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Efficient wastewater management for smart cities using Internet of Things (IoT) and blockchain technology

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ABSTRACT

Access to clean and sufficient water is considered a basic right for humans and other living organisms sharing the environment. However, factors like rapid urban growth, climate change, population increase, and the overproduction of industrial and agricultural goods have contributed to water shortages and quality problems in many communities worldwide. Digital technologies, such as blockchain, machine learning, and the Internet of Things (IoT), offer opportunities to develop new solutions for creating smart and sustainable environments. In this paper, we introduce a unified water management system (IB-WMS) using IoT and blockchain technologies to monitor water quality, level, temperature, pressure, and consumption. This system is designed to be reliable, scalable, and transparent due to the integration of blockchain and IoT. Simulations indicate that the IB-WMS system achieves 89% efficiency, a 90% wastewater reuse rate, and a 95% water recycling rate.

1. Introduction

The world is facing an acute water scarcity problem today (Satilmisoglu et al., 2024; Ait-Kadi, 2016). The rapid increase in world population over the last several decades has accelerated water utilization in domestic and industrial capacities (Pereira and Marques, 2021). This over-exploitation has caused so much strain on water resources that almost half of the world's population lives in a water-stressed environment (Semadeni-Davies, 2004). Providing access to clean water resources is one of the sustainable development goals defined by the United Nations (Sørup et al., 2020). Effective management of water resources, including treatment, supply, distribution, and fair access, is increasingly important for modern smart societies facing the immense challenges posed by climate change. Ensuring sustainability and transparency in these efforts is essential (Sørup et al., 2020; Jacobsen et al., 2012; Salleh, 2016).

Wastewater management is a set of processes and techniques that can be utilized to reclaim polluted water from industrial and domestic consumers by removing pollutants and excess minerals efficiently and sustainably (Daigger, 2007). Reusing wastewater without treatment and allowing it to be merged into clean water can lead to disastrous consequences for all the stakeholders in the ecosystem, e.g., hazardous to humanity and living creatures, unfit for drinking, cooking, farming, and most domestic consumption use cases (Salleh, 2016).

Some challenges causing stress on the water cycle and contributing to its pollution are created by technology itself. For example, water pollution often results from the overproduction and overuse of natural resources through modern manufacturing processes and household practices (Bain et al., 2020; Amador-Castro et al., 2024). Ironically, smart and sustainable technologies are also the most effective potential tools available to mankind to manage water resources.

A wastewater management system's primary objective is to reclaim water polluted and rendered unusable by domestic and industrial waste (Crini and Lichtfouse, 2019). Treatment of water to make it safe and reusable for human and animal

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consumption is very important and one of the primary benefits of water recovery (Droste and Gehr, 2018). An effective wastewater management system should also incorporate the preservation of water resources, efficiency, and transparency in the utilization of these resources. Transparency and traceability in the process can allow us to monitor the quality of water and assign responsibility to the respective stakeholders. Proper management of wastewater can yield a multitude of benefits. For example, processing polluted water from domestic and industrial exhausts to allow its reuse can lead to environmental sustainability, energy efficiency, and reduced stress on water aquifers. However, this requires continuous, transparent, and traceable monitoring of domestic and industrial waste.

Effective monitoring of parameters relevant to the quality of the consumed water will enable the wastewater management system to provide incentives to consumers to adopt practices that improve their wastewater quality. On the other hand, the consumers who are wasteful in their use and run processes that harm the quality of the water might be penalized in the form of additional taxes and surcharges. Appropriate monetizing and assigning credits to the consumer for the preservation of water quality will encourage them to improve their processes so that the water quality is not distorted beyond repair. This reward/penalty model that acts in proportion to the environmental impact of released wastewater can also lead to the introduction of third parties into the market who may provide water treatment as a service (WTaaS) to consumers and metropolitan authorities.

The adoption of smart digital disruptive technologies, such as the Internet of Things (IoTs) (González-Vidal et al., 2019), artificial intelligence (AI), cloud computing, and Blockchain (BC), has created a revolutionary impact on several facets of our lives. Humanity is looking towards these technologies to serve at the forefront of solutions to solve critical environmental challenges. The IoTs is a convergence of technologies that encompasses classical wireless sensor networks, edge and fog devices, data analytics, smart applications, and protocols for data acquisition from a network that is unreliable, energy-starved, heterogeneous, and vulnerable to attacks (Kaarthik et al., 2023). IoT relies on machine learning, wireless protocols, and cloud computing to provide advanced solutions for society, such as smart cities, smart homes, smart industries, precision agriculture, and smart healthcare (Kalirajan et al., 2021).

