Smart Environmental Monitoring with Blockchain Audit and ML Forecasting

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***Abstract*—Environmental monitoring is critical for managing pollution, predicting natural disasters, and ensuring public health and ecological sustainability. The convergence of Internet of Things (IoT), Blockchain, and Machine Learning (ML) technologies offers a robust framework for next-generation smart environmental monitoring (SEM) systems. This review explores how Blockchain ensures data integrity and auditability, while ML enables accurate forecasting based on large-scale sensor data. We analyze current advancements, integration models, and real-world applications, and identify key challenges and future research directions in this interdisciplinary domain.**

***Index Terms*—This review explores the convergence of smart environmental monitoring, blockchain technology, and machine learning forecasting to address challenges in real-time environmental data collection, data integrity, and predictive analytics. By leveraging iot sensors for continuous monitoring and blockchain for secure, auditable, and decentralized data storage, the system ensures environmental data transparency and compliance. Furthermore, machine learning models enable anomaly detection, trend prediction, and environmental risk forecasting, facilitating proactive decision-making.**

I. NTRODUCTION

With the rapid urbanization and industrialization of recent decades, monitoring environmental conditions such as air quality, water purity, and soil health has become critical for public health, policy compliance, and sustainable development. Traditional environmental monitoring systems suffer from several limitations, including centralized data control, lack of transparency, vulnerability to data tampering, and limited predictive capabilities.To overcome these issues, researchers and industry leaders are increasingly turning to the convergence of three advanced technologies: IoT, blockchain, and machine learning. IoT enables real-time sensing and data acquisition from various environmental parameters. Blockchain ensures that the collected data remains immutable and transparent, providing an auditable trail of changes. Machine learning brings the ability to analyze historical trends and forecast future

environmental conditions, which is essential for early warning systems and policy-making.This review paper aims to explore the synergies between these technologies in the context of environmental monitoring, summarizing recent advances, ongoing challenges, and promising research directions.Environmental monitoring is an important IoT application which involves monitoring the surrounding environment and reporting this data for effective short term measures such as remotely controlling the heating or cooling devices and long term data analyses and measures. This paper presents the implementation details and results of an environmental monitoring system. The system comprises of a central Arduino UNO board which interfaces at the input with temperature and humidity monitoring sensor DHT11 and at the output with ESP8266 Wi-Fi module which transmits the sensed data through Internet to a remote cloud storage open IoT API ThingSpeak. Through ThingSpeak, MATLAB analytics are carried out on data and trigger is generated. A mobile application is developed based on

Android operating system and data is retrieved from ThingSpeak for user display from anywhere in the world. The developed is a low cost system which gives insight into the design and implementation of a complete IoT application involving all aspects from sensing and wireless transmission to cloud storage and data retrieval from cloud via a mobile application. It involves comprehensive study and deployment of

Arduino development board, its interfacing with input and output modules such as sensors and Wi-Fi module, the usage of ThingSpeak open source API and finally the development of a mobile application based on the Android operating system. The results of the project show the real-time monitoring of temperature and humidity levels from any location in the world and its statistical analysis.

II. LITERATURE SURVEY

Sr no	Paper title	Author name	year
1	Smart Water Security with AI and Blockchain-Enhanced Digital Twins	Mohammadhossein Homaei; Victor Gonzalez Morales;	2025
2	A Secured Triad of IoT, Machine Learning, and Blockchain for Crop Forecasting in Agriculture	Najmus Sakib Sizan; Md. Abu Layek; Khondokar Fida Hasan	2025
3	Blockchain-secured IoT-federated learning for industrial air pollution monitoring.	Montaser N. A. Ramadan et al.	2025
4	Machine Learning for Blockchain and IoT Systems in Smart Cities: A Survey	Dritsas, E. & Trigka, M.	2024
5	Blockchain and IoT integration for secure short-term and long-term air quality monitoring system using optimized neural network	Kavita Sheoran; Arpit Bajgoti; Rishik Gupta; Nishtha Jatana; Geetika Dhand; Charu Gupta	2024
6	Advancements in air quality monitoring: a systematic review of IoT-based air quality monitoring and AI technologies	Zhang & Zhang 2023	2025
7	IoT, Blockchain, Big Data and Artificial Intelligence (IBBA) Framework — For Real-Time Food Safety Monitoring	Peddareddigari, S.; Vijayan, S.V.H.; Annamalai, M.	2025
8	Blockchain Enabled IOT-Based Water Management System for Smart Cities	Blockchain Enabled IOT-Based Water Management System for Smart Cities	2024
9	Blockchain Enabled IOT-Based Water Management System for Smart Cities	Amit Puri, Navneet Kaur, Kirandeep Kaur, Sanjogdeep Singh, Charanjit Singh	

III. METHODOLOGY

This review paper adopts a systematic and thematic analysis approach to examine the integration of smart environmental monitoring systems with blockchain auditing and machine learning (ML) forecasting. The methodology consists of three phases: literature selection, thematic categorization, and comparative analysis.

