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Blockchain-Based Tokenization of Soil-Health Data for Secure Precision Agriculture

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Abstract-- **Precision agriculture increasingly depends on reliable soil-health data to support informed decision-making and sustainable farming. Although IoT-based soil monitoring systems enable continuous data collection, most existing solutions rely on centralized storage, leading to challenges such as data tampering, lack of transparency, and absence of farmer-centric data ownership. To address these issues, this paper proposes a blockchain-based soil-health data tokenization framework for precision agriculture. In the proposed approach, real-time soil parameters including moisture, temperature, pH, and nutrient indicators are collected using IoT sensors and validated at a backend server. Each validated soil-health record is tokenized using blockchain smart contracts, ensuring immutability, traceability, and secure ownership. Tokenization enables farmers to maintain control over their soil data while allowing permission-based sharing with agricultural experts and service providers. Extensive experimental analysis demonstrates stable sensor performance, efficient token creation, minimal latency, and strong data integrity guarantees. The proposed system enhances trust, transparency, and security in precision agriculture and establishes a foundation for future decentralized agricultural data ecosystems.**

Keywords-- **Precision agriculture, soil-health monitoring, blockchain, data tokenization, smart contracts, IoT security**

I. Introduction

Soil health directly influences crop productivity, water utilization, fertilizer efficiency, and environmental sustainability. Traditional soil-testing methods are often manual, time-consuming, and infrequent, making them unsuitable for modern precision agriculture. IoT-enabled soil monitoring systems address these limitations by providing continuous, real-time measurements of key soil parameters.

Despite these advancements, most deployed systems store soil data in centralized cloud servers. Such architectures introduce risks related to data integrity, unauthorized modification, lack of transparency, and limited ownership for farmers. Moreover, farmers rarely have control over how their data is accessed or monetized.

Blockchain technology provides a decentralized and tamper-resistant data management paradigm. By combining IoT-based sensing with blockchain-based tokenization, this work introduces a secure and farmer-centric soil-health monitoring framework that ensures data integrity, ownership, and controlled sharing.

II. Related Work

Existing research on precision agriculture has focused extensively on IoT-based soil monitoring, wireless sensor networks, and cloud-based analytics. Recent studies have also explored blockchain adoption in agriculture, primarily for supply chain traceability and food provenance.

However, limited attention has been given to soil-health data ownership and secure data sharing mechanisms. Most blockchain-based agricultural systems store only transaction records, while soil data remains vulnerable in off-chain databases. This work differentiates itself by introducing a structured soil-health data tokenization model that enforces ownership, traceability, and access control at the data level.

TABLE 1:
COMPARISON OF EXISTING AGRICULTURAL DATA MANAGEMENT APPROACHES

Approach	**Data Integrity**	**Farmer Ownership**	**Decentralization**	**Security Level**
Centralized Cloud	Medium	No	No	Medium
IoT + Cloud	Medium	Partial	No	Medium
Blockchain Supply Chain	High	Limited	Partial	High
Proposed Tokenized Model	**Very High**	**Yes**	**Yes**	**Very High**

The table highlights the advantages of the proposed tokenized soil-health data framework over existing approaches.

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III. System Architecture Overview

The proposed system integrates IoT sensing, backend validation, and blockchain-based tokenization in a layered architecture.

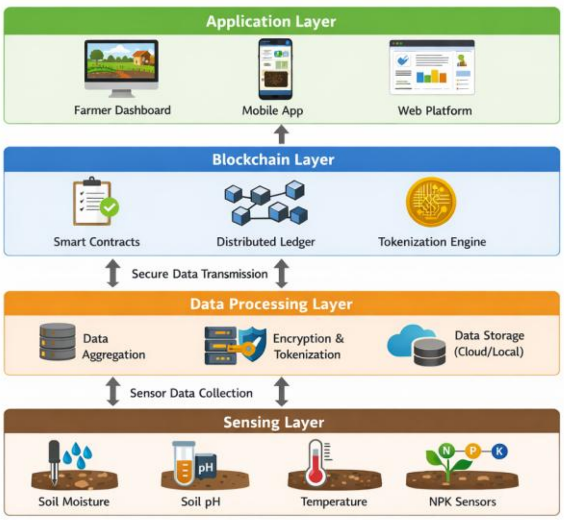

FIGURE 1: LAYERED ARCHITECTURE OF THE PROPOSED SYSTEM

The architecture consists of four layers: (i) sensing layer with soil sensors, (ii) communication layer for data transmission, (iii) application layer for data processing, and (iv) blockchain layer for token storage and access control.