Blockchain is another disruptive technology, which is essentially a distributed digital ledger secured by cryptographic techniques and provides transparency, traceability, scalability, reliability, and resilience against several cryptographic attacks (Della Valle and Oliver, 2021). The distributed structure of a blockchain database means that information is stored across multiple nodes in a network as a linked chain of blocks connected by cryptographic hashing. This data cannot be modified without approval from the majority of nodes, ensuring integrity. Because the data is accessible without a single point of failure, it allows for independent verification, enhancing transparency and traceability. These features make blockchain well-suited for applications that require reliability, consensus, and accountability among stakeholders. Initially developed for recording cryptocurrency transactions, blockchain has evolved to include features like smart contracts—self-executing contracts that trigger automatically when specified conditions are met. This enables contract agreements without third parties and avoids subjective interpretation of terms. Blockchain is ideal for applications where a centralized data center is impractical or where systems operate in a peer-to-peer setup (Chohan, 2019).

In this paper, we propose a framework for wastewater management for a smart community using a combination of IoT and blockchain technologies. The proposed system could be deployed in a smart community to monitor water pollution caused by the mixing of potable and clean water with sewerage and industrial pollutants. Such a system can help consumers participate in the process of achieving a sustainable water supply, distribution, and recovery system. Fair access to fresh water is essential to survival and a basic right of every citizen and living creature. IoT system is a multi-layered approach to solving water management issues by deploying several wireless-enabled sensors and actuators throughout the community (Dogo et al., 2019). These sensors measure several parameters related to wastewater management systems, such as fluid flow, detection of hazardous chemicals and pollutants, organic materials, optical properties of water, etc. Miscellaneous measurements may allow us to monitor water and chemical leakage detection, temperature, and pressure variations throughout the water distribution system and in natural water bodies. Sensors are typically battery-operated and thus severely constrained in terms of available power and size. The data captured by the sensors is forwarded to the edge computing devices that apply appropriate filters on the data and perform preprocessing tasks before forwarding it to a network of routers, switches, and other low-energy personal communication networks that ultimately supply the data to compute, network and storage resources in the cloud. Cloud computing resources not only enable the storage of data but also enable us to apply smart artificial intelligence algorithms on the captured data to inform the administrators about the network state and facilitate them in making decisions that impact all the community stakeholders. A blockchain-based smart contract deployed on user nodes and the hybrid distributed cloud allows the flexibility to design and deploy applications that can provide transparency, scalability, and water quality credits to the community stakeholders. These stakeholders include domestic and industrial customers, water suppliers and distributors, metropolitan authorities, and public representatives. Water quality credits are assigned relative to the environmental impact of the actions of each stakeholder. Depending upon whether these actions contribute to improvement in water quality or lead to its deterioration, the stakeholders either gain or lose their credits. These credits function like a cryptocurrency in the proposed water management system, and they can be exchanged for miscellaneous services and goods, including the ability to be transformed into a virtual currency.

Blockchain technology also strengthens the system's resilience against attacks and prevents a single point of failure. Additionally, the system includes an anomaly detection algorithm that can identify irregular events, such as fluid leaks, hazardous chemical presence, or attempts to tamper with the blockchain. In this paper, we make the following contributions:

- An IB-WMS system for wastewater management is proposed that includes the supply, treatment, and recovery of water in a smart community.
- Designed the system based on blockchain technology to allow transparency, scalability, and traceability. An efficient system design provides a superior system as compared to state-of-the-art systems in terms of water recovery rate and wastewater reuse.
- A simulation study is performed to determine the efficiency of the proposed system relative to some recent notable works.

The rest of the paper is organized as follows. Section 2 presents related work, and Section 3 includes a discussion of the design aspects of the proposed IB-WMS system. Section 4 presents simulation results, and Section 5 lists the conclusions of the study.

2. Literature survey

In this section, we present some recent work related to the proposed wastewater management system (IB-WMS) and establish the novel contribution of the proposed work and its relevance.

Hakak et al. (2020) presented the concept of the application of blockchain technology to industrial wastewater treatment. The objective of the proposed wastewater treatment system is to rid industrial water of pollutants and toxic elements before discharge into the environment. The authors propose a conceptual framework based on blockchain and present several case studies to demonstrate the overall concept. Kassou et al. (2021) explored the use of blockchain technology for medical waste and its safe disposal in the environment, especially water resources. The healthcare industry produces significant waste that is hazardous if discharged into the environment untreated. An initial design, along with a preliminary evaluation of the system, is presented in this work.

Salam et al. (2020) presented an innovative and sustainable approach to managing and treating water developed on top of an IoTs network. The author emphasizes the significance of monitoring water quality using sensors for sewer and stormwater. They also discuss the limitations of the methodology in attaining water quality and demonstrate system effectiveness by applying IoTs to water treatment and management.