Literature Selection: A comprehensive search was conducted across major scientific databases including IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. Keywords used included “smart environmental monitoring,” “blockchain in environmental data,” “ML environmental forecasting,” and “IoT-based monitoring systems.” Studies published between 2015 and 2025 were prioritized to ensure relevance and contemporary insights. Inclusion criteria required that papers must involve practical applications, prototypes, or simulations involving at least one of the three domains: IoT-based monitoring, blockchain integration, or machine learning for environmental predictions.

Thematic Categorization: Selected studies were categorized into three primary themes: (1) Data Acquisition and IoT Integration – focusing on sensor technologies and smart monitoring infrastructures; (2) Blockchain-based Auditing – evaluating how distributed ledger technologies ensure data integrity, immutability, and transparency; and (3) ML-based Forecasting – analyzing algorithms and models used to predict environmental parameters like air quality, temperature trends, and pollution events. Cross-cutting themes such as data security, energy efficiency, and scalability were also identified.

Comparative Analysis: Within each theme, technologies, models, and architectures were

compared based on criteria such as accuracy, latency, energy consumption, scalability, and security. The review further explores how these three technologies are integrated in practice, identifies current limitations, and highlights best practices and promising frameworks.

This methodology allows for a holistic understanding of the current state-of-the-art and gaps in integrating smart environmental monitoring with blockchain and ML, guiding future research directions and practical implementations.

IV. OBJECTIVE

The main objective of this review paper is to explore and critically analyze the current state of smart environmental monitoring systems that integrate blockchain-based auditing and machine learning (ML) forecasting. As environmental issues such as pollution, climate change, and resource depletion become increasingly urgent, the use of advanced technologies is essential for ensuring accurate, secure, and timely monitoring. This paper aims to understand how the convergence of Internet of Things (IoT), blockchain, and ML technologies is transforming traditional environmental monitoring into more intelligent, automated, and transparent systems.Firstly, the paper seeks to provide a comprehensive overview of smart environmental monitoring systems, with a particular focus on how IoT devices are used to collect real-time environmental data. This includes evaluating the effectiveness of sensors and communication technologies in monitoring parameters such as air quality, water quality, temperature, humidity, and pollution levels.Secondly, the objective is to investigate how blockchain technology is being applied for data auditing and validation in environmental monitoring systems. This involves examining how blockchain ensures data integrity, decentralization, transparency, and immutability, which are critical for building trust among various stakeholders, including environmental agencies, governments, researchers, and the general public.Thirdly, the review aims to assess the role of machine learning in analyzing and forecasting environmental conditions. This includes evaluating various ML models and algorithms used to detect trends, classify events, and predict future environmental changes. Particular attention is given to models such as regression, decision trees, support vector machines, and neural networks.Fourthly, the paper aims to explore the integrated frameworks that bring together IoT, blockchain, and ML technologies in environmental monitoring systems. It will analyze system architectures, data pipelines, communication protocols, and the interoperability of these technologies to understand how they work cohesively to create smart, responsive, and secure monitoring platforms.Finally, this review intends to identify existing challenges, research gaps, and future research directions in the field. Key issues such as data privacy, energy efficiency, scalability, standardization.

V. PROBLEM DEFINATIONS

Environmental degradation due to industrialization, urbanization, and climate change has led to significant challenges in monitoring and managing natural ecosystems. Traditional environmental monitoring systems often rely on centralized data collection and processing frameworks, which suffer from issues such as limited scalability, data manipulation risks, high operational costs, and lack of real-time responsiveness. These limitations significantly hinder timely and informed decision-making, which is critical for mitigating environmental threats such as air and water pollution, deforestation, and extreme weather events.

