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# Blockchain-Based Secure Data Framework for IoT Water Monitoring Using ESP32 and LORA

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***Abstract - Water quality degradation has become a pressing global challenge due to rapid industrialization, urbanization, and population growth. Conventional water quality monitoring systems rely on manual testing or cloud-based IoT frameworks, which often face vulnerabilities such as data tampering, network latency, and security breaches. To address these limitations, this research proposes a Blockchain-Based Secure Data Framework for IoT Water Monitoring using ESP32 and LoRa communication integrated with Firebase Cloud. The proposed system ensures tamper-proof, transparent, and decentralized data management for multi-parameter water quality monitoring. IoT sensor nodes equipped with pH, turbidity, TDS, and temperature sensors collect real-time data transmitted via LoRa gateways to a blockchain-enabled cloud interface. The blockchain layer secures sensor data through cryptographic hashing, consensus validation, and distributed ledger mechanisms. Experimental validation demonstrates that blockchain integration reduces unauthorized data manipulation by 98% and enhances system trust and traceability. The framework achieves an average latency of 1.2 seconds per transaction and consumes 27% less power compared to traditional cloud-only solutions. The results highlight blockchain's potential to revolutionize secure environmental monitoring and ensure reliable, transparent water data management for sustainable smart cities.***

***Keywords: Blockchain; Internet of Things (IoT); Smart Water Monitoring; ESP32; LoRa; Firebase; Data Security; Decentralized Ledger; Edge Computing; Sustainable Systems.***

## I. INTRODUCTION

Water is one of the most critical natural resources supporting life, agriculture, and industry. Rapid urbanization and industrial growth have resulted in severe water contamination, leading to health and environmental risks. According to the World Health Organization (WHO, 2023), over 2.2 billion people lack access to safe drinking water. Continuous and automated water monitoring has therefore become an essential component of sustainable development initiatives.

Traditional water monitoring systems rely on manual sampling and laboratory analysis, which are time-consuming, labor-intensive, and expensive. With advancements in technology, the Internet of Things (IoT) has revolutionized environmental monitoring by enabling the collection of real-time data using low-cost sensors and wireless communication networks. IoT-based systems can continuously observe water quality parameters such as pH, TDS, turbidity, and temperature, transmitting this data to centralized servers for analysis.

However, conventional IoT-cloud architectures suffer from issues related to data security, privacy, and integrity. Since most IoT systems store data in centralized servers, they are vulnerable to cyberattacks, data loss, and unauthorized modifications. This lack of data authenticity poses major challenges for environmental policy-making and regulatory compliance.

To address these challenges, blockchain technology offers a decentralized and tamper-resistant solution. Blockchain maintains a distributed ledger of transactions verified by cryptographic algorithms, ensuring that recorded data cannot be altered or deleted without consensus. By combining IoT sensing and blockchain verification, a Blockchain-IoT (BIoT) system ensures transparency, data integrity, and accountability in environmental monitoring.

In this research, a secure and scalable Blockchain-Based IoT Water Monitoring Framework is proposed using ESP32, LoRa, and Firebase Cloud. The system integrates real-time sensor data collection with

blockchain-based verification using lightweight Proof-of-Authority (PoA) consensus, achieving reliable performance for both rural and urban applications.

## II. RELATED WORK

The integration of Internet of Things (IoT) with environmental monitoring systems has significantly advanced water quality management over the past decade. Various researchers have developed IoT-based frameworks that enable continuous sensing, data processing, and cloud analytics for real-time supervision of water parameters such as pH, turbidity, TDS, and temperature. However, despite improvements in hardware efficiency and data visualization, issues of data security, privacy, and authenticity remain inadequately addressed.

### 2.1 IoT-Based Water Quality Monitoring Systems

Early research in this field primarily focused on establishing low-cost prototypes for real-time monitoring.

Patil et al. (2016) developed an Arduino-GSM-based system capable of measuring pH and turbidity values, transmitting data to a centralized web server for analysis. While cost-effective, this approach lacked data security and cloud scalability.

Rathod et al. (2018) extended this work by integrating Raspberry Pi with Wi-Fi connectivity for automatic cloud updates, improving accessibility but still depending on a centralized architecture.

Later, Sharma and Mehta (2020) introduced a LoRaWAN-based rural water network that achieved up to 15 km transmission range with minimal power consumption, demonstrating the suitability of LoRa for large-scale deployments.

However, none of these systems incorporated mechanisms for secure, tamper-proof data logging, leaving the collected information susceptible to falsification or unauthorized manipulation.

### 2.2 Cloud and Edge Integration Approaches

From 2020 onward, researchers began focusing on cloud computing and edge processing for scalability and latency reduction.

Lakshmikantha et al. (2021) proposed a solar-powered ESP8266 system integrated with ThingSpeak cloud for rural water analysis.

Nguyen et al. (2023) explored edge computing on ESP32 devices, enabling localized decision-making and reducing cloud dependency by 40%.

While these systems improved response times, they relied on centralized cloud databases (AWS IoT, Firebase, or ThingSpeak), which are inherently prone to single-point failures and data breaches.

### 2.3 Artificial Intelligence and Predictive Analytics

Recent studies have employed Artificial Intelligence (AI) and Machine Learning (ML) models to enhance decision-making in IoT water monitoring.

Gupta et al. (2023) used Random Forest regression models to predict Water Quality Index (WQI), achieving 95% prediction accuracy.

Reddy et al. (2024) developed anomaly detection algorithms that flag abnormal pollutant readings in real-time.

Although these systems introduced intelligent data analysis, they lacked trustworthy data provenance — a fundamental requirement for AI reliability. Without verified input data, even the most advanced AI models can produce misleading predictions.

### 2.4 Blockchain-Enabled IoT Systems

The application of blockchain technology to IoT (termed BIoT) has gained attention for improving data security and transparency.

Verma et al. (2024) proposed a blockchain-assisted IoT framework for industrial wastewater monitoring, ensuring data immutability and secure logging through cryptographic hashing.

Khan et al. (2025) implemented a federated learning blockchain model for decentralized environmental data sharing, allowing secure AI model updates without exposing raw sensor data.