Landa-Cansigno et al. (2020) proposed a framework that integrates urban water metabolism with the water-energy-pollution nexus to evaluate the efficiency of wastewater recycling methods. The authors discuss metabolic efficiency and its influence on several centralized and distributed reuse policies for contaminated water. Authors suggest that metabolic monitoring of parameters in such a complex system can demonstrate the degree of interactions and nexus among various system components.

Water contamination from sewage and industrial waste has significantly risen in recent decades. Villarín et al. (2020) provided a comprehensive review of increasing wastewater hazards and suggested potential solutions that could create a major shift in this field. The authors also emphasize that effective wastewater management should include public awareness about water scarcity, achieved through transparency and access to relevant data.

Spirandelli et al. (2019) applied policy gap analysis to develop a decentralized wastewater management approach. They proposed on-site wastewater treatment (OWTS) techniques to enable decentralized wastewater management and water recovery directly at the site. This approach highlights the need for coordinated use of land resources and the establishment of a water baseline. Key factors for improving water treatment and management efficiency include system inventories, public participation, domestic awareness, regular inspection, and maintenance of water supply and distribution networks.

Nie et al. (2020) proposed using data analysis and IoT for underwater operation safety management. For long-term well-being, intelligent communities need to ensure the sustainability of the environment and resources like water for residents and other stakeholders. ICT technologies enable environmental monitoring and help reduce damage to natural resources. This paper applies a Supervisory Controller and Data Acquisition (SCADA) approach to propose a wastewater treatment system for smart cities. The system relies on big data analytics and IoT, with big data analysis processing large volumes of data to monitor system status, efficiency, and reuse metrics effectively.

Jeong and Park (2020) presented a Water Metabolism Framework (WMF) to assess and compare water management efficiency among three urban regions in Korea. The objective of sustainable water conservation and its reuse is to protect the environment against climate change and miscellaneous environmental transitions, which are raising the prospects of water scarcity and a serious decline in water quality. For example, in the Ulsan region, authors found that the use of water resources is less sustainable, and that makes Seoul and the larger Ulsan region more vulnerable and susceptible to environmental degradation.

Narendran et al. (2017) identified the relentless exploitation of groundwater resources as leading to the loss of the ability of the aquifers to recharge and regenerate through natural environmental processes. The authors provide a unique perspective on the state of underground water resources in India and propose an IoT-based solution for the automatic distribution and storage of water to regulate its usage and minimize the wastage and contamination of water resources. The analysis of the system for a model remote village demonstrates its effectiveness in achieving sustainability.

Xia et al. (2022) introduced a blockchain-based system for water resource management, highlighting that existing systems are inefficient, costly, and centralized, leading to water loss and reduced quality. They identify blockchain as a secure, reliable, and decentralized solution for water resource management. The authors demonstrate that a blockchain-based system provides greater reliability and transparency for preserving water quality information. A summary of related work is provided in Table 1.

Table 1: Summary of related work

Reference	Problem addressed	Technique employed
Hakak et al. (2020)	Efficient removal of pollutants and toxic elements from industrial wastewater	A blockchain-based conceptual framework applied across three case studies
Kassou et al. (2021)	Management of medical and water waste in healthcare facilities	Proposed design for a medical and water waste management system using blockchain and IoT
Salam et al. (2020)	Sustainable monitoring and management of water resources for environmental quality	System design using internet-connected sensors to maintain quality despite rate limitations
Landa-Cansigno et al. (2020)	Integrating urban water metabolism with the water-energy-pollution nexus	Conceptual model of urban water metabolism combined with the water–energy–pollution nexus (UWM-WEPN)
Villarín et al. (2020)	Wastewater treatment for recycling scarce water resources to support a circular economy, with wastewater epidemiology to inform public health	Comprehensive analysis of the recent shift in public attitudes toward wastewater reuse and its economic impacts
Spirandelli et al. (2019)	Assessing the performance of on-site wastewater treatment systems on a Pacific Island	Policy gap analysis to evaluate the efficiency and performance of wastewater treatment systems
Nie et al. (2020)	Wastewater treatment for sustainable, smart city development	Application of IoT for data collection and big data analytics
Jeong and Park (2020)	Comparative analysis and evaluation of water management in urban centers	Blockchain-based conceptual framework utilized in three case studies
Narendran et al. (2017)	Sustainable wastewater treatment for efficient resource management	IoT-based solution for automating water distribution, storage, and recycling processes
Xia et al. (2022)	Secure, decentralized information management system for water resources	Blockchain-based system implemented in a decentralized, secure wastewater management framework

3. Proposed model

Water scarcity is a major challenge for humanity as the population keeps growing. Recycling and recovering water through water treatment methods is indispensable. Sensors deployed throughout the water supply and distribution network enable round-the-clock monitoring of the wastewater management processes. In this section, we propose a comprehensive framework for wastewater management, referred to as IBWMS. The proposed framework is developed based on IoT and blockchain technologies. IB-WMS proposes the implementation of blockchain-based credits to reward or penalize the customer depending on their respective water utilization patterns. The basic stakeholders and components of the proposed IB-WMS system are depicted in Fig. 1.