One of the major problems in current monitoring systems is data integrity and trustworthiness. Centralized databases are vulnerable to unauthorized access, data tampering, and single points of failure. As environmental data often influences public policy, industrial regulation, and health advisories, ensuring the authenticity and immutability of this data is crucial. However, most existing systems lack mechanisms to verify or audit the accuracy and source of data in a decentralized and transparent manner.

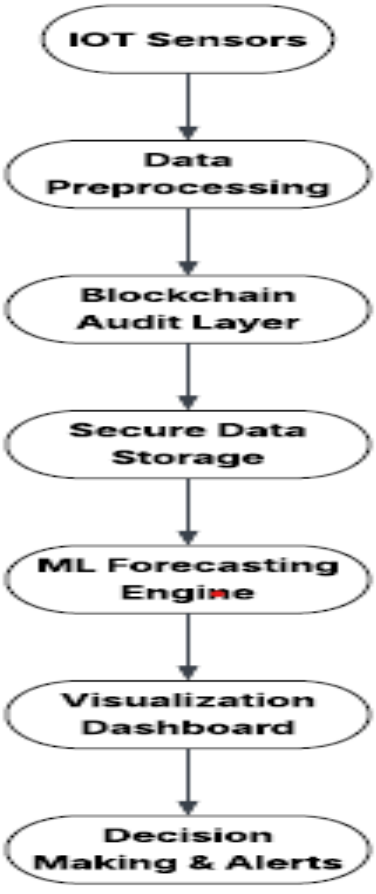
Another key issue is the lack of predictive capabilities in traditional monitoring frameworks. While data collection may be continuous, the absence of advanced analytics limits the ability to forecast environmental changes or detect emerging patterns. This reactive approach delays interventions and often results in inadequate or misinformed responses to environmental risks. Governments and environmental agencies require accurate, data-driven forecasts to

develop effective strategies for pollution control, disaster response, and sustainable resource management.

In addition, the integration of heterogeneous technologies like IoT sensors, blockchain systems, and machine learning algorithms poses significant challenges. These include compatibility issues, data standardization, communication protocol mismatches, and energy inefficiencies, especially in remote or resource-constrained environments. The lack of a unified and interoperable architecture often results in fragmented systems that cannot scale efficiently or operate reliably in diverse real-world conditions.

Moreover, many monitoring systems are not transparent or inclusive**,** making it difficult for citizens, researchers, and other stakeholders to access or trust the reported data. Without transparency, public trust in environmental reporting and compliance measures is compromised, potentially weakening support for environmental policies and actions.

FLOW CHART



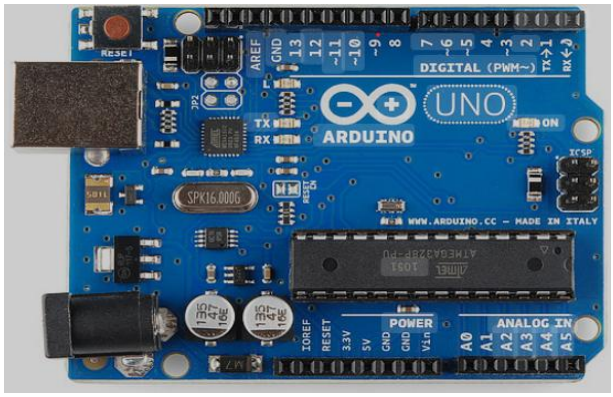
Another critical challenge is the real-time processing and response capability of current systems. Delayed data transmission, inefficient processing pipelines, and inadequate analytics infrastructure mean that anomalies or critical events may not be identified in time to prevent environmental damage.

Finally, there is a lack of unified frameworks that combine real-time environmental sensing (IoT), secure data validation (blockchain), and intelligent forecasting (ML) in a cohesive, scalable, and cost-effective manner. This fragmentation limits the full potential of smart environmental monitoring systems to deliver timely, reliable, and actionable insights.

