

AgriTrustChain: A Decentralized Certification and Edaphic Data Traceability Framework with Zero-Leak for Sustainable Farming Using Blockchain

Wafa Ben Slama Souei¹^a, Mohamed Amine Hattab¹, Layth Sliman²^b, Raoudha Ben Djemaa¹^c,
and Faiza Khebour Allouche³^d

¹University of Sousse, ISITCOM, Sousse, Tunisia

²Paris Pantheon-Assas University, Efrei Research Lab, Villejuif, France

³University of Sousse, High Institute of Agronomic Science of Chott Mariem, Sousse, Tunisia

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Abstract: Agriculture relies heavily on the storage and management of Electronic Land Records (ELRs), which are usually maintained in centralized datacenters and shared among farmers, government agencies, and soil experts. However, these traditional storage methods suffer from several limitations, including risks of tampering, unauthorized disclosure of confidential data, and challenges in efficient data retrieval caused by inconsistent formats across institutions. Centralized systems are also vulnerable to fraudulent activities, such as falsification of soil information and land certifications, manipulation to secure unjustified subsidies, and non-compliant export operations. These infractions lead to significant financial losses for governments, distort agricultural funding distribution, undermine the credibility of certification frameworks, and can result in restrictive trade measures or penalties. To overcome these challenges, this work proposes AgriTrustChain, a blockchain-based platform that enables the secure storage and retrieval of Electronic Land Records (ELRs), including terrain and soil data as well as the Normalized Difference Vegetation Index (NDVI). This facilitates enhanced interoperability among diverse agricultural institutions. All land-related information is extracted from the blockchain and displayed in real time through an interactive map. Additionally, it provides a reliable mechanism to generate land certificates based on the NDVI for agricultural land suitable for planting olive trees. Our platform leverages IPFS, interactive soil visualization, and NFT-based certification to enable secure, transparent, and efficient agricultural land certification. The evaluation confirms that AgriTrustChain securely protects land and soil information, ensuring zero data leakage in soil data management while providing a reliable solution for modern agricultural data handling.

1 INTRODUCTION

Modern agriculture is increasingly shaped by the need for sustainability, transparency, and intelligent data utilization (Sangha, 2014). Among the core components of digital agriculture are Electronic Land Records (ELRs), which store critical information about land and soil properties, particularly edaphic characteristics that influence crop suitability. These records are essential for stakeholders such as farmers, regulatory authorities, soil experts, and institutional

partners, who rely on them for decision-making, land certification, and policy enforcement (Pretty et al., 2001). However, traditional ELR systems are typically managed through centralized data centers, making them vulnerable to unauthorized access, data leakage, and tampering. Additionally, inconsistencies in data formats across agricultural institutions hinder efficient information retrieval and sharing. These limitations not only reduce the operational efficiency of agricultural systems but also open the door to fraudulent practices—including the falsification of soil certificates (Manning and Kowalska, 2021a)(Mukome et al., 2013) (Awasthi, 2024), and unjustified claims for agricultural subsidies ((OLAF), 2021). Such misuse leads to significant financial losses (Camp-

^a <https://orcid.org/0000-0002-9133-3112>

^b <https://orcid.org/0000-0003-3369-7302>

^c <https://orcid.org/0000-0002-7831-112X>

^d <https://orcid.org/0000-0002-7544-5421>

bell, 2024), (Manning and Kowalska, 2021b), disrupts fair distribution of agricultural aid (Décodeurs, 2022), and undermines trust in certification frameworks (Roberts and Bryant, 2006). However, despite the progress made, most existing blockchain-based solutions for agriculture remain limited in scope and adaptability. Many focus solely on product traceability within supply chains (Sarpong, 2014), neglecting the certification of land eligibility (Tuunanen, 2024), (Tian, 2016) and the integration of edaphic data into decision-making processes (Kamilaris et al., 2019), (Kshetri, 2018). Additionally, several approaches lack support for flexible data querying (Kim and Laskowski, 2018), are not tailored to specific crop requirements—such as olive cultivation—and often fail to ensure the privacy of sensitive land and farmer data. Furthermore, the absence of standardized mechanisms for verifying soil analysis provenance compromises data reliability (Even et al., 2025). Existing platforms also tend to overlook the regulatory and environmental compliance dimension (Theocharopoulos et al., 2001), making it difficult to align certifications with national or international sustainability standards.