Fig. 1 depicts a smart community with both industrial and domestic consumers. Water supply companies are responsible for maintaining water storage facilities and distribution networks. Sensors and actuators are installed in the network as well as at the premises of the provider and consumer to measure water quality and quantity supplied and consumed. Data from sensors is accumulated through the edge devices onto the cloud, which could be a distributed facility with several blockchains deployed throughout the network.

Data is processed and analyzed and shown on the dashboard to facilitate the decision-making of the stakeholders, such as utility providers, metropolitan authorities, regulatory bodies, environmental monitoring institutions, and industrial and domestic consumers. Actuators could be manipulated by authorized agents based on the decision taken.

Water usage and quality data, as well as smart contracts, are stored on a blockchain to enhance transparency, traceability, and auditability. To protect data privacy, a permissioned blockchain such as Hyperledger Fabric is recommended. This system can also manage contracts that enforce policies like issuing and exchanging tokens or credits for the quality of water discharged into the environment. Clients, such as consumers, suppliers, or water treatment facilities, can initiate transactions, which are recorded via ordering services. Sensitive data can be restricted to a private channel accessible only to authorized agents within the water management system. Hyperledger Fabric thus supports a secure, permissioned blockchain environment. The IoT-based Wastewater Management System (IB-WMS) also includes an anomaly detection algorithm to identify unusual events, such as unauthorized water use. Data from meters and sensors is gathered over time to train machine learning models, assisting in decision-making. The IB-WMS system has five logical layers, as shown in Fig. 2. The first layer, the perception layer, consists of sensors and actuators that measure physical quantities like temperature, pressure, volume, contaminants, and flow. These devices, usually battery or renewable-powered, are limited in size and energy. The second layer, the data collection layer, includes gateways that collect sensor data and distribute it to actuators through various interfaces (e.g., Bluetooth, Ethernet, Zigbee, WiFi, 4G, and 5G). The choice of interface depends on the sensor's capabilities and available network spectrum.

The third layer contains edge computing devices that can request sensor data and perform light preprocessing. These devices may store small data amounts temporarily before sending it to a cloud repository. Edge nodes aggregate data and record it on a blockchain, possibly in a hybrid cloud environment.

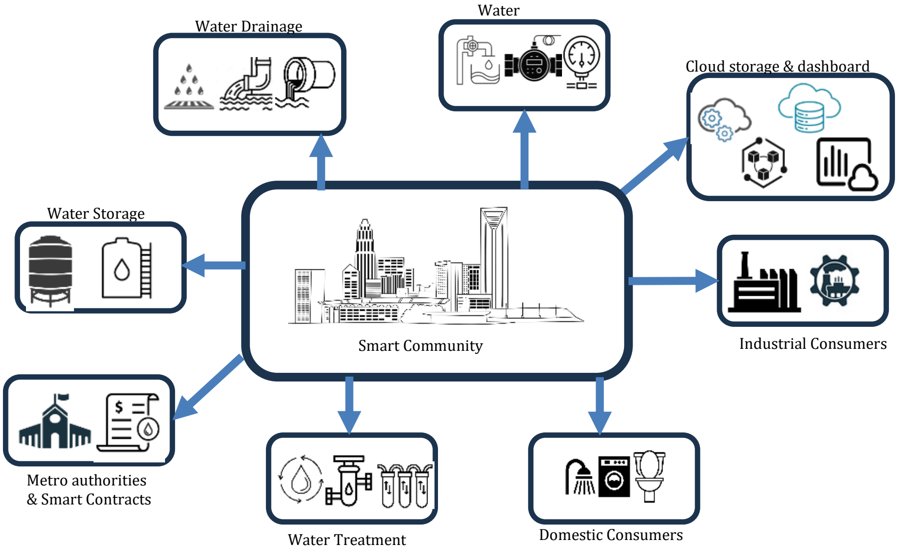

Fig. 1: Wastewater management system in a smart community consists of various stakeholders that interact through several devices and subsystems

The cloud computing layer provides virtualized computing, network, and storage resources for further data processing and storage on the blockchain. It can also host smart contracts and record transactions related to water quality credits for suppliers and consumers. This layer has load balancing to ensure application availability and reliability. The application layer, at the top, grants IB-WMS users access to data and applications, enabling machine learning analysis to detect trends and offering a dashboard for monitoring key metrics.

