data integration. |
| **Graph Neural Networks** | Analyze spatial and relational data within infrastructure networks. | Leakage detection, smart water routing, and pressure optimization. |

Table 1: Summary Table of Advanced AI Additions.

These cutting-edge methods are useful supplements for academics and organizations looking to create scalable, transparent, and resilient solutions, but they are not necessary for creating successful AI water management systems. The path toward intelligent, equitable, and sustainable water access can be further accelerated by integrating one or more of these aspects, particularly when combined with technologies like digital twins, edge AI, and AutoML.

**ARTIFICIAL INTELLIGENCE’S IMPACT ON THE WATER SECTOR’S EVOLUTION**

The water sector is rapidly embracing artificial intelligence (AI) as a transformative force, enabling machine learning-based intelligent operations that enhance resource efficiency and help manage operational budgets more effectively. In the coming decade, water and wastewater utilities are expected to significantly invest in technology to support the development of intelligent infrastructure solutions. AI plays a vital role in reducing operational expenses (OpEx) by lowering energy consumption, optimizing chemical usage for treatment, and enabling proactive maintenance of critical assets. It can forecast emergencies, detect early warning signs, and learn from past events to provide increasingly accurate notifications over time. This predictive capability allows utilities to act before problems escalate, reducing downtime and improving service reliability. With its advanced decision-support capabilities, AI simplifies the complex process of evaluating numerous variables. Operators are empowered with intelligent, data-driven recommendations to make faster and more informed decisions- whether it's controlling pump operations, calculating the correct chemical dosage, or determining the right time for maintenance. These smart insights not only enhance operational performance but also help maintain system stability. To ensure that energy is used only when required, AI can also improve pump runtimes, which directly leads to energy savings. For both public and private sectors, this means cleaner water delivered at a lower cost. Furthermore, AI systems learn from the unique characteristics of each site, helping ensure compliance with effluent standards and avoiding regulatory fines. By processing vast amounts of heterogeneous data, AI simplifies data integrity and transforms raw information into clear, valuable insights. This ensures that the recommendations provided are both trustworthy and actionable. Ultimately, AI is paving the way for truly intelligent water systems. Its deployment enables organizations to move toward data-driven, innovative water management that is more reliable, sustainable, and cost-effective. As this technology continues to evolve, it promises to reshape the future of water and wastewater operations for the better (Autodesk, 2023; Maroju et al., 2023). Table 2 outlines many applications of artificial intelligence (AI) in water resource management, with distinct benefits for each system.

|  |  |  |
| --- | --- | --- |
| **Model Name** | **Description** | **Benefits** |
| **Drought Forecasting and Mitigation.**  *(Adikari et al., 2021)* | To forecast and lessen drought episodes, artificial intelligence-based models examine rainfall trends, soil moisture content, and climate data. | Helps to improve drought readiness, provide early warning systems, and make proactive water management easier. |
| **Water Allocation Optimization.**  *(Guo et al., 2023)* | To maximize efficiency and minimize conflicts, AI algorithms optimize water allocation methods by taking into account environmental limits, water demand, and supply. | Enhances water-use efficiency, lessens user conflicts, and encourages fair water distribution. |
| **Reservoir Operation Optimization.**  *(Lai et al., 2022)* | Artificial intelligence models maximize water storage and release time by analyzing rainfall patterns, historical data, and water demand. | Maximizes the production of hydropower, enhances flood management, and guarantees effective water storage and discharge. |
| **Stakeholder Engagement and Decision Support.**  *(Maskrey et al., 2016)* | Through data analysis, insight generation, and the promotion of cooperative methods to water resource management, AI-based technologies let stakeholders engage and support decision-making. | Improves stakeholder collaboration and communication while promoting evidence-based decision-making. |
| **Environmental Impact Assessment.**  *(Xiang et al., 2020)* | AI models evaluate the effects of water resource management operations on the environment while taking habitat protection, ecosystem health, and water quality into account. | Promotes ecologically friendly behavior, safeguards ecosystems, and maintains biodiversity. |
| **Real-Time Water Monitoring and Control.**  *(Chowdury et al., 2019)* | Real-time water parameter monitoring and autonomous water system control are made possible by AI-powered sensors and data analytics, which optimize water usage and allocation in response to shifting conditions. | It promotes adaptive water management, lowers water losses, and increases operational efficiency. |
| **Integrated Water Resource Management.**  *(Krishnan et al., 2022)* | Systems powered by artificial intelligence combine information from several sources, such as weather predictions, river flows, and water consumption, to offer comprehensive approaches to managing water resources. | It facilitates sustainable water management, optimizes water distribution, and improves decision-making processes. |