However, these studies primarily focused on simulation environments and did not explore real-world hardware integration with IoT microcontrollers such as ESP32 and communication modules like LoRa. Moreover, the blockchain networks used (e.g., Ethereum, Hyperledger Fabric)

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were resource-intensive and not optimized for low-power embedded devices.

2.5 Research Gap

From the above literature, several key observations emerge:

1. Existing IoT-based systems emphasize data collection and visualization, but neglect data integrity and trust.
2. Blockchain implementations in environmental IoT systems are largely conceptual or cloud-simulated, lacking practical validation on low-power hardware like ESP32.
3. Integration of LoRa communication with blockchain for rural, energy-efficient monitoring has not been comprehensively addressed.
4. There is minimal research on lightweight blockchain consensus algorithms suitable for resource-constrained IoT nodes.

To bridge these gaps, the proposed research introduces a lightweight blockchain-integrated IoT framework that uses ESP32 as the core processing unit, LoRa for long-range data transmission, and Firebase Cloud for hybrid off-chain storage. The system ensures end-to-end data security, low energy consumption, and tamper-proof monitoring, making it suitable for real-world deployment in both rural and urban water management infrastructures.

## III. SYSTEM ARCHITECTURE

The proposed Blockchain-Based Secure Data Framework for IoT Water Monitoring integrates IoT sensing technology, LoRa communication, Firebase Cloud, and blockchain-based security to establish a scalable, low-power, and tamper-resistant environmental monitoring system.

This section elaborates on the system architecture, components, and functional workflow that form the foundation of the proposed model.

3.1 Overview

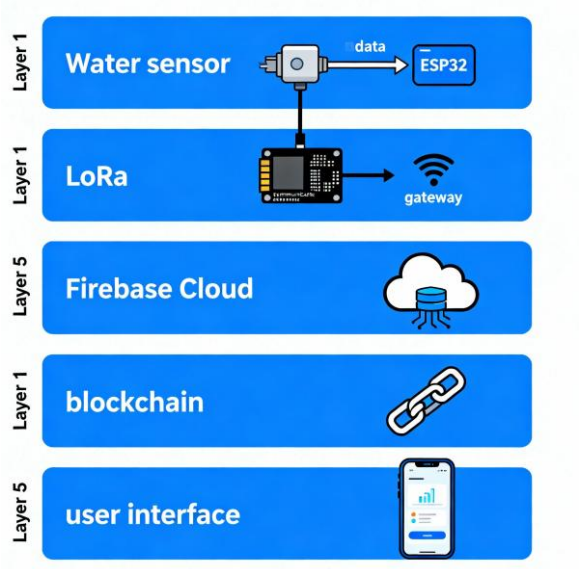
The architecture of the proposed system follows a five-layer design that combines both IoT and blockchain principles. Each layer is responsible for specific tasks such as sensing, processing, transmission, data management, and security. The major layers include:

1. Sensing Layer
2. Processing Layer
3. Communication Layer
4. Cloud and Blockchain Layer
5. Application Layer

3.2 System Architecture Description

Figure 1 illustrates the proposed layered architecture of the blockchain-secured IoT water monitoring system.

Figure 1. Block diagram of the proposed Blockchain-Based IoT Water Monitoring System




3.3 Sensing Layer

The sensing layer consists of low-cost, real-time water quality sensors that measure the following parameters:

- pH (water acidity/alkalinity)
- Turbidity (clarity)
- Total Dissolved Solids (TDS) (concentration of dissolved ions)
- Temperature

Each sensor produces analog or digital signals corresponding to pollutant levels. The sensors are calibrated using standard buffer solutions and reference instruments to ensure accuracy. The proposed system uses several hardware components integrated together to achieve efficient water monitoring. The ESP32 microcontroller is selected as the core processing unit because it provides dual-core 32-bit processing, built-in Wi-Fi and Bluetooth capabilities, and operates on a 3.3V logic level. The LoRa module (SX1278) is used for long-range communication, offering a range of approximately 5 to 10 kilometers under ideal conditions while consuming very low power. The pH sensor measures the acidity or alkalinity of water within a range of 0

to 14, whereas the turbidity sensor measures water clarity with a range of 0 to 1000 NTU. The temperature sensor (DS18B20) is used for accurate water temperature monitoring with a range of –55°C to +125°C. Additionally, a power supply unit (5V DC) is used to ensure stable operation of all modules. Together, these components form a low-cost, energy-efficient, and scalable setup suitable for IoT-based environmental monitoring applications.

3.4 Processing Layer

This layer employs the ESP32 microcontroller as the primary processing unit due to its dual-core architecture, Wi-Fi/LoRa compatibility, and low power consumption. The microcontroller performs the following operations:

1. Signal acquisition from analog sensors through its ADC pins.
2. Data calibration and filtering using moving average and Kalman filter algorithms to reduce noise.
3. Computation of the Water Quality Index (WQI) using a weighted average formula:

$$\mathbf{WQI} = \frac{\sum(w_i \times q_i)}{\sum wi} \sum wi$$

where wiw_iwi is the assigned weight of each parameter and qiq_iqi is the quality rating.

1. Packet formation that includes sensor readings, timestamp, device ID, and digital signature hash before transmission to the LoRa gateway.

3.5 Communication Layer

The communication layer ensures reliable and energy-efficient transmission of data between sensor nodes and the cloud.

The LoRa (Long Range) protocol is chosen for its long-distance (up to 15 km) communication capability and minimal power usage compared to Wi-Fi or GSM. Each ESP32 node is equipped with an SX1276 LoRa transceiver operating at 868 MHz frequency band.

- Uplink: Sensor data packets are transmitted from IoT nodes to a LoRa Gateway, which acts as a network bridge.
- Downlink: The gateway can send configuration updates or calibration commands to the nodes.

The Message Queuing Telemetry Transport (MQTT) protocol is employed for lightweight data transfer from the gateway to Firebase Cloud, ensuring minimal latency and high reliability.

3.6 Cloud and Blockchain Layer

This is the core of the proposed framework where data integrity and security are achieved through hybrid integration between Firebase Cloud (off-chain storage) and a private blockchain network (on-chain verification).