These limitations highlight the need for a comprehensive, secure, and intelligent framework that not only leverages blockchain's immutability and transparency but also integrates domain-specific knowledge, supports fine-grained traceability, and facilitates stakeholder collaboration through verifiable and tamper-proof digital certifications (Yang et al., 2021). This research work aims to address key challenges in the secure management and certification of agricultural land data. The primary objective is to design and implement a blockchain-based platform that allows the secure sharing of agricultural data, with a particular focus on soil information and land suitability for olive planting.

Our first goal is to establish a decentralized system that ensures:

- Full traceability of soil data, including the Organic Matter (OM), Electrical Conductivity (EC), Hydrogen Potential (pH) and Bicarbonate organized by soil depth (0-20 cm, 20-40 cm, 40-60 cm). In addition to the Normalized Difference Vegetation Index (NDVI) of land.
- Reliable and secure data access for farmers to support informed decision-making and optimize plantation strategies based on the NDVI;
- Proof of data integrity through the immutability and transparency offered by blockchain technology;

- And efficient, trusted sharing of shared data among key stakeholders such as farmers, researchers, and institutional partners.

Our second goal is to enable the digital certification of land eligibility for olive cultivation in a transparent, tamper-proof, and verifiable manner, based on the Normalized Difference Vegetation Index (NDVI). The generated certification will be stored on the blockchain and made accessible to diverse stakeholders.

To address these challenges, we introduce AgriTrustChain—a permissioned blockchain-based framework specifically designed for the management and certification of ELRs. AgriTrustChain aims to provide data security, privacy preservation, traceability, and non-falsifiability through a modular and scalable architecture. It includes flexible data storage and retrieval using IPFS (InterPlanetary File System), enhancing interoperability and usability across heterogeneous systems. Furthermore, AgriTrustChain integrates a blockchain-based digital certification mechanism that leverages NFTs (Non-Fungible Tokens) to represent unique land suitability certificates for olive cultivation. These NFTs link to detailed edaphic parameters stored securely and immutably on IPFS, ensuring provenance and data integrity. This approach guarantees transparent, tamper-proof certification aligned with validated soil analysis and sustainability standards. The use of NFTs enables easy verification, transfer, and tracking of land certifications on the Ethereum blockchain, while off-chain agronomic rules are applied through a dedicated validation engine.

The remainder of the paper is organized as follows. Section 2 provides background information on blockchain and smart contracts. Section 3 discusses how these technologies can be leveraged in the agricultural sector. Section 4 presents the proposed solution and describes the architecture of the AgriTrustChain platform. Section 5 outlines the implementation details and reports the experimental results. Finally, Section 6 concludes the paper and highlights potential directions for future work.

2 BACKGROUNDS

This section presents an overview of blockchain technology and smart contracts, emphasizing their significance in the agricultural sector.

2.1 Blockchain Technology

A blockchain is a decentralized digital ledger that records transactions in sequential blocks (Ben Slama Souei et al., 2021),(Abdelhamid et al., 2024). These blocks are stored across numerous nodes, with each node representing a copy distributed over multiple computers. The system ensures security by cryptographically linking each new block to the one before it, making tampering virtually impossible (Di Pierro, 2017). Unlike traditional systems, it does not rely on a central authority, such as a bank, for management or oversight. As new transactions occur, all nodes in the network automatically receive the updated version of the ledger (Nofer et al., 2017).

2.2 Smart Contract

Multiple blockchain platforms (Kuo et al., 2019), such as Bitcoin, Ethereum, and Hyperledger, support the development and deployment of smart contracts. As defined in, a smart contract is essentially a code module that operates on a blockchain (Zou et al., 2019). It is referred to as a "contract" because it represents an agreement whose logic governs the control and exchange of digital assets, tokens, or services. A smart contract acts as a software entity that offers services through the blockchain by embedding a specific sequence of transactions, which are triggered either by predefined events or by explicit calls from network nodes (Souei et al., 2023).