The main goal of the proposed IB-WMS system is to monitor the water treatment system's performance, including the volume and quality of water released. Wastewater treatment plants remove harmful chemicals and pollutants to make water suitable for reuse. The system records transactions from suppliers, consumers, and recycling agents related to water consumption, supply, treatment, and distribution. Using blockchain for these transactions provides a secure, unchangeable database, ensuring transparency, reliability, availability, and traceability of water sources and distribution. This work proposes a permissioned blockchain, Hyperledger Fabric, which provides an open, modular framework to establish trusted data privacy among stakeholders.

A blockchain is a distributed database shared among networked nodes, where data reading, writing, updating, and deleting are decentralized. Blockchain has four key characteristics that set it apart from conventional centralized databases. First, it enables peer-to-peer interactions, allowing nodes to interact directly without a central authority. Transactions and interactions are recorded transparently across the network, ensuring that a single node cannot alter them later, nor can the transaction be denied by its initiator.

The second feature is the distributed ledger, which records transactions transparently and immutably. This ledger can only be changed by a consensus of the majority of nodes, making all transactions traceable and secure from tampering. Third, blockchain includes a consensus mechanism to resolve conflicts among nodes in the network. Different consensus algorithms are used, some requiring authorization from specific nodes, while others, like proof-of-work, require computational effort. These consensus mechanisms allow nodes to agree on a single, unified chain of blocks linked by cryptographic hashes.

The fourth feature of blockchain is its ability to execute smart contracts, or chain code, which are automated contracts that activate transactions when agreed-upon conditions are met. Through these contracts, suppliers and consumers can conduct transactions using tokens. These tokens could be redeemed for benefits or exemptions in exchange for maintaining water quality or adhering to sustainable water-use policies.

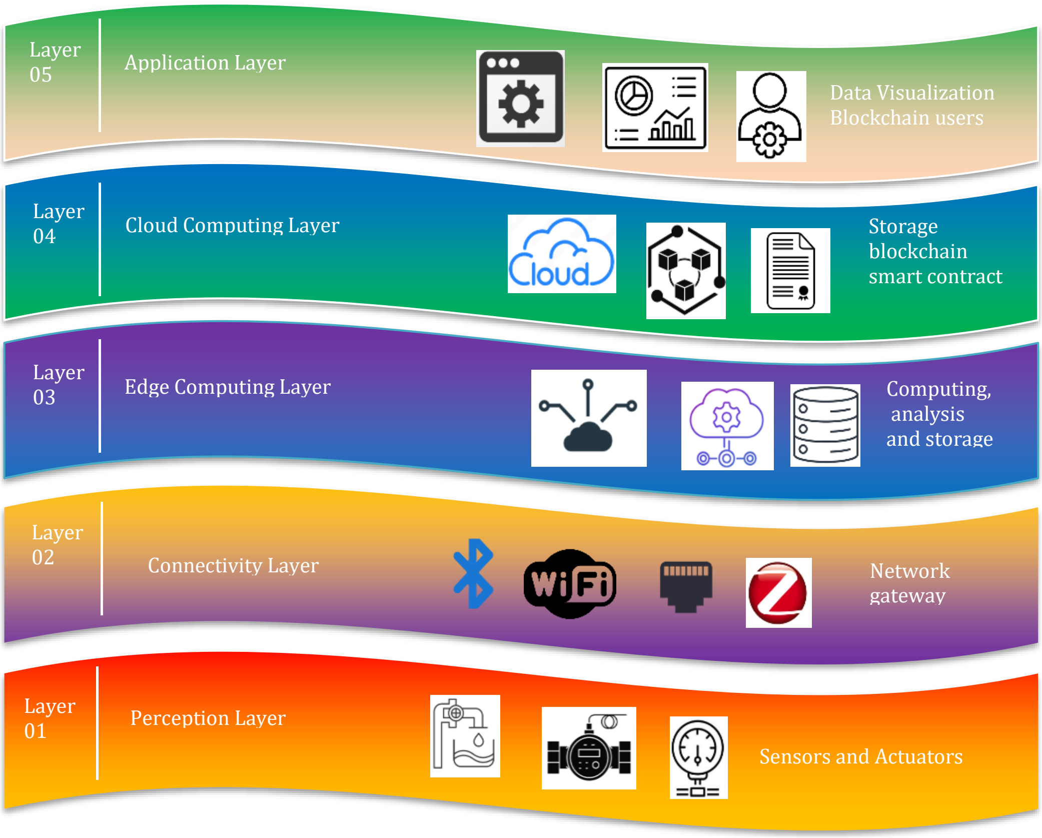

Fig. 2: Conceptual framework for five layered-architecture adopted in the proposed IB-WMS

This work employs Hyperledger Fabric, a specific type of blockchain that is open-source and modular, designed for permissioned networks. Unlike public blockchains, Hyperledger Fabric restricts data access, ensuring that consumer data is kept private and only accessible to authorized nodes. In Hyperledger Fabric, nodes can be placed on isolated channels, allowing access control and permission validation through specific nodes. These nodes can validate the identity of peers by issuing certificates.