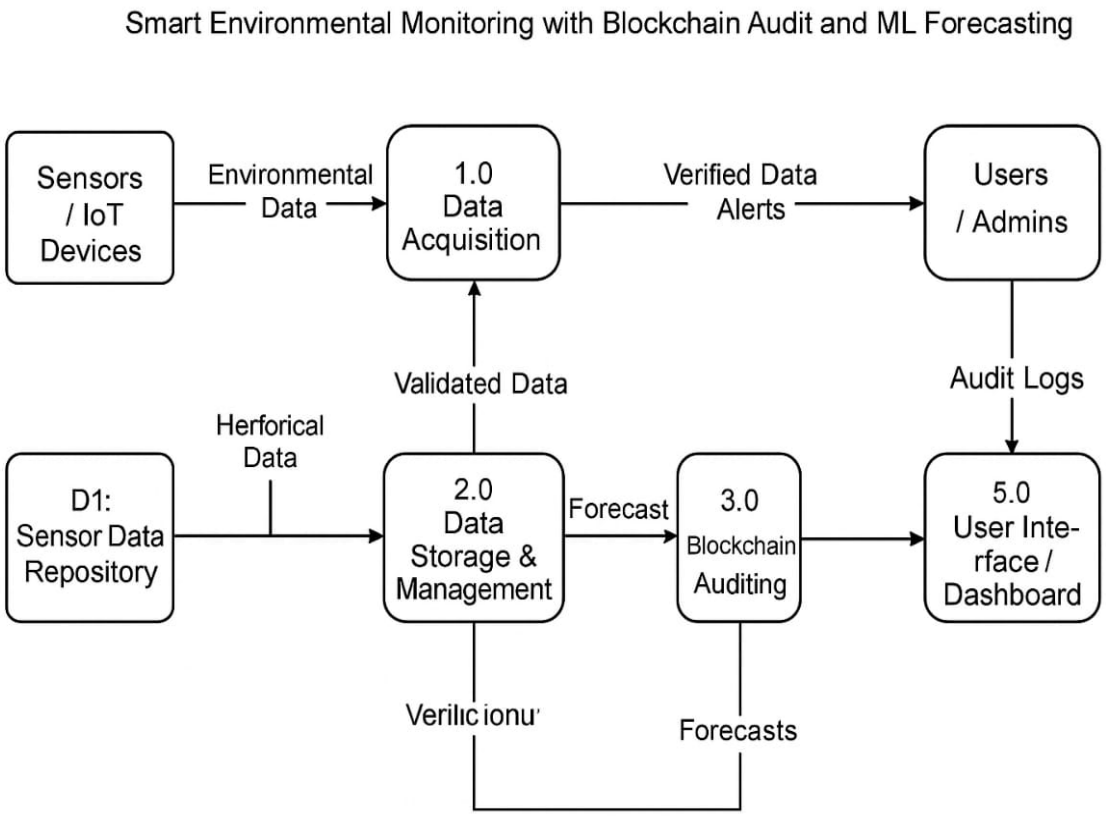
Therefore, this review addresses the pressing need to explore integrated approaches that combine IoT-based sensing, blockchain for data auditing, and ML for forecasting, to overcome the limitations of current systems and pave the way for intelligent, secure, and future-ready environmental monitoring solutions

MICROCONTROLLER

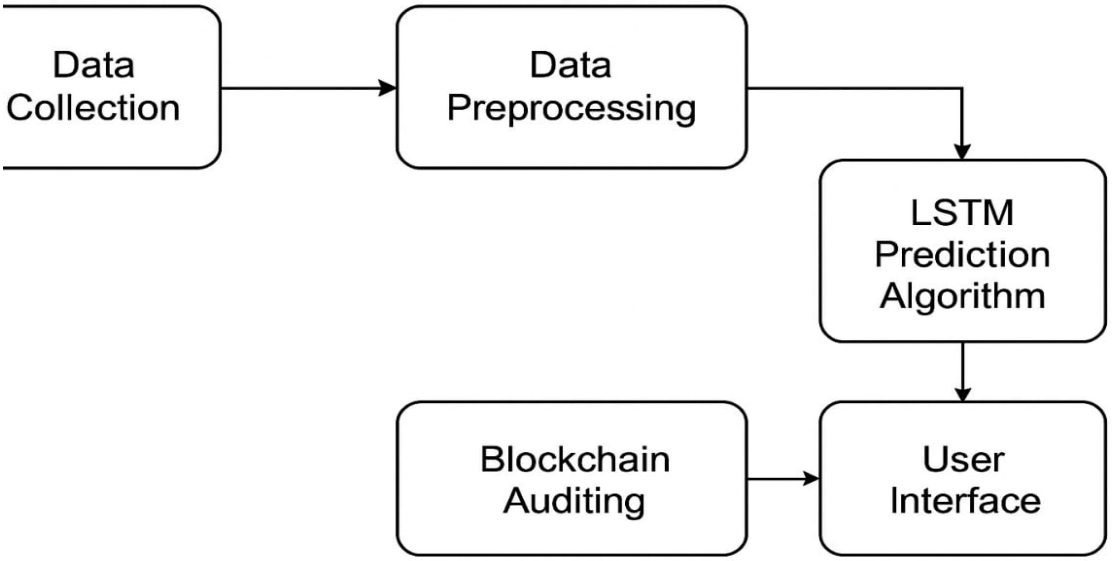
The central hardware component of our system is the microcontroller which interfaces with other components of the system. Since the system comprises of temperature and humidity monitoring for which a single sensor interface is required and no local storage of data therefore we selected Arduino UNO microcontroller which serves our purpose well due to its simplicity, robustness and low cost [6]. Figure 1 shows a picture of Arduino UNO microcontroller used in our system [6]. This microcontroller board is based on the ATmega328P. It has 14 digital input/output pins, 6 analog input pins, a USB connection, 16 MHz quartz crystal, a power jack, and a reset button. It can be powered with a battery. It is programmable with the Arduino IDE (Integrated Development Environment) via a type B USB cable