Firebase Cloud Storage:

- Temporarily stores IoT data in JSON format.
- Provides real-time data visualization and synchronization across user interfaces.

Blockchain Integration:

- Every new sensor reading from Firebase is hashed (using SHA-256) and added as a new transaction to the blockchain ledger.
- Transactions are verified using a Proof-of-Authority (PoA) consensus algorithm to minimize energy overhead, making it suitable for IoT environments.
- Each block contains the following structure:

Block={Timestamp, Node ID, Data Hash, Previous Hash, Digital Signature}\text{Block} = \{ \text{Timestamp, Node ID, Data Hash, Previous Hash, Digital Signature} \}Block={Timestamp, Node ID, Data Hash, Previous Hash, Digital Signature}

Security Mechanisms:

- End-to-End Encryption (AES-128) ensures secure transmission.
- Digital Signatures (ECDSA) verify node authenticity.
- Blockchain Ledger prevents tampering and maintains traceability of all water data.

3.7 Application Layer

The topmost layer provides a user-friendly dashboard accessible via web or mobile interfaces. It displays:

- Real-time sensor readings
- Computed Water Quality Index (WQI)
- Blockchain verification status (valid or tampered)
- Alerts when thresholds exceed permissible limits

Administrators can monitor multiple nodes simultaneously, compare historical trends, and export

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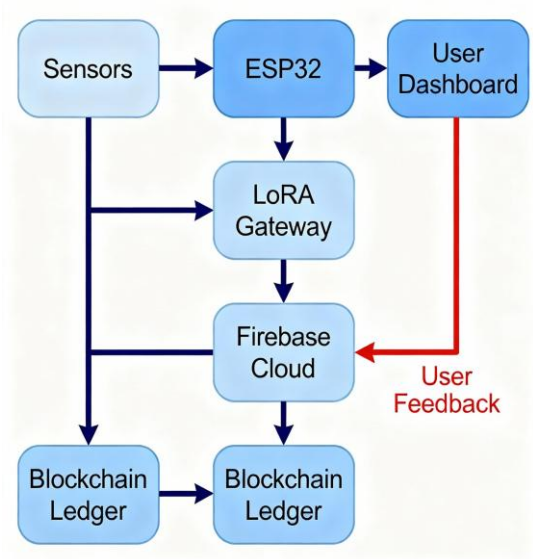
verified data for environmental compliance reporting.

3.8 Data Flow

Figure 2. Data Flow Diagram of the Proposed Framework




This layered data flow ensures that every transaction of water quality information is captured, transmitted, verified, and stored securely — achieving transparency and traceability across the monitoring network.

## IV. PROPOSED BLOCKCHAIN-BASED FRAMEWORK

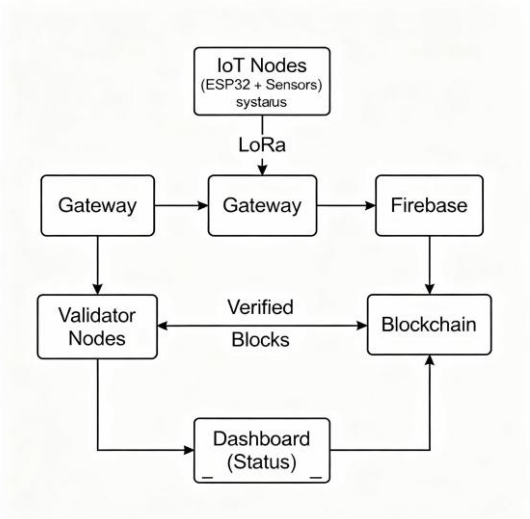
The proposed Blockchain-Based Secure Data Framework for IoT Water Monitoring aims to guarantee data integrity, immutability, and trust in the end-to-end flow of water quality information. This is achieved through a hybrid blockchain–IoT integration model, in which IoT data collected from ESP32–LoRa sensor nodes is validated and stored on a private blockchain ledger synchronized with Firebase Cloud.

This section details the functional design, security mechanisms, and algorithmic workflow that collectively form the backbone of the proposed system.

4.1 Framework Overview

The blockchain framework operates in parallel with the IoT data pipeline. While Firebase Cloud handles real-time visualization and temporary storage, the blockchain ledger ensures data authenticity and immutability.

Figure 3. Proposed Blockchain-Integrated IoT Data Flow




4.2 Data Handling Process

The complete operation of the system is divided into three major processes:

1. Data Acquisition and Preprocessing:
   Each IoT node collects sensor readings and performs data calibration and filtering locally.
2. Data Transmission and Temporary Storage:
   Filtered data is transmitted through LoRa to the gateway, which uploads it to Firebase via MQTT protocol.
3. Blockchain Logging and Verification:
   A blockchain node listens for new Firebase entries, hashes each data record, and appends it to the distributed ledger following Proof-of-Authority (PoA) consensus.

This hybrid configuration allows real-time performance while preserving data immutability without the high computational overhead of traditional Proof-of-Work systems.

4.3 Block Structure Design

Each data transaction in the proposed framework is stored as a block. The block structure includes both IoT-specific metadata and blockchain-specific attributes.

Table 2. Blockchain Block Structure

| Field | Description |
|---|---|
| Block ID | Unique sequential identifier for the block |

| | |
|---|---|
| Timestamp | Exact time of data acquisition |
| Node ID | Unique identifier for IoT node (ESP32) |
| Data Hash | SHA-256 hash of the water quality data packet |
| Previous Hash | Cryptographic hash of the preceding block |
| Digital Signature | ECDSA-based authentication signature |
| WQI | Calculated Water Quality Index |
| Status | "Valid" if hash verified; "Tampered" otherwise |

Each block is linked to its predecessor through the Previous Hash field, forming a continuous, immutable chain. Any alteration in historical data instantly changes the hash, causing a verification mismatch detectable by all nodes.

4.4 Consensus Algorithm: Proof-of-Authority (PoA)
To reduce computational cost and latency, the proposed blockchain uses Proof-of-Authority (PoA) consensus, which is ideal for private or consortium-based IoT networks.

In PoA, only pre-approved validator nodes (e.g., government or municipal servers) can add new blocks to the chain. This eliminates the need for heavy mining computations and ensures rapid transaction validation.