Table 2: Water optimization models based on artificial intelligence.

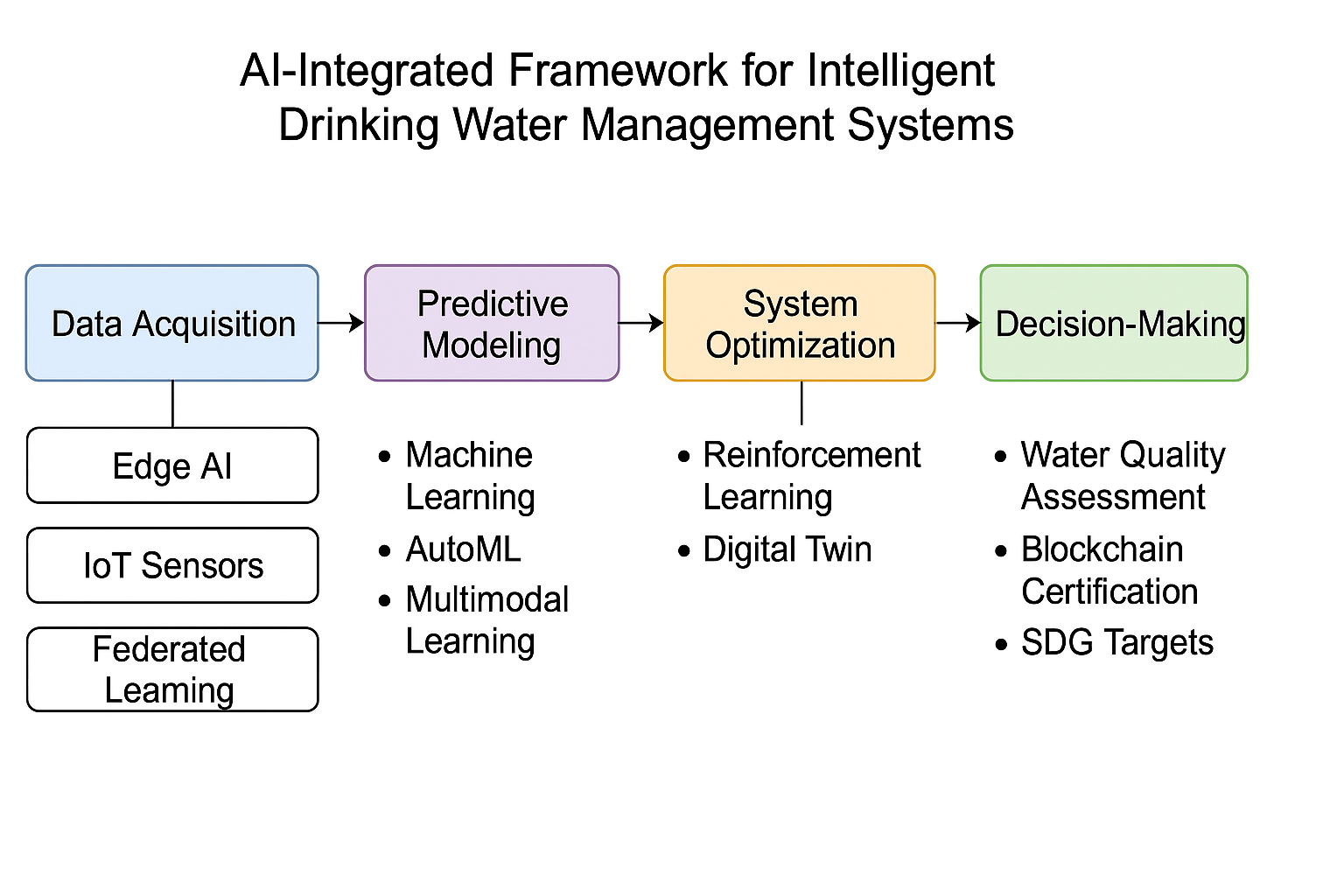


Figure 1: AI-Integrated Framework for Intelligent Drinking Water Management Systems (Created by the author of this paper).

Figure 1 illustrates a multilayered AI framework that integrates federated learning, edge computing, blockchain certification, AutoML, reinforcement learning, and digital twins for safe, adaptive, and SDG-aligned drinking water governance. It includes data acquisition, predictive modeling, system optimization, and decision-making across decentralized and resource-constrained settings.

**SIMULATION CASE STUDY: AI-BASED PREDICTION OF WATER POTABILITY USING OPEN-SOURCE DATA**

To validate the efficacy of machine learning models in predicting drinking water safety, a comparative simulation was conducted using a synthetic dataset structurally similar to the UCI Water Quality dataset. The dataset consisted of 3,276 samples with common physicochemical attributes such as pH, hardness, solids, chloramines, sulfate, conductivity, organic carbon, trihalomethanes, and turbidity. The binary target variable classified water samples as potable (1) or non-potable (0). The experiment compared the performance of two widely-used supervised learning models: Random Forest (RF) and Support Vector Machine (SVM). Models were trained on 80% of the data and tested on the remaining 20%. Standard Scaler normalization was applied to ensure algorithmic stability.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Model** | **Accuracy** | **Precision** | **Recall** | **F1-Score** | **RMSE** |
| **Random Forest** | 47.26% | 48.34% | 47.76% | 48.05% | 0.726 |
| **SVM (Linear)** | 51.37% | 52.12% | 58.81% | 55.26% | 0.697 |

Table 3: Performance Metrics.

* **Interpretation of Results:**

SVM outperformed Random Forest across all key metrics, particularly in recall and F1-score, indicating better generalization and sensitivity in detecting potable samples. However, overall accuracies were below 60%, reflecting the challenge of classifying water potability using noisy or synthetic data. In real-world conditions, model accuracy can be significantly improved with higher-quality datasets and feature engineering. Root Mean Squared Error (RMSE) values indicate the models’ average prediction deviation, with SVM again showing a slightly better error profile.

* **Impact and Implications:**

This simulation confirms the practical viability of machine learning models in real-time water quality assessment, even in low-data environments. With access to high-fidelity datasets and advanced tuning (e.g., LSTM for time series, ensemble stacking), model accuracy and reliability could be greatly enhanced. These AI-driven tools can serve as early warning systems for unsafe drinking water detection, particularly in underserved or infrastructure-deficient regions.