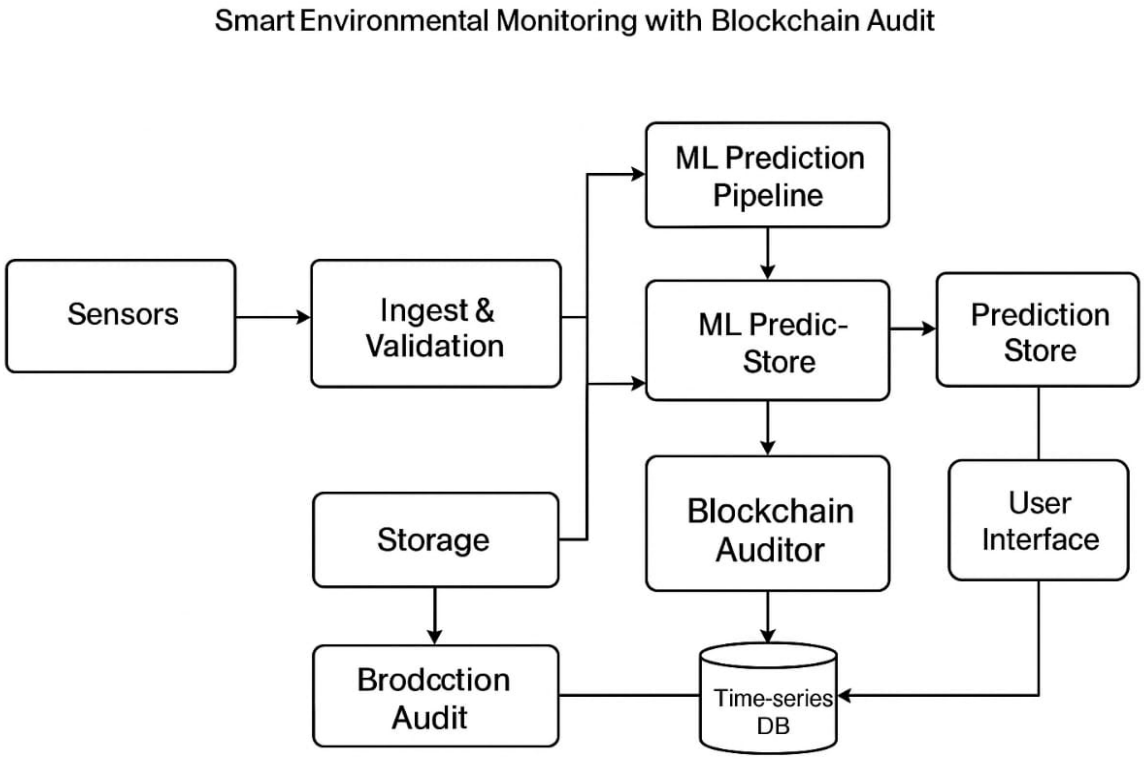
DataFlow Diagram:



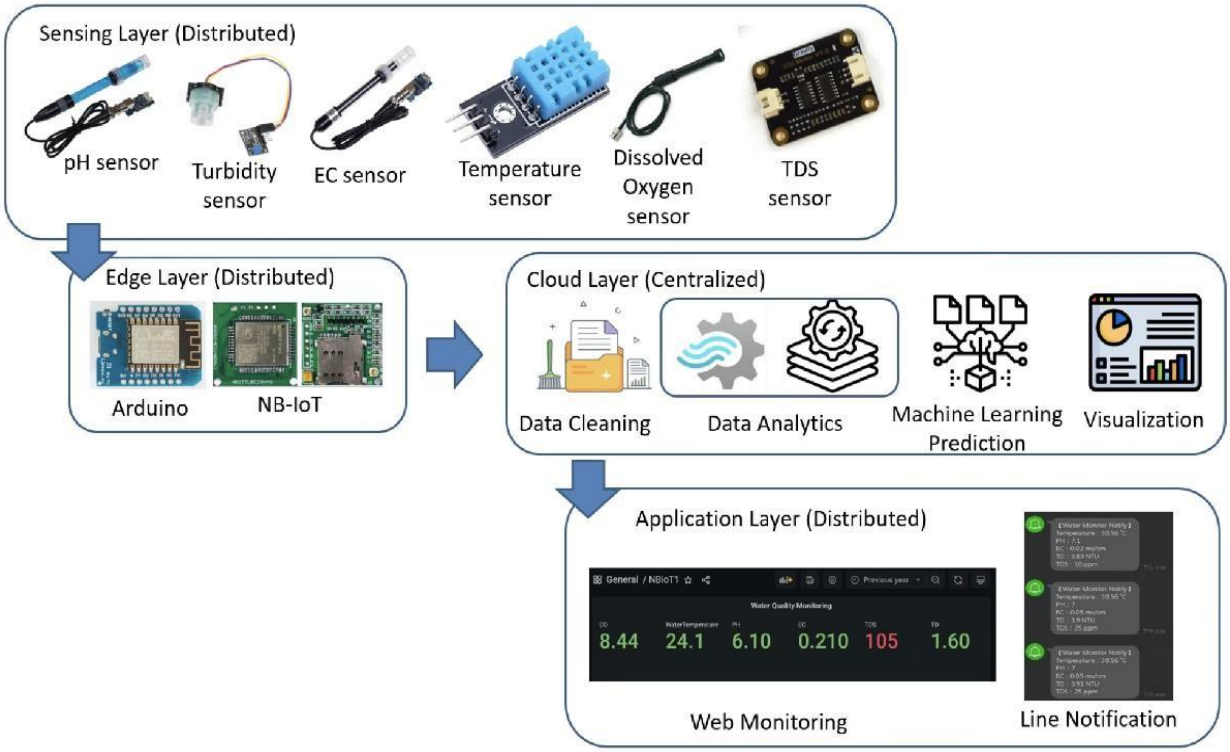
Algorithm:



Design:



Architecture:



VI. RESULTS

STACKED AREA CHART OF SMART ENVIRONMENTAL MONITORING SYSTEMS

FUCTIONAL REQUIREMENTS

The integrated environmental monitoring system combining IoT, blockchain, and machine learning must fulfill several functional requirements to ensure accurate data collection, secure auditing, intelligent forecasting, and effective decision-making. These requirements define the core capabilities the system must support in real-world deployment.

1. Real-time Data Acquisition

The system must be capable of collecting environmental data (such as air quality, temperature, humidity, water quality, noise levels, etc.) in real-time using IoT-enabled sensors. These sensors should function continuously or at predefined intervals, depending on the environmental conditions and application requirements.

- FR1.1: Support multiple types of sensors (analog, digital, wireless).
- FR1.2: Enable timestamping and geotagging of collected data.
- FR1.3: Allow calibration and configuration of sensors remotely.

2. Data Preprocessing and Transmission

Collected sensor data must be filtered, formatted, and transmitted efficiently to a central processing unit or cloud storage.

- FR2.1: Perform noise filtering, missing value handling, and normalization.
- FR2.2: Compress data for low-bandwidth environments.
- FR2.3: Support edge computing for local preprocessing and immediate actions.

3. Blockchain-based Data Auditing

To ensure data integrity and transparency, all data entries must be securely logged on a blockchain ledger.

- FR3.1: Generate cryptographic hashes of each data point or batch.
- FR3.2: Store metadata and hash on a blockchain network (e.g., Ethereum, Hyperledger).
- FR3.3: Enable audit trails to verify data authenticity and origin.
- FR3.4: Provide tamper-proof and immutable records.