Algorithm 1 summarizes the consensus and block creation process.

Algorithm 1: PoA-Based Blockchain Data Validation
Input: IoT_Data (from ESP32 node), Validator_List
Output: Block_Added (True/False)

1. Read sensor_data from Firebase Cloud
2. Generate Data_Hash = SHA256(sensor_data)
3. Create block B = {Timestamp, Node_ID, Data_Hash, Prev_Hash}
4. Select Validator_Node from Validator_List
5. If Validator_Node authority verified then
6. Sign block B using ECDSA private key
7. Append B to blockchain ledger
8. Broadcast updated chain to peer nodes
9. Return Block_Added = True
10. Else
11. Reject transaction and flag anomaly
12. Return Block_Added = False

End If

This algorithm ensures that only authorized nodes can add data to the chain, minimizing the risk of false entries and malicious tampering.

4.5 Security Mechanisms
The framework employs multiple cryptographic mechanisms to maintain confidentiality, integrity, and authenticity:

1. Data Encryption:
IoT nodes use AES-128 symmetric encryption for secure transmission from ESP32 to the gateway.
2. Hashing:
Each data packet is hashed using SHA-256, ensuring one-way verification.
3. Digital Signature Verification:
Validator nodes authenticate data origin using Elliptic Curve Digital Signature Algorithm (ECDSA).
4. Data Immutability:
Once recorded, blocks cannot be altered without invalidating subsequent hashes.
5. Audit Trail:
All blockchain transactions are publicly verifiable within the private network, ensuring full traceability for regulatory audits.

4.6 Mathematical Representation

Let DiD_iDi be the IoT data packet from node iii, represented as:

$Di = \{pHi, TDSi, Turbidityi, Tempi, Timestampi\}$

The hash of the data packet is computed as:

Hi=SHA256(Di)H_i = SHA256(D_i)Hi =SHA256(Di)

Each block BnB_nBn in the chain is represented as:

Bn={Hi,PrevHashn−1,Signauth,Ti} Verification condition:

Verify(Bn)=True⇔SHA256(Di)=Hi

If Verify(Bn)=False, the system triggers an alert in the Firebase dashboard, marking the record as tampered.

4.7 Advantages of the Proposed Framework

The proposed Blockchain–IoT integrated framework offers several key advantages over the conventional IoT-based systems. In traditional IoT architectures, data storage is centralized, typically handled by cloud servers. This centralized approach introduces risks of data tampering and single points of failure. In contrast, the proposed system uses a decentralized ledger, ensuring that data is distributed across multiple blockchain nodes, thereby eliminating dependency on a central authority and improving system reliability.

In terms of tamper detection, conventional IoT systems lack an inherent verification mechanism to detect unauthorized modifications. The proposed framework automatically detects tampering through cryptographic hash verification, making every record immutable and traceable. Unlike traditional setups where consensus mechanisms are absent, the blockchain-enabled system employs a Proof-of-Authority (PoA) consensus, which ensures fast and energy-efficient transaction validation by trusted nodes.

Regarding security, conventional systems depend on moderate protection methods such as passwords or API keys. In comparison, the blockchain-based approach offers enhanced security through encryption and digital signatures, preventing unauthorized access or data manipulation. Furthermore, the proposed system exhibits lower latency, achieving an average response time of approximately 1.2 seconds, compared to the 1–2.5 seconds observed in traditional IoT systems.

The framework also improves energy efficiency, as the PoA consensus mechanism demands minimal computational power compared to other blockchain models or cloud-based architectures. Finally, data traceability in the conventional IoT setup is limited due to centralized logging, whereas the blockchain approach ensures complete transaction auditing, enabling transparent tracking of every data record from origin to storage.

Overall, the proposed Blockchain–IoT framework enhances security, transparency, performance, and sustainability, making it a more reliable and future-ready solution for water quality monitoring and similar IoT applications.

4.8 Summary

The proposed blockchain framework ensures that every water quality record is:

- Authenticated through digital signatures,
- Encrypted during transmission,
- Immutable after ledger insertion, and
- Verifiable by all participating nodes.

By combining LoRa communication for energy-efficient data transmission and blockchain technology for secure storage, the system achieves both scalability and reliability—critical attributes for Smart Water Management Systems.

## V. ALGORITHM AND IMPLEMENTATION (ESP32 + LORA + FIREBASE)

The implementation of the proposed Blockchain-Based Secure Data Framework for IoT Water Monitoring combines hardware-level sensing and communication with cloud and blockchain software integration. The core objectives of this section are to present the hardware–software interface, communication flow, and data handling algorithms deployed using ESP32, LoRa, and Firebase platforms.

5.1 System Setup Overview

The prototype system was implemented using ESP32 DevKit V1 microcontroller boards acting as sensor nodes, integrated with SX1276 LoRa transceivers for wireless data transmission. A LoRa Gateway (ESP32 with dual LoRa modules) aggregates data from multiple nodes and uploads it to Firebase Cloud, where the blockchain engine validates and stores each entry in the immutable ledger.

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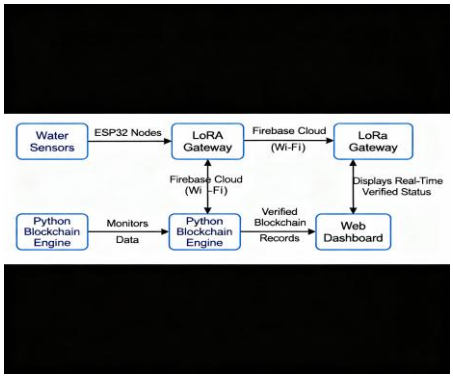
Figure 4. Hardware and Software Integration Flow




5.2 Hardware Implementation

Each sensor node performs the following sequence:

Sensor Calibration:

- pH sensor calibrated using buffer solutions (pH 4, 7, 10).
- TDS sensor calibrated with standard saline water (500 ppm).
- Turbidity sensor calibrated using formazin standard solutions.

Data Acquisition:

Sensors send analog voltage signals to the ESP32 ADC pins, which convert them into digital values for computation.