Smart contracts enable secure and automated interactions between untrusted and anonymous participants, eliminating the need for centralized authorities, legal frameworks (Hamdi et al., 2025), or third-party enforcement. Additionally, they enhance the integrity of transactions by ensuring they are transparent, verifiable, and irreversible (Mohanta et al., 2018).

The lifecycle of a smart contract consists of two main phases: the off-chain development phase, where the contract is designed and coded, and the on-chain execution phase, where the contract is deployed and triggered within the blockchain environment (Souei et al., 2023).

Beyond cryptocurrencies, Smart contracts have found applications across a wide range of domains, offering automation, transparency, and trust in decentralized environments. In the healthcare sector, projects such as MedRec (Ekblaw et al., 2016) leverage smart contracts for secure and interoperable management of medical records (Lee et al., 2022). In supply chain management, based on blockchain trusted platforms (IBM, 2025) uses smart contracts to enhance traceability and product safety

by recording transactions on the blockchain, (Bhat et al., 2021),(Ghannem et al., 2024),(Vasanthraj et al., 2025). The energy sector has also seen adoption through peer-to-peer energy trading platforms like Power Ledger(Powerledger, 2025), which use smart contracts to automate energy exchanges between consumers and producers. Moreover, in agriculture, smart contracts support transparent subsidy distribution (Xiong et al., 2020) and crop insurance automation (LB, 2022), as demonstrated in initiatives like AgUnity (AgUnity Pty Ltd, 2025). These applications highlight the transformative potential of smart contracts across multiple sectors, as noted in recent surveys and systematic reviews (Xu et al., 2019),(Casino et al., 2019).

3 RELATED WORKS

In this section, we highlight how blockchain and smart contracts can be leveraged in the agricultural sector. The integration of blockchain technology and smart contracts into the agricultural sector offers promising solutions to long-standing challenges such as traceability, transparency, and trust among stakeholders.

Blockchain ensures secure and immutable recording of transactions and data, making it ideal for tracking the origin and movement of agricultural products throughout the supply chain (Demestichas et al., 2020). The work proposed by (Chun-Ting et al., 2020) presents a blockchain-based platform using Ethereum to ensure trustworthy farm-to-fork traceability of agricultural products. The platform utilizes blockchain technology, specifically Ethereum, to securely store and manage data collected from IoT sensors throughout the agricultural supply chain. It employs smart contracts to automate financial transactions and enforce trustworthiness, ensuring data integrity, transparency, and traceability from farm to fork. The paper authored by(Hua et al., 2018) expose a new distributed, peer-to-peer system designed for agricultural product provenance. This approach aims to improve food safety, reduce costs, and build trust across the whole supply chain. The system maintains a shared, ledger-based record of farming activities, transportation, and handling processes, providing transparency, data integrity, and trust among all participants.

Smart contracts, as self-executing programs deployed on the blockchain, automate agreements between parties, reducing the need for intermediaries and ensuring that terms are enforced without human intervention. The work (Hua et al., 2018) primar-

ily concerns agreements related to the production, processing, and distribution of agricultural products. These agreements include, but are not limited to, compliance with standards such as organic or green certifications, proper usage of fertilizers and pesticides, quality testing, and traceability of operations like fertilization, irrigation, and testing procedures. The work proposed by (Vangala et al., 2022) explores enhancing precision agriculture through the integration of blockchain and mobile vehicles in IoT environments. It introduces AgroMobiBlock, an authenticated key agreement scheme that ensures secure data exchange. By leveraging elliptic curve cryptography on hybrid blockchains, the approach minimizes computational and communication overhead.