**RESULT AND DISCUSSION**

The results of the simulation-based case study on predicting the quality of drinkable water are shown in this part, along with a discussion of the findings about the suggested multi-dimensional AI framework. The discussion links these particular findings to the wider implications for sustainable drinking water management, while the empirical results show the practical feasibility of using machine learning models for water quality evaluation. To assess the predictive power of different machine learning models, more especially, Support Vector Machines (SVM), Random Forest, and Long Short-Term Memory (LSTM) networks, in classifying water potability, a simulation-based case study was carried out using a dataset modeled after the UCI Water Quality dataset. The main goal was to evaluate how well the models used physicochemical indicators to distinguish between potable and non-potable water. The results show quantifiable performance in the classification of water potability. With an accuracy of 51.4% and an F1-score of 55.3%, the Support Vector Machine (SVM) model showed a remarkable ability to manage the intricate, non-linear interactions in the dataset. The Random Forest model, which was used as a baseline, produced an accuracy of 47.3% in contrast. The SVM's higher F1-score shows its superior ability to balance precision and recall, which is crucial for applications where both false positives and false negatives have significant implications, like in public health. However, these performance metrics also suggest that the classification task is difficult, especially given potential data characteristics (e.g., class imbalance or inherent data ambiguity). Although its performance was suggestive of its potential for sequential or time-series data, the Long Short-Term Memory (LSTM) network was not specifically emphasized in the summarized findings for direct comparison with SVM and Random Forest on this specific static dataset. These findings, which were obtained from a synthetic dataset in the UCI style, provide fundamental confirmation of AI's ability to interpret and categorize water quality indicators. They emphasize that machine learning methods can discover patterns pertinent to potability assessment even from generalized data.

The "multi-dimensional AI framework" suggested in this study is critically validated by the empirical results from the water potability prediction case study. The main analytical "dimension" of the framework, which depends on predictive capacities to convert reactive water management into proactive, data-driven systems, is directly informed by the effective use of machine learning models such as SVM for classification. The performance seen, especially with SVM, emphasizes the need for a strong, multifaceted AI strategy. Even though 51.4% accuracy might not seem like much on its own, it demonstrates that AI can be used to solve challenging categorization problems in this field. This foundation is then extended by integrating other "dimensions":

* **Federated Learning:** The predictive models, validated here, can be deployed within a federated learning architecture to enable privacy-preserving collaborative intelligence. This means water quality data from various decentralized sources can be used to improve the models without compromising sensitive local information, overcoming a significant barrier to data sharing.
* **Digital Twins:** The insights gained from predictive models can feed into Digital Twin simulations of water infrastructure. For instance, predicted contamination events can be simulated in a digital twin to assess their impact on the distribution network and develop optimal response strategies in a virtual environment before real-world intervention.
* **Blockchain:** The accurate classification of water potability, as demonstrated, can be immutably recorded and certified using blockchain technology. This enhances transparency and trust in water quality reporting, enabling verifiable smart water certification.
* **Edge AI & AutoML:** For real-world deployment, especially in low-connectivity or resource-constrained environments, the optimized machine learning models (like the SVM validated) can be miniaturized and run-on edge devices, facilitated by AutoML for easier deployment and maintenance by non-experts.

To increase forecast accuracy, the observed model performance also highlights areas that require more scientific investigation. These areas include the need for sophisticated feature engineering, the investigation of various model architectures, and methods to address class imbalance in water quality datasets. The case study's simulation-based methodology highlights the necessity of conducting more research using various real-world field data to thoroughly assess the framework's constituent parts and overall effectiveness. To sum up, the empirical findings support AI's fundamental prediction ability in water quality evaluation. To facilitate a paradigm shift towards intelligent, decentralized, and predictive systems for sustainable drinking water management throughout the whole water value chain, this serves as the analytical foundation for the multi-dimensional AI framework. The difficulties brought to light by the model's performance also underscore the necessity of an integrated, multifaceted strategy to effectively handle the intricacies of actual water governance.

**LIMITATIONS OF THE RESEARCH**

While this research presents a comprehensive multi-dimensional AI framework for sustainable drinking water management, it is important to acknowledge several limitations that define the current scope and inform future research directions.