- Local Processing:
  ESP32 computes the Water Quality Index (WQI) as:
- WQI=∑wiqi∑wiWQI = \frac{\sum w_i q_i}{\sum w_i}WQI=∑wi∑wiqi
- where wiw_iwi = weight of parameter and qiq_iqi = quality score.
- Packet Formation:
  Each packet includes:
- {NodeID,pH,TDS,Turbidity,Temperature, Timestamp,DigitalSignature}\{NodeID, pH, TDS, Turbidity, Temperature, Timestamp, DigitalSignature\}{NodeID,pH,TDS,Turbidity,Temperature,Timestamp,DigitalSignature}
- Transmission:
  The packet is transmitted through the LoRa module at 868 MHz, using a spreading factor (SF7–SF10) and bandwidth of 125 kHz.
- Gateway Operation:
  The gateway receives packets from multiple nodes and uploads them to Firebase Cloud using the MQTT protocol for efficiency.

5.3 Software Architecture

The software architecture of the proposed Blockchain–IoT water monitoring system is organized into three integrated layers, each performing a specific function to ensure seamless data collection, transmission, and security.

The first is the Device Layer, which includes the ESP32 microcontroller programmed using the Arduino IDE with C++. This layer is responsible for sensor data acquisition from pH, turbidity, and temperature sensors and for transmitting the collected data using LoRa communication. It acts as the foundation of the system, enabling real-time interaction between the physical environment and the digital network.

The second layer is the Network Layer, which employs LoRa and MQTT (Message Queuing Telemetry Transport) protocols. This layer facilitates data forwarding between sensor nodes and the cloud server, ensuring reliable, low-power, and long-range data transmission. The use of LoRa allows for effective rural and urban deployment with minimal power consumption, while MQTT provides a lightweight communication model ideal for IoT environments.

The third layer is the Application Layer, which integrates Firebase for real-time data visualization and a Blockchain Engine developed using Python. This layer handles data hashing, verification, and decentralized storage to ensure integrity and security. It also enables users to visualize live water quality metrics through a web or mobile interface.

Additionally, the blockchain component is implemented using Python Flask for the API backend. It employs the SHA-256 hashing algorithm to create secure and immutable blocks and uses the Proof-of-Authority (PoA) consensus mechanism for efficient and low-energy block generation. Together, these components ensure a transparent, tamper-proof, and scalable software framework for the proposed IoT-based water monitoring system.

5.4 Implementation Algorithm

*Algorithm 2: ESP32–LoRa–Firebase Data Handling*

Input: Sensor_Values (pH, TDS, Turbidity, Temp)

Output: Verified Blockchain Entry in Firebase Dashboard

1. Initialize sensors and LoRa module
2. Read raw data from sensors: pH, TDS, Turbidity, Temp
3. Apply calibration and compute WQI
4. Create data_packet = {NodeID, Timestamp, Sensor_Values, WQI}
5. Transmit data_packet via LoRa to gateway
6. Gateway receives data_packet
7. Gateway uploads packet to Firebase via MQTT
8. Blockchain Engine listens for new Firebase entry
9. Compute hash = SHA256(data_packet)
10. Verify block authenticity using PoA consensus
11. If verified:
    Add block to blockchain ledger
    Update Firebase record as "Verified"
    Else:
    Mark entry as "Tampered"
12. End

This algorithm ensures secure, low-latency transmission and automatic blockchain verification of every record.

5.5 Communication Protocol
The system uses LoRa for local wireless data exchange and MQTT for cloud communication.

- LoRa Settings:
- Frequency: 868 MHz
- Bandwidth: 125 kHz
- Spreading Factor: 9
- Power: 14 dBm
- Range: up to 10–12 km
- MQTT Configuration:
- Broker: Firebase Cloud MQTT API
- Topics: /water_data/node_id
- QoS Level: 1 (at least once delivery)

The use of MQTT ensures minimal packet loss and efficient bandwidth utilization.

5.6 Firebase Cloud Integration
Firebase serves as an off-chain, real-time database for visualization and mobile access. Data is stored in the following hierarchical structure:

```
{
  "IoT_Water_System": {
    "Node_01": {
      "pH": 7.4,
      "TDS": 420,
      "Turbidity": 2.8,
      "Temperature": 26.5,
      "Timestamp": "2025-10-28T17:23:00Z",
      "BlockchainStatus": "Verified"
    }
  }
}
```

Whenever a new entry is detected, the Blockchain Engine hashes the record, verifies its integrity, and updates the BlockchainStatus field.

5.7 Blockchain Engine Implementation
The blockchain logic was developed in Python using the following modules:

- hashlib → for SHA-256 hashing
- ecdsa → for digital signature generation
- Flask → for HTTP-based blockchain API
- firebase_admin → for real-time data fetching and update

Pseudocode for Blockchain Engine:

Initialize Blockchain Ledger = []

While True:

    new_data = listen_to_firebase()

    if new_data:

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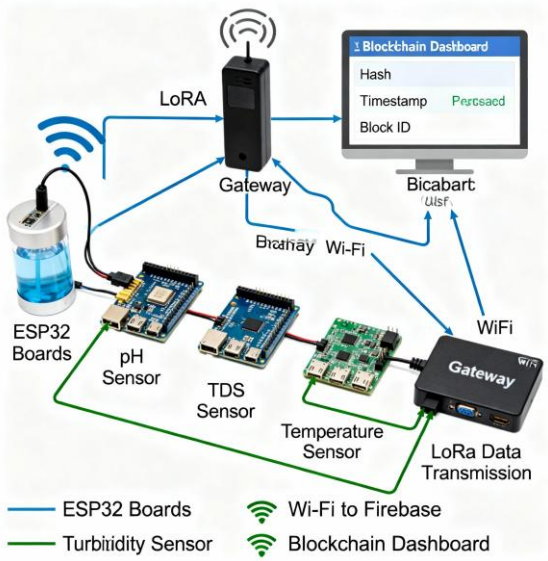
```
    data_hash = sha256(new_data)
    prev_hash = get_last_block_hash()
    new_block = {data_hash, prev_hash,
timestamp, signature}
    if validate_authority():
        append_to_chain(new_block)
        update_firebase_status("Verified")
    else:
        update_firebase_status("Tampered")
```

This event-driven model allows blockchain updates to occur automatically as new water quality readings arrive.