**TABLE 2:
FUNCTIONAL DESCRIPTION OF SYSTEM LAYERS**

Layer	Components	Function
Sensing Layer	Soil sensors, MCU	Collect real-time soil data
Communication Layer	Wi-Fi/GSM	Transmit data securely
Application Layer	Flask server, DB	Validation and preprocessing
Blockchain Layer	Smart contracts	Tokenization and ownership

IV. Soil-Health Data Tokenization Model

Tokenization converts each validated soil-health record into a digital asset on the blockchain. Instead of storing raw data on-chain, cryptographic hashes and metadata are recorded, ensuring scalability and privacy.

Token Generation Process:

1. Sensor data acquisition
2. Backend validation and normalization
3. Hash generation
4. Token creation via smart contract
5. Token storage and ownership assignment

**TABLE 3:
SOIL-HEALTH TOKEN STRUCTURE**

Field	Description
Token ID	Unique identifier
Sensor ID	Source of data
Timestamp	Time of capture
Data Hash	Integrity verification
Owner Address	Farmer wallet

V. Smart Contract Design

Smart contracts automate the token lifecycle and enforce access control policies. Each contract is deployed on an Ethereum-compatible blockchain.

Core Smart Contract Operations:

- Register soil data token
- Verify token ownership
- Grant or revoke access
- Audit transaction history

**TABLE 4:
SMART CONTRACT FUNCTIONS AND PURPOSE**

Function	Purpose
createToken()	Generate new soil-data token
verifyOwner()	Confirm data ownership
grantAccess()	Enable controlled sharing
revokeAccess()	Restrict unauthorized access

VI. Implementation Details

The prototype system was implemented using commercially available soil sensors connected to a microcontroller. A Flask-based REST API server handled data validation and storage. Blockchain integration was achieved using a private Ethereum network.

**TABLE 5:
IMPLEMENTATION ENVIRONMENT**

Component	Technology Used
Sensors	Moisture, Temperature, pH
Backend	Flask, REST APIs
Database	MongoDB
Blockchain	Ethereum, Ganache
Interface	Web3.js

VII. Experimental Results And Analysis

Experiments were conducted over multiple days under controlled field conditions.

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TABLE 6:
STATISTICAL ANALYSIS OF SOIL SENSOR READINGS

Parameter	Min	Max	Mean	Std. Dev
Moisture (%)	27	69	47.8	6.4
Temperature (°C)	21	36	29.1	3.8
pH	5.8	7.5	6.7	0.5

TABLE 7:
BLOCKCHAIN TOKEN PERFORMANCE METRICS

Metric	Observed Value
Avg. Token Creation Time (ms)	790
Avg. Confirmation Time (s)	2.2
Transaction Failure Rate (%)	0

TABLE 8:
SECURITY AND INTEGRITY EVALUATION

Aspect	Observation
Data Tampering	Not possible
Unauthorized Access	Blocked
Traceability	Complete

VIII. Discussion

The results confirm that blockchain-based tokenization significantly enhances soil-data security and trust. Farmers gain explicit ownership of their data, while token-based access control supports transparent collaboration. The modular design also allows future integration with AI-based analytics and agricultural advisory services.

IX. Conclusion And Future Work

This paper proposed a blockchain-enabled tokenization framework for soil-health monitoring in precision agriculture. By integrating IoT sensing, backend validation, and smart contracts, the system ensures secure, transparent, and farmer-centric data management. Experimental analysis demonstrates efficient performance and strong integrity guarantees.

Future work will focus on large-scale deployment, AI-driven soil health prediction, and the development of a decentralized agricultural data marketplace.

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