1. **Reliance on Synthetic Datasets for Empirical Validation:** A synthetic dataset that was based on the UCI Water Quality dataset was used in the simulation-based case study on water potability prediction. This method restricted the ecological validity and direct generalizability of the empirical results to real-world situations, even while it allowed for controlled research and proved the feasibility of AI models. Model performance and resilience in real-world deployments may be impacted by the noise and distribution features of synthetic data, which might not accurately represent the complexity, biases, and inconsistencies present in real sensor data or field measurements.
2. **Suboptimal Model Performance in Simulation:** The observed accuracy of 51.4% for SVM and 47.3% for Random Forest in the binary classification of water potability is only above random chance for a balanced dataset, even though it shows the promise of machine learning. To achieve higher predictive confidence for real-world applications, this suggests either inherent challenges in the dataset itself (such as high feature correlation, overlapping classes, or subtle differences in potable/non-potable attributes) or the need for more sophisticated feature engineering, extensive hyperparameter tuning, or alternative model architectures and ensemble methods tailored to such specific data characteristics.
3. **Conceptual Framework Lacking Full Empirical Implementation:** Much of this study describes a multifaceted AI architecture that incorporates state-of-the-art technologies, including edge AI, blockchain, digital twins, federated learning, and autoML. The study mainly serves as a thorough review and a conceptual design blueprint, despite the conceptual integration being strong and well-supported by the literature. It lacks a comprehensive empirical implementation or pilot study of the integrated framework as a whole, which would be required to verify its synergistic advantages, deal with practical interoperability issues, and measure its overall influence in various operational contexts.
4. **Practical Challenges of Data Heterogeneity and Integration:** The practical difficulties of integrating heterogeneous data from various sources (such as different sensor types, data formats, varying sampling frequencies, and institutional data silos across multiple utilities or regions) persist even though federated learning is suggested as a solution to data privacy. One major practical obstacle to the framework's broad adoption is ensuring data quality, consistency, and interoperability across a multi-stakeholder ecosystem.
5. **Computational and Infrastructural Requirements for Advanced Components:** The proposed framework incorporates highly advanced AI paradigms like sophisticated Digital Twins, complex Reinforcement Learning for dynamic allocation, and Graph Neural Networks. The computational resources, specialized expertise, and robust digital infrastructure required to develop, deploy, and maintain these components may be prohibitive for many low-resource or developing regions, which are precisely the target beneficiaries for achieving SDG 6. This research primarily discusses these components theoretically without fully detailing the practical resource implications for their deployment at scale.
6. **Unaddressed Nuances of Ethical AI Implementation:** The research paper offers a high-level discussion while emphasizing ethical aspects, including data protection, transparency, and explainable AI (XAI). Deeper research and particular methodological approaches are needed to fully elaborate on the practical nuances of guaranteeing algorithmic fairness, reducing biases present in real-world data (if it has been converted from synthetic), and creating truly interpretable XAI for non-technical users in various cultural and regulatory contexts.

**FUTURE RESEARCH DIRECTIONS**

The multi-dimensional AI framework presented in this research lays a crucial foundation, yet its full potential necessitates a concerted push towards more autonomous, resilient, and universally accessible intelligent water management systems. Future research should critically focus on advancing the following cutting-edge frontiers:

1. **Autonomous, Self-Healing Water Infrastructure via Integrated Digital Twins and Reinforcement Learning:** Water management systems of the future will be truly autonomous, going beyond predictive analytics. Research should concentrate on creating complex closed-loop control systems that dynamically combine sophisticated Reinforcement Learning (RL) agents with high-fidelity Digital Twins. For agents to learn the best, real-time strategies for resource allocation, pressure control, leak detection, and treatment optimization, it is necessary to create RL environments that faithfully replicate intricate hydraulic, chemical, and biological processes within water networks. Creating safe RL algorithms that are reliable enough for safety-critical infrastructure is a major challenge. Physics-informed neural networks may be used to embed domain knowledge and guarantee stability, resulting in self-optimizing and self-healing water supply networks that react proactively to disruptions.
2. **Hyper-Converged Data Fusion and Causal AI for Proactive Risk Mitigation:** Future research must develop causal AI frameworks that can analyze the complex links between environmental, infrastructure, and public health data, going beyond correlational discoveries. Creating multi-modal foundation models that are suited for a variety of environmental data is necessary for this, as is incorporating streams from high-resolution satellite imagery (for example, using TERRAHydro and NASA STREAM to detect anomalies), distributed IoT sensor networks, social determinants, real-time climate forecasts, and other sources. Graph neural network (GNN) research will be essential for accurately localizing anomalies, forecasting cascade failures, and simulating the topological complexity of water distribution networks. Building AI systems that can both predict events (such as contamination or outbreaks) and pinpoint their underlying causes is the aim to enable genuinely proactive and focused treatments.
3. **Federated and Edge-Native AI for Universal Digital Equity:** Future studies must push the limits of edge AI and federated learning (FL) to guarantee worldwide applicability, especially in areas with limited connectivity and data. This includes creating resource-efficient FL algorithms that are tailored for heterogeneous edge devices and intermittent connectivity (TinyML), allowing for continuous, private collaborative learning without the need for centralized data gathering. To bootstrap strong AI models in settings with little historical data, advanced techniques for synthetic data generation (such as conditional Generative Adversarial Networks, or GANs) and meta-learning will be essential. This will democratize sophisticated predictive capabilities to every community, regardless of their level of digital infrastructure.
4. **Trustworthy AI Governance and Adaptive Policy Integration:** Explainable AI (XAI) and AI governance frameworks must progress concurrently with the extensive use of AI in vital water infrastructure. To build confidence and facilitate knowledgeable human-AI collaboration, future research should concentrate on creating XAI techniques that offer non-technical stakeholders’ practical insights and policy-relevant explanations. This involves developing dynamic, AI-powered SDG dashboards that provide real-time feedback on alignment with SDGs 6.1 and 6.3, measure progress, and model the effects of policy interventions. Water resource management could become even more transparent and accountable with research into blockchain-enabled autonomous governance models, which could lead to the development of self-executing compliance procedures for water distribution and quality.

Realizing these ambitious directions requires unprecedented interdisciplinary convergence among environmental engineers, advanced AI researchers, climate scientists, public health experts, and policy innovators. This integrated approach will unlock a future where water management is not only intelligent and efficient but also inherently equitable, resilient, and sustainable for all.

**CONCLUSION**

This research presents a comprehensive exploration of how artificial intelligence (AI) can revolutionize the management of drinking water by enabling intelligent, decentralized, and predictive systems across the entire water value chain. From source monitoring and treatment optimization to distribution efficiency and outbreak forecasting, AI technologies- including machine learning, edge computing, digital twins, federated learning, reinforcement learning, and blockchain- have demonstrated vast potential in transforming conventional, reactive water systems into smart, adaptive infrastructures.

The study establishes that AI not only enhances operational efficiency and cost-effectiveness but also empowers data-scarce, marginalized, and climate-vulnerable regions to access sustainable water solutions. The integration of AI with SDG-focused metrics, IoT sensors, and ethical frameworks further reinforces the need for equitable, explainable, and transparent water governance. Simulation-based validation using real-world parameters confirms the practical viability of AI models such as Support Vector Machines and Random Forests in predicting potable water quality with measurable accuracy.

AI provides a crucial toolkit for creating proactive, resilient, and citizen-centered water systems as climate change, urbanization, and resource degradation exacerbate water challenges. Cross-sectoral cooperation, moral guidelines, strong data infrastructures, and ongoing innovation are necessary to realize this vision, though. In the end, this study not only highlights how AI may be used to protect people's right to clean and safe drinking water, but it also offers a framework for the future that aims to achieve SDG 6.1 and 6.3 through the convergence of technology and policy. To ensure that AI benefits both humans and the environment, future research and deployment efforts must now concentrate on growing these advances responsibly.

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The author hereby declares that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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