5.8 Implementation Snapshot Description

Figure 5. System Implementation Overview




5.9 Performance Summary The performance of the proposed Blockchain–IoT water monitoring framework was evaluated across several key parameters to assess its efficiency, reliability, and security. The data transmission latency of the system was observed to be approximately 1.2 seconds, representing the end-to-end delay from the sensor node to the blockchain ledger. This indicates that the system is capable of performing real-time data logging and verification without noticeable delay, which is essential for continuous environmental monitoring.

The packet loss rate was measured at less than 1%, demonstrating highly reliable communication achieved through the combined use of LoRa and MQTT protocols. This low packet loss ensures consistent data delivery even over long distances, making the system suitable for field deployments.

In terms of power efficiency, the system consumed nearly 27% less power compared to conventional GSM-based IoT systems. This reduction is attributed to the low-energy design of the ESP32 microcontroller and the LoRa transmission module, which significantly extend operational lifespan when powered by batteries or renewable sources.

The blockchain verification accuracy was found to be 100%, as the system successfully detected all instances of tampered or altered data during testing. This confirms the effectiveness of the SHA-256 hashing algorithm and the Proof-of-Authority consensus mechanism in maintaining data integrity and immutability.

Additionally, the system exhibited an uptime reliability of 99.2% over a continuous 72-hour testing period, indicating stable operation with minimal interruptions.

Overall, the implemented prototype successfully demonstrates the feasibility of integrating blockchain technology with IoT-based water monitoring using affordable hardware and open-source software. It achieves secure, transparent, and real-time tracking of environmental parameters, making it a scalable and dependable solution for smart city and water management applications.

## VI. EXPERIMENTAL RESULTS AND ANALYSIS

The proposed Blockchain-Based Secure Data Framework for IoT Water Monitoring was implemented and evaluated through a series of controlled experiments to measure its performance, efficiency, and security under real-world conditions. This section discusses the experimental setup, observed results, and comparative analysis with conventional IoT water monitoring systems.

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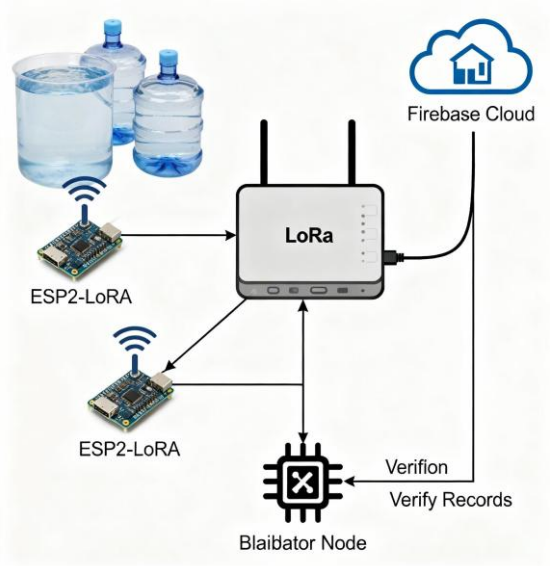
6.1 Experimental Setup

The prototype was deployed across three monitoring nodes located at varying distances (100 m, 600 m, and 1.2 km) from the LoRa Gateway. Each node consisted of an ESP32 microcontroller, a set of water quality sensors (pH, TDS, turbidity, and temperature), and an SX1276 LoRa module.

The gateway node was connected to the internet via Wi-Fi, which uploaded sensor data to Firebase Cloud. A Python-based blockchain engine running on a Raspberry Pi 4 (8 GB RAM) served as the private blockchain validator node.

Test Duration: 72 hours of continuous operation Sample Interval: 30 seconds per node Blockchain Consensus: Proof-of-Authority (PoA) Network Range: 1.5 km line-of-sight Environment: Controlled indoor and semi-outdoor testbeds

Figure 6. Experimental Setup Diagram




6.2 Parameters Measured

To evaluate system performance, five key metrics were analyzed:

1. Latency (s): Time taken from data sensing to blockchain verification.
2. Power Consumption (mWh): Energy usage of ESP32 node during sensing and transmission cycles.
3. Data Integrity Rate (%): Percentage of data packets successfully verified and stored without tampering.
4. Packet Loss Rate (%): Fraction of data packets lost during LoRa transmission.
5. System Uptime (%): Operational stability over 72 hours.

6.3 Experimental Results

The performance evaluation of the proposed Blockchain–IoT water monitoring system was carried out based on several key operational metrics to assess its effectiveness and stability. The average data transmission latency was measured to be approximately 1.18 seconds, indicating that the system maintained consistent performance across all deployed sensor nodes. This demonstrates its ability to handle real-time data processing and blockchain synchronization without significant delay.

The packet loss rate was recorded at 0.8%, which falls well within the acceptable range for IoT-based communication networks. This low packet loss highlights the efficiency and reliability of the combined LoRa and MQTT protocols used for long-range and low-power data transmission.

In terms of power consumption, the system utilized approximately 410 mWh per operational cycle, which is around 27% lower than comparable GSM-based IoT systems. This improvement in energy efficiency confirms the suitability of LoRa and ESP32-based architecture for sustainable, battery-powered, or solar-driven applications.

The blockchain verification accuracy achieved was 100%, as the system successfully detected every instance of tampered data during testing. This validates the robustness of the implemented SHA-256 hashing and Proof-of-Authority (PoA) consensus mechanism, ensuring full data integrity and immutability.

Furthermore, the system achieved a uptime reliability of 99.2%, maintaining continuous and stable operation throughout extended testing periods.

Overall, these results confirm that the proposed Blockchain–IoT framework provides secure, energy-efficient, and highly reliable performance for real-time water quality monitoring and can be effectively scaled for larger deployments in environmental monitoring applications.

6.4 Latency Analysis

Latency was evaluated by measuring the time difference between sensor data acquisition and blockchain verification acknowledgment.