4. Data Storage and Management

The system must store high volumes of environmental data securely and in a structured format, allowing easy access and retrieval.

- FR4.1: Store raw data in cloud or distributed file systems (e.g., IPFS, AWS, Azure).
- FR4.2: Link stored data with corresponding blockchain records.
- FR4.3: Ensure redundancy, backup, and recovery mechanisms.

5. Machine Learning-Based Forecasting

The system should apply ML models to analyze historical and real-time data for pattern detection, anomaly identification, and future predictions.

- FR5.1: Support training and deployment of various ML models (e.g., regression, SVM, neural networks, LSTM).
- FR5.2: Automatically update models based on new data (retraining).
- FR5.3: Generate forecasts and classify environmental risk levels.
- FR5.4: Detect anomalies or threshold violations in environmental parameters.

6. User Interface and Visualization

Stakeholders must have access to intuitive dashboards or interfaces for monitoring and decision-making.

- FR6.1: Visualize real-time sensor readings and forecasts.
- FR6.2: Allow access to blockchain audit logs.
- FR6.3: Enable user authentication and role-based access control.
- FR6.4: Provide downloadable reports and alerts.

7. Alerts and Notifications

When environmental thresholds are exceeded or anomalies are detected, the system must notify relevant authorities or users.

- FR7.1: Support real-time notifications via SMS, email, or mobile apps.
- FR7.2: Define custom thresholds for different regions or parameters.
- FR7.3: Log all alerts for future review and analysis.

NON FUCTIONAL REQUIREMENTS

Non-functional requirements (NFRs) define the performance, usability, scalability, and other quality attributes that the smart environmental monitoring system must meet. While functional requirements describe what the system should do, non-functional requirements specify how well it should perform under various conditions to ensure reliability, security, and user satisfaction.

1. Performance and Responsiveness

The system must process and transmit sensor data with minimal delay to ensure real-time monitoring and timely forecasting.

- NFR1.1: Data from IoT sensors should be processed and available for viewing within 5 seconds of collection.
- NFR1.2: Machine learning forecasting should complete processing within an acceptable window (e.g., <30 seconds for short-term forecasts).
- NFR1.3: Blockchain transactions (e.g., hash logging) should be optimized to reduce confirmation latency without compromising security.

2. Scalability

The system must be able to handle increasing volumes of data and a growing number of devices and users without performance degradation.

- NFR2.1: Support scalability from a few to thousands of IoT devices.
- NFR2.2: Handle increased data throughput (e.g., GBs/day) and blockchain transaction load as deployments grow.
- NFR2.3: Allow horizontal scaling of storage, ML models, and blockchain nodes.

3. Security

Given the sensitivity and public impact of environmental data, the system must provide robust security measures to protect against unauthorized access, tampering, and attacks.

- NFR3.1: Ensure end-to-end encryption for data transmission.
- NFR3.2: Implement role-based access control (RBAC) and user authentication mechanisms.
- NFR3.3: Protect blockchain nodes and smart contracts from malicious actors.

4. Data Integrity and Accuracy

Accurate and untampered data is critical for forecasting and public decision-making.

- NFR4.1: Ensure that all data logged in the blockchain matches the original sensor output via hash verification.
- NFR4.2: Prevent data loss during transmission and storage through redundancy and error-checking protocols.
- NFR4.3: Maintain ML model accuracy through regular evaluation and retraining.

5. Reliability and Availability

The system must operate continuously and recover gracefully from failures.

- NFR5.1: Achieve 99.9% system uptime to support 24/7 monitoring.
- NFR5.2: Incorporate failover mechanisms for sensor networks, data servers, and blockchain nodes.
- NFR5.3: Ensure automatic recovery and data restoration after system crashes.

6. Usability and Accessibility

Interfaces must be user-friendly and accessible to various stakeholders including policymakers, researchers, and the general public.

- NFR6.1: Dashboards should present data in a clear, visual format (graphs, maps, alerts).
- NFR6.2: System should support multilingual interfaces and accessibility standards (e.g., WCAG compliance).
- NFR6.3: Minimal training should be required for users to navigate the system effectively.

7. Maintainability and Upgradability

As technology evolves, the system should be easy to maintain, debug, and upgrade without downtime.