These technologies can enhance efficiency in processes such as land certification, where systems based on smart contracts are adopted (Roberts and Bryant, 2006) to generated trusted certification. Each certificate is commonly represented as a Non-Fungible Token (NFT) (Colamartino et al., 2025), ensuring its uniqueness and traceability (Ramirez Lopez and Morillo Ledezma, 2025),(Rao et al., 2025). To handle storage of large files such as PDF documents, decentralized storage solutions like the InterPlanetary File System (IPFS) are employed. IPFS generates a Content Identifier (CID), a cryptographic hash that uniquely references the content off-chain (Enaya et al., 2025). In addition, many crop insurance based blockchain platforms are proposed in literature (Vasanthraj et al., 2025), (Eswaran et al., 2025). These platforms leverage blockchain's features to improve transparency, trust, and efficiency in the crop insurance process (Liu et al., 2025). Furthermore, Blockchain technology is increasingly utilized to build transparent and tamper-proof systems for product authentication (Aissaoui et al., 2025),(Cordeiro and Ferreira, 2025) and fair trade compliance (Owsianowski and Bitsch, 2025). By recording product origins, manufacturing processes, and supply chain movements on an immutable ledger, stakeholders can verify the authenticity and ethical sourcing of goods. The work proposed by (Tegeltija et al., 2022) presents the SAFE platform that addresses the challenges of organic agriculture certification by streamlining administrative processes for producers and enhancing consumer trust through blockchain-based data security. the SAFE platform (Tegeltija et al., 2022) collects sensor data directly from the fields to support certification, ensuring that information remains tamper-proof. Furthermore, it is fully aligned with organic food legislation to guarantee compliance and legitimacy (Rao et al., 2025).

By enabling real-time data sharing and reducing the risk of fraud or data manipulation, blockchain and smart contracts are transforming agriculture into a more transparent, reliable, and sustainable domain.

4 AGRITRUSTCHAIN PLATFORM

This research focuses on the development of the AgriTrustChain platform. AgriTrustChain allows;

- The storage of land and soil data on the blockchain based on IPFS;
- The real-time retrieving of land and soil data from the blockchain and displaying it on an interactive cart.
- The generation of land certification is automatically triggered on the smart contract and NFT. Information of certifications will be stored using IPFS and retrieved through the interactive cart.

As illustrated in Figure 1, the AgriTrustChain platform's architecture is designed to enable secure, transparent, and efficient data management and certification processes within the agricultural ecosystem. The architecture of the AgriTrustChain platform is

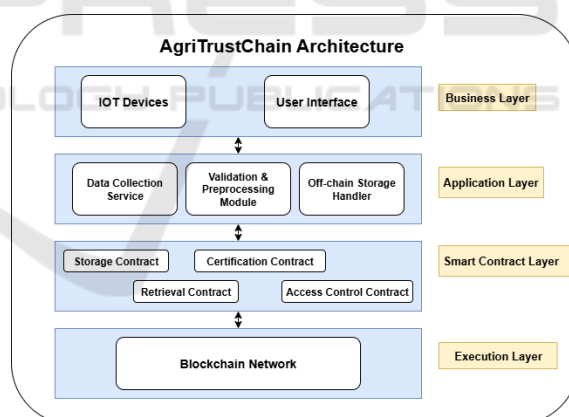


Figure 1: Architecture of the AgriTrustChain platform.

based on a layered design, comprising four essential layers.

1. **Business Layer:** it is the interface between end-users and the system, handling data input, visualization, and interaction. It serves both human and machine actors, ensuring seamless communication with the underlying platform. It is composed of two components. The first is called the IoT Devices component, and encapsulates physical sensors deployed in agricultural environments that capture real-time data such as soil electrical

conductivity, organic matter, pH and bicarbonate levels, and GPS location. It enables automated, trustworthy, and timely data acquisition. The second is called User Interface (UI). It is a web application that provides stakeholders with access to the system. Users can visualize the stored data displayed on an interactive cart and access the certifications.

This layer facilitates the usability and accessibility of our decentralized systems. It links cyber-physical systems (IoT) with blockchain via intuitive interfaces.