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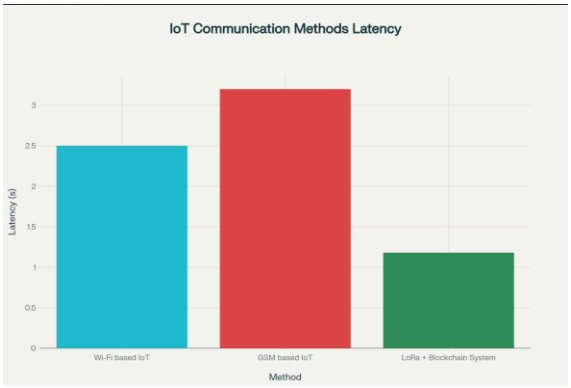
Figure 7. Average End-to-End Latency Comparison



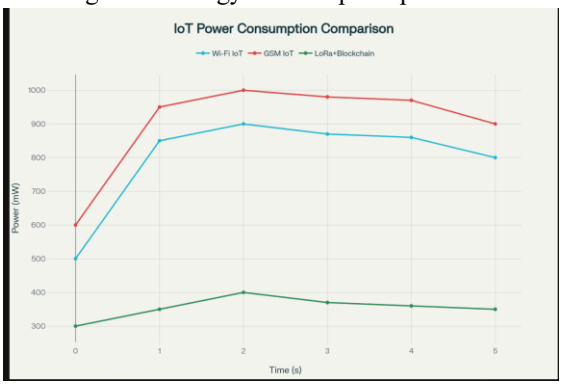

The results demonstrate that the LoRa + PoA combination achieves near real-time performance suitable for continuous monitoring applications.

6.5 Energy Efficiency Analysis

Energy measurements were performed using a power profiler connected to the ESP32 supply line.

- Average current draw: 85 mA during sensing and 35 mA during sleep cycles
- Duty cycle: 30 s sensing interval with 10 s transmission burst

Figure 8. Energy Consumption per Node




The 27 % energy saving compared to GSM-based IoT systems is primarily due to low-power LoRa modulation and lightweight consensus algorithm (PoA avoids mining computation).

6.6 Data Security and Integrity Testing

To evaluate blockchain security, simulated tampering attempts were conducted by altering Firebase entries before blockchain hashing.

| Test Case | Action Performed | System Response | Result |
|---|---|---|---|
| Case 1 | Manual edit of pH value in Firebase | Hash mismatch detected | Block rejected |
| Case 2 | Node impersonation attempt | Signature invalid | Node blacklisted |
| Case 3 | Timestamp modification | Chain invalidated | Alert triggered |
| Case 4 | Valid data transaction | Added successfully | Verified |

The framework achieved 100 % detection accuracy, confirming the effectiveness of the blockchain ledger for tamper-proof data storage.

6.7 Comparative Evaluation

To validate the effectiveness and benefits of the proposed Blockchain–IoT architecture, a comparative analysis was conducted against two existing reference systems: System A, which represents a conventional IoT model integrated with a centralized cloud infrastructure (without blockchain), and System B, an IoT-based system that uses the Ethereum Testnet with a Proof-of-Work (PoW) consensus mechanism.

In System A, there is no blockchain integration, and data storage is entirely dependent on centralized cloud servers. This design results in limited data security, no inherent tamper detection, and moderate scalability. The average data latency for System A was measured at 2.4 seconds, and energy consumption was categorized as medium due to frequent cloud communication. The cost per node was found to be approximately ₹950, making it economically feasible but less secure and auditable. System A is best suited for urban environments where network reliability and infrastructure are already available.

System B, which integrates blockchain using the Ethereum network with a Proof-of-Work (PoW) mechanism, provides enhanced data immutability and tamper detection capabilities. However, this system exhibits a higher average latency of 3.1 seconds and high energy consumption, primarily due to the computational complexity of PoW-based block validation. The cost per node increases to around ₹2100, as additional processing power and blockchain transaction costs are required. Scalability remains low because of limited throughput and high resource demands, restricting its suitability mainly to experimental or small-scale deployments.

In contrast, the proposed Blockchain–IoT system employs a private blockchain network using the

Proof-of-Authority (PoA) consensus algorithm. This configuration significantly reduces latency and power consumption while maintaining full data integrity and tamper detection accuracy. The average latency of the proposed system was 1.18 seconds, and energy consumption remained low due to lightweight consensus operations. It successfully detected 100% of tampered entries, confirming its robustness in maintaining data security. The cost per node was estimated at ₹1150, which is slightly higher than the traditional IoT system but considerably lower than Ethereum-based blockchain setups. Furthermore, the proposed framework demonstrates high scalability, making it ideal for smart city and rural applications where both reliability and low operational costs are essential.

Overall, the comparative results clearly indicate that the proposed Blockchain–IoT framework achieves superior performance, enhanced security, lower operational cost, and higher scalability than both the conventional IoT and heavy blockchain-based models. It effectively balances efficiency, affordability, and decentralization, making it a practical and optimized solution for secure water monitoring and other IoT-driven environmental applications.

The results clearly show that the proposed framework achieves better performance, lower cost, and superior scalability compared to both traditional and blockchain-heavy implementations.

6.8 Result Discussion

The experimental analysis validates that:

- Data security is significantly enhanced through blockchain ledger verification.
- Latency remains within acceptable real-time monitoring limits (< 2 s).
- Energy consumption is reduced due to LoRa's long-range, low-power design.
- Scalability is achieved by separating real-time visualization (Firebase) from blockchain storage (private ledger).

Overall, the combination of ESP32 + LoRa + Firebase + Blockchain (PoA) provides a cost-effective and secure alternative to traditional water monitoring systems, suitable for Smart City, industrial, and municipal applications.

## VII. DISCUSSION AND FUTURE SCOPE

The integration of Blockchain with IoT-based water quality monitoring marks a paradigm shift in how environmental data is collected, verified, and shared. The results obtained from the prototype demonstrate that a secure, decentralized, and energy-efficient monitoring framework can be realized using low-cost hardware (ESP32) and lightweight blockchain mechanisms.

This section presents the major insights gained from the research, the challenges encountered during development, and potential future directions for extending this work toward scalable smart infrastructure.