In the Hyperledger Fabric framework, transactions can be initiated by any node, but they must be validated by endorser nodes. Once validated, the transaction is recorded on the ledger by a privileged node called the orderer. The orderer manages the ordering service and, after validation, allows nodes to update their ledgers.

As shown in Fig. 3, the Hyperledger transaction process involves a client node proposing a transaction, which is then endorsed by peer nodes on the same channel. Endorsing peers simulate the transaction to ensure its validity. Once the client collects endorsement responses, it requests the ordering service to broadcast the transaction. After verification, each peer completes the transaction through the hosted chain code. Unlike Bitcoin, Hyperledger Fabric does not require an energy-intensive proof-of-work process, as it can be configured with various consensus algorithms due to its modular structure. Here, we propose the use of the yet-another-consensus (YAC) algorithm, used in certain Hyperledger variants, for efficient transaction processing. The endorsement, ordering, and peer verification steps together create a highly secure process for consensus on the distributed ledger. Below, we outline the main steps involved in data measurement, transmission, and recording on the blockchain.

1. In the initial step, the system integrates sensors and actuators at consumer and supplier locations to monitor and control the quality and quantity of water used or supplied. These sensors may include flow and level monitors, while actuators can control water flow via valves.
2. The sensors and actuators are internet-enabled, allowing data and control information to be transmitted over the internet to water distribution and management authorities. These IoT devices measure water storage levels, consumption volumes, and the quality of recycled water in wastewater treatment plants. The data gathered by these sensors is consolidated through edge devices connected to gateways, which link to the network and cloud resources.
3. Edge computing devices collect data from sensors via wired or wireless channels using various communication protocols. They authenticate IoT sensors and actuators, preventing unauthorized agents from accessing the network or corrupting data processed in the cloud. Edge devices also perform simple processing tasks to reduce the amount of data sent over the network and enable quick, low-latency actions when fast decision-making is required.
4. On the blockchain network, chain code is deployed on each peer node, setting conditions related to water usage and wastewater treatment standards

that award tokens to nodes meeting these criteria. The blockchain's consensus mechanism prevents nodes from gaining undeserved tokens through malicious actions. These tokens serve as credits, which can be redeemed by stakeholders for benefits like tax subsidies or utility bill reductions. This incentive system encourages responsible water resource management, balancing rewards with sustainable wastewater policies.

5. Chain code deployed on peers initiates, endorses, and verifies each transaction before it is committed to the blockchain. The ledger maintains a comprehensive record, or "state of the world," enabling authorized agents to track all transactions related to a stakeholder within a specific channel. This smart contract in the chain code ensures secure, automated interactions with the ledger's transaction records.