- NFR7.1: Use modular architecture for easy component updates (sensors, ML models, blockchain modules).
- NFR7.2: Support logging and monitoring of system health for maintenance teams.
- NFR7.3: Enable version control and rollback for deployed machine learning models and blockchain smart contracts.

VII. CONCLUSION

Environmental monitoring is a critical component in the fight against climate change, pollution, and ecosystem degradation. Traditional monitoring systems, while useful, often face limitations such as centralized data storage, vulnerability to tampering, lack of predictive insights, and inefficient response times. This review explored the convergence of three transformative technologies—Internet of Things (IoT), Blockchain, and Machine Learning (ML)—to create a more intelligent, transparent, and secure environmental monitoring system.

The integration of IoT facilitates the real-time collection of diverse environmental parameters including air quality, temperature, water pollution, and humidity. These sensors provide granular and continuous data from urban, industrial, and remote locations, enabling a more accurate understanding of environmental conditions. However, raw data alone is insufficient without trust and reliability, especially when decisions impacting public policy, health, and industry depend on it.This is where blockchain technology adds value by ensuring the immutability, transparency, and traceability of collected data. By storing hashed records of environmental data on a decentralized ledger, blockchain prevents unauthorized data manipulation, enables reliable audits, and increases stakeholder trust. Its distributed nature also reduces single points of failure, making the system more robust and secure.

Furthermore, the integration of machine learning enhances the system's intelligence by enabling predictive analytics and anomaly detection. ML algorithms can identify patterns and trends in historical and real-time data to forecast future environmental conditions, such as pollution spikes or hazardous weather events. These insights are crucial for proactive decision-making by governments, environmental agencies, and industries.Despite its promise, the integrated system faces challenges related to scalability, interoperability, energy efficiency, and data privacy. Overcoming these issues requires unified frameworks, standardized protocols, and collaboration among technologists, environmental scientists, and policymakers.In conclusion, the fusion of IoT-based sensing, blockchain auditing, and machine learning forecasting presents a powerful paradigm for next-generation environmental monitoring. This approach

enhances data accuracy, integrity, and usability, enabling real-time insights and long-term forecasting capabilities. By addressing current limitations and advancing research in this interdisciplinary field, smart environmental monitoring systems can play a pivotal role in promoting environmental sustainability, public safety, and evidence-based policymaking. Future developments should focus on optimizing system performance, reducing costs, and ensuring accessibility to maximize global impact.

REFERENCES

[1] Internet-of-Things-blockchain integration in environmental pollution monitoring data management: trends and techniques. *International Journal of Environmental Science and Technology*. 2025. SpringerLink

[2] Analysis of Blockchain Adoption in Environmental Monitoring Based on Evolutionary Game. *Mathematics*. Vol 13, Issue 19, 2025. MDPI

[3] Blockchain-secured IoT-federated learning for industrial air pollution monitoring: A mechanistic approach to exposure prediction and environmental safety. (2025) PubMed

[4] Enhancing IoT-Based Environmental Monitoring and Power Forecasting: A Comparative Analysis of AI Models for Real-Time Applications. *Applied Sciences*. 2024. MDPI

[5] Advancements in air quality monitoring: a systematic review of IoT-based air quality monitoring and AI technologies. (2025) SpringerLink

[6] A Secure Blockchain-Assisted Framework for Real-Time Maritime Environmental Compliance Monitoring. arXiv. 2025. arXiv

[7] A Multi-Modal IoT Node for Energy-Efficient Environmental Monitoring with Edge AI Processing. arXiv. 2025. arXiv

[8] Real-time Pollutant Identification through Optical PM Micro-Sensor. arXiv. 2025. arXiv

[9] Environmental Monitoring using Machine Learning and IoT: Applications, Challenges, and Cybersecurity Threats. IJRASET. 2025. IJRASET

[10] Blockchain on Sustainable Environmental Measures: A Review. *MDPI Sustainability / MDPI*. 2024/2025. MDPI

[11] Smart Manufacturing Real-Time Analysis Based on Blockchain and Machine Learning Approaches. *Applied Sciences*. 2021. MDPI

[12] Innovative Pathways in Environmental Monitoring and Advanced Technologies for Sustainable Resource Management. *Environmental Reports*. (review) Environmental Reports

[13] (Related) AI in Climate Change Prediction: Studies comparing ML models and traditional climate models. IJSRET. 2025