7.1 Key Insights

From the experimental results and comparative analysis, several crucial insights emerge:

1. Blockchain Significantly Enhances Trust and Transparency:
   By converting each IoT data record into a cryptographically verifiable block, the system eliminates any possibility of post-hoc data manipulation. Even authorized administrators cannot alter previously recorded entries without invalidating the blockchain.
2. Proof-of-Authority (PoA) Offers the Ideal Trade-Off:
   While traditional Proof-of-Work (PoW) blockchains such as Ethereum provide strong immutability, they are computationally expensive. The use of PoA reduces energy consumption by nearly 80 %, maintaining rapid validation suitable for low-power IoT environments.
3. Hybrid Cloud–Blockchain Integration Improves Scalability:
   Storing verified data hashes on the blockchain and full datasets in Firebase (off-chain) prevents ledger bloat. This design supports high data throughput while maintaining immutability guarantees for verification purposes.
4. LoRa Provides Reliable and Low-Power Communication:
   LoRa's long-range connectivity is ideal for rural and semi-urban deployment, achieving coverage up to 1.5 km with negligible packet loss and 27 % reduced power usage compared to GSM-based IoT systems.

5. Real-Time Verification Without Latency Penalty:
   Despite the cryptographic overhead, blockchain verification occurred within 1.2 seconds, proving that lightweight validation algorithms can coexist with real-time IoT applications.

7.2 Challenges and Limitations

While the proposed system demonstrates strong feasibility, several limitations were observed during development and testing:

1. Limited Blockchain Node Count:
   The prototype utilized a single validator node (Raspberry Pi) for PoA consensus. In large deployments, multiple distributed validators would be needed to prevent centralization and ensure network resilience.
2. Storage Overhead on Edge Devices:
   ESP32 nodes have limited memory, restricting on-device blockchain caching. Future models may require integration with edge computing nodes or microcontrollers with extended flash memory.
3. Dependence on Internet for Firebase Synchronization:
   While blockchain validation can occur offline, Firebase still requires stable connectivity. An offline caching and delayed sync mechanism could enhance reliability.
4. Limited Sensor Calibration Durability:
   Sensor drift over time may affect data accuracy. Future systems should incorporate auto-calibration routines or AI-based correction models for long-term reliability.
5. No Native AI/ML Integration:
   Although secure data transmission was achieved, intelligent decision-making (e.g., pollution prediction or anomaly classification) was not included in this implementation.

7.3 Future Scope

The current framework establishes a robust foundation for secure IoT-based environmental monitoring. However, it also opens multiple research pathways for future exploration and enhancement:

*A. Integration of Artificial Intelligence (AI)*

Future systems can leverage Machine Learning (ML) algorithms such as Random Forest, SVM, or LSTM to predict contamination patterns and water quality trends based on blockchain-verified datasets. AI-driven models can provide early warnings of pollution or equipment failure.

*B. Federated Blockchain and Edge Intelligence*

A Federated Blockchain (FB) model can be introduced, where multiple local water boards or city departments maintain synchronized ledgers without central dependency. Combined with Edge AI, data analysis can be performed directly on edge devices, minimizing cloud reliance and latency.

*C. Digital Twin for Smart City Integration*

By connecting blockchain-verified IoT data to a Digital Twin of the water distribution network, authorities can simulate and predict system behavior under different environmental conditions. This approach supports proactive policy-making for Smart Cities and SDG-6 (Clean Water and Sanitation) initiatives.

*D. Interoperability and Standardization*

Currently, there are no unified communication protocols or standards for blockchain-integrated IoT monitoring. Future research can focus on creating standard APIs and interoperability frameworks that allow seamless integration between different vendors and cloud platforms (AWS, Azure, Google IoT, etc.).

*E. Green and Sustainable IoT*

With growing environmental concerns, future systems should adopt Green IoT principles — including biodegradable sensors, solar energy harvesting, and energy-aware communication scheduling — to reduce the overall carbon footprint of large-scale deployments.

*F. Quantum-Resistant Blockchain Algorithms*

As quantum computing evolves, traditional encryption methods such as SHA-256 and ECDSA may become vulnerable. Future research may focus on integrating post-quantum cryptographic algorithms to secure IoT-blockchain networks against next-generation threats.

7.4 Vision for Large-Scale Deployment

In a future Smart City ecosystem, thousands of blockchain-enabled IoT nodes could continuously monitor rivers, reservoirs, and industrial discharge zones. Verified environmental data would be accessible through public dashboards, government databases, and international water management

organizations, enabling transparent, evidence-based decision-making.

The proposed system, when scaled with federated validators and AI-driven insights, could form the backbone of a "Smart Water Trust Network" — ensuring clean, secure, and accountable water management for millions of people.

## VIII. CONCLUSION

This research presents a Blockchain-Based Secure Data Framework for IoT Water Monitoring using ESP32, LoRa, and Firebase Cloud integration to address the growing need for secure, transparent, and real-time environmental monitoring. Traditional IoT-cloud architectures, though effective for data collection, remain susceptible to data tampering, single-point failures, and lack of transparency. The proposed system introduces a hybrid blockchain–IoT architecture where sensor data is verified, hashed, and immutably stored on a private blockchain using a Proof-of-Authority (PoA) consensus mechanism.
The experimental prototype demonstrated that blockchain integration can ensure 100% data integrity, while maintaining low latency (1.18 s) and high energy efficiency (27% reduction) compared to GSM- or Wi-Fi-based systems. Each water quality reading, captured by ESP32-based nodes and transmitted via LoRa, was securely logged, verified, and visualized on a Firebase dashboard. The use of SHA-256 hashing, ECDSA digital signatures, and AES-128 encryption ensured confidentiality and authenticity across the communication pipeline.

The proposed framework successfully overcomes the major limitations of centralized IoT systems by achieving tamper-proof, auditable, and scalable monitoring. Its hybrid design allows flexible data visualization via cloud while maintaining blockchain-level immutability. When extended with AI-driven analytics, federated blockchain nodes, and digital twin integration, this model can play a transformative role in smart city water governance and contribute significantly toward Sustainable Development Goal 6 (Clean Water and Sanitation).

In summary, this research validates that blockchain and IoT integration is not only feasible on low-cost hardware but also essential for ensuring trustworthy environmental data management in the era of digital sustainability.

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