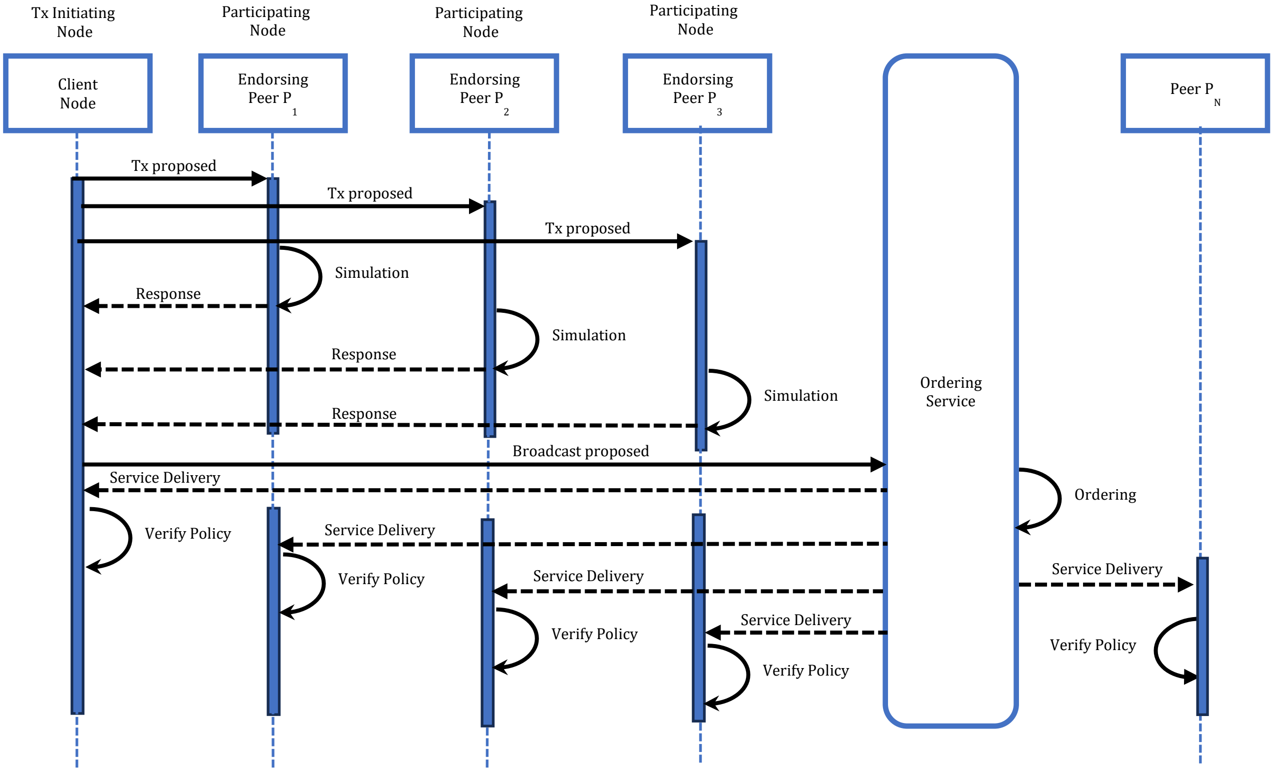

Fig. 3: Transaction (Tx) flow for Hyperledger blockchain framework

Transactions recorded on Hyperledger can be analyzed to assess water consumption and quality, such as the volume of toxic water discharged or the volume of treated water released. These metrics can be evaluated for rewards or penalties based on whether the water use is domestic or industrial. Consumers demonstrating responsible practices over time—such as low fresh water usage, low toxin levels in discharged water, and effective toxin removal through treatment—receive tokens. These tokens can be exchanged in a smart city for other goods and services, incentivizing sustainable practices. The most responsible participants, who minimize water wastage, gain the most benefits. This system encourages the entire community to adopt responsible behaviors, promoting water conservation through sustainable practices. The quantity factor Q_f and quality factor Q'_f can be computed as follows:

$$Q_f = \frac{V_r}{V_p}, \quad (1)$$

$$Q'_f = q(h, s, o, p), \quad (2)$$

where, V_r and V_p are the volume of water that is recycled and polluted, respectively. Now, the number of reward tokens issued to a consumer can be calculated as a weighted sum of the quantity and quality factors as follows:

$$T = w_1 Q_f + w_2 Q'_f. \quad (3)$$

The chain code issues reward tokens only when specific weight thresholds are met. It can be further tailored to consider the consumer's history or additional factors related to consumption behavior. The threshold weights can also be adjusted to account for the complexities of removing different types of toxins. When these weights exceed the set limit, the stakeholder receives tokens, which can be used as credits for tax subsidies or applied to utility bill payments.

Anomaly Detection Algorithm: Anomaly detection algorithms analyze time series data to identify outliers, helping to detect unusual or potentially malicious behavior. This strengthens security by identifying actors who might attempt to compromise or misuse the distributed ledger or chain code-based reward system. In this setup, we employ a polynomial regression analysis algorithm to detect outliers effectively.

The polynomial regression algorithm predicts a relationship between independent I variables and the dependent variables D. We assume that the regression analysis expresses the dependent variable D as a relationship that is a polynomial of degree d, i.e.,

$$D_n = \sum_{j=1}^{d} a_i I_n^j + e_n + c, \tag{4}$$

where, a_i are the regression factors, c is a constant threshold value, and e_n is the rate of error, while n is an integer that represents the time index. Now, the abnormal behavior is observed when the mean square error exceeds the threshold value c. The error threshold is usually calculated by using training data and characterizes the error in modeling the output (dependent) variable in terms of the polynomial of d-th degree. The degree of the polynomial is a hypermeter that could be adjusted according to the characteristics of the data. If the error for test data exceeds the threshold, the algorithm signals an anomaly, which can be analyzed to ensure smooth and secure operation of the wastewater management system.

4. Simulation results

In this section, we perform numerical simulations to assess the performance of the wastewater management model proposed in the previous section, named IB-WMS. The proposed system is designed to monitor and incentivize the recycling and reuse of wastewater in a smart community that may consist of several water suppliers, domestic consumers, and industrial customers.

In this scenario, we compute several performance measures, such as the efficiency ratio, wastewater reuse ratio, and wastewater recycling ratio. For this simulation, number of devices ranges from 5 to 30 in increments of 5. We assume that each device can support a maximum of 10 sensors. The simulation results have been averaged over several configurations of sensor and actuator placement in a two-dimensional space. Devices are assumed to perform disparate roles in the wastewater management system, e.g., water storage tanks, water consumption systems, drainage units, and recycling process units. The blockchain-based implementation enables the use of water quality credits to incentivize the treatment of water before discharge. It also penalizes the consumers who do not process wastewater before releasing it into the environment.

The performance of the proposed IB-WMS framework has been compared with several state-of-the-art approaches, e.g., SCADA (Nie et al., 2020), WMF (Jeong and Park, 2020), and UWM-WEPN (Landa-Cansigno et al., 2020). Figs. 4, 5, and 6 illustrate the efficiency ratio, reuse ratio, and wastewater recycling rate, respectively. These three parameters are very important in determining the performance of the system. The horizontal axis shows a varying number of IoT devices in the network. In general, an increase in the number of sensors results in enhanced performance in terms of all three performance measures. Also, it can be observed that among the selected techniques, IB–WMS shows very good performance in considered scenarios and in terms of the performance metrics considered in this paper. Fig. 4 shows the efficiency ratio for different numbers of devices in the system. The results indicate that the efficiency of UWM-WEPN is close to that of the proposed system.

Similarly, Fig. 5 shows the wastewater reuse ratio, which is a measure of how much of the reclaimed water is effectively utilized by the system. The graph in Fig. 5 indicates that the proposed system's performance is very good, especially when the number of devices in the system is large.

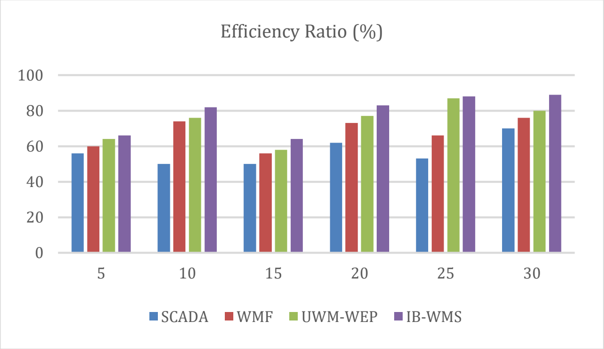

Fig. 4: Efficiency ratio

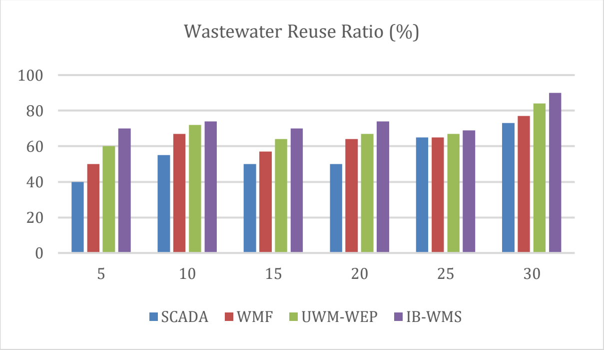

Fig. 5: Wastewater reuse ratio

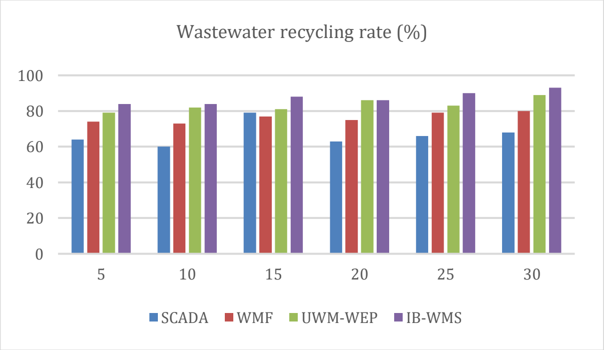

Fig. 6: Wastewater recycling rate

Fig. 6 illustrates the wastewater recycling rate as the number of devices increases. The performance of SCADA and WMF systems tends to saturate, showing minimal improvement as more devices are added. In contrast, the proposed system and UWM-WEPN demonstrate significant performance gains under similar conditions, effectively handling the increased number of devices and enhancing recycling efficiency.

5. Conclusions

Water scarcity and pollution pose significant threats to communities and our planet's fragile ecosystems. Releasing untreated industrial or domestic wastewater into the environment can harm aquatic life and disrupt the food chain. The proposed wastewater management system, based on blockchain and IoT technologies, demonstrates high efficiency, wastewater reuse, and recycling rates. The IB-WMS system effectively monitors water quality, levels, temperature, pressure, and consumption volume. Compared to traditional approaches, it offers greater reliability, scalability, and transparency through blockchain technology. Simulation results indicate that the IB-WMS system achieves 89% efficiency, a 90% wastewater reuse ratio, and a 95% water recycling rate.

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Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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