2. **Application Layer:** it decouples computation-intensive and non-transactional operations from the blockchain, improving scalability and performance. It orchestrates data flows between the business and smart contract layers. It is composed of three components. Firstly, the **Data Collection Service**, this module aggregates raw data from IoT devices and manual inputs, performs data normalization, unit conversion, and preliminary validation before it is passed to certification logic. Secondly, **Validation and Preprocessing Module** that applies rule-based methods to assess whether data meets predefined agricultural standards. Thirdly, the *Off-chain Storage Handler* is responsible for storing large and non-sensitive data in decentralized file systems called IPFS, and recording only their cryptographic hashes on-chain to ensure immutability.
3. **Smart Contract Layer:** it comprises the on-chain logic and rules that enforce certification, access control, and data storage in a secure and decentralized manner. This layer integrates a set of smart contracts, each serving a distinct purpose. **The Storage Contract** enables the storage of processed data or IPFS hash pointers on the blockchain, providing immutable references for future verification. **The Retrieval Contract** displays the stored data of terrains and soil on an interactive cart. The stored data include the Organic Matter (OM), Electrical Conductivity (EC), Hydrogen Potential (pH), and Bicarbonate, organized by soil depth (0-20 cm, 20-40 cm, 40-60 cm) based on the land's GPS coordinates. In addition to the Normalized Difference Vegetation Index (NDVI) of each terrain. **The Certification Contract** encodes domain-specific rules and issues tamper-proof digital certificates upon compliance. Finally, the **Access Control Contract** leverages Decentralized Identity (DID) systems and verifiable credentials to enforce role-based permissions, ensuring that only authorized entities can issue or visualize data.

4. **Execution Layer:** The foundation of the entire architecture, this layer is responsible for executing transactions, maintaining consensus, and securing data permanence. It is composed *the Blockchain Network* where smart contracts are deployed and transactions are confirmed. It ensures data integrity, fault tolerance, and consensus.

Agritrustchain allows the collection, analysis, and sharing of agricultural data on the blockchain. Furthermore, it generates digital certifications of the eligibility of agricultural land for olive tree cultivation in a transparent and tamper-proof manner.

5 IMPLEMENTATION AND EXPERIMENTS

In this section, we present the implementation details of the AgriTrustChain platform. In addition, we describe a series of experiments conducted to evaluate the effectiveness and correctness of our proposed solution. Figure 9 exposes the software architecture of our platform, where the flow of data is exposed to illustrate the main purpose of our solution.

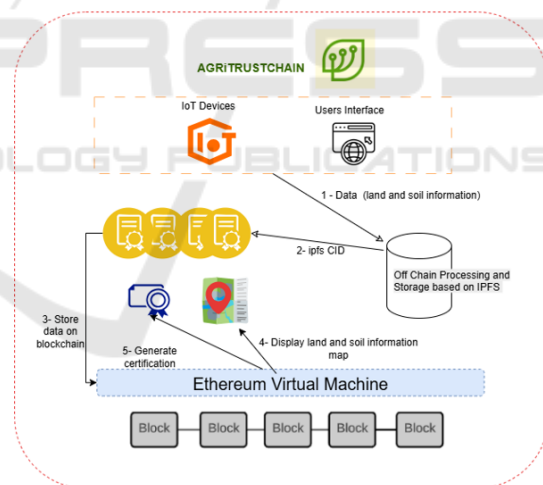


Figure 2: The software architecture of AgriTrustChain.

5.1 Implementation Details

The proposed architecture has been designed to enable transparent, secure storage and retrieval of land and soil information. In addition, it enables the automated certification of agricultural land using blockchain technology, IoT integration, off-chain storage, and privacy-preserving computation. The implementation of this architecture involves a synergy of decentralized technologies and conventional system engineering practices across four layers.

5.1.1 Business Layer: Human and Device Interaction

The Business Layer is composed of two components. First, the *IoT Devices component* that encapsulates sensors that collect real-time environmental and soil data. The sensors used include pH probes, electrical conductivity meters, GPS modules, visible and near-infrared (VIS-NIR) spectrometers, and ion-selective electrodes. These devices are programmed using Arduino microcontrollers and communicate with a central gateway via HTTP protocols. The NDVI data are extracted from satellite imagery to assess vegetation health and land eligibility. Second, the *User Interface component* A ReactJS-based web application allows users to register land plots, submit data from IoT or manual inspections, and view issued certificates. For user authentication, we chose to handle it using Decentralized Identifiers (DIDs) compliant with the W3C standard through Ceramic Network platforms.

5.1.2 Application Layer: Off-Chain Intelligence and Preprocessing

The application Layer is responsible for reducing on-chain computation and enhancing scalability via its three components.

1. The Data Aggregation Component is implemented as a lightweight Node.js server that acts as the entry point for collecting, validating, and preprocessing agricultural soil data collected from both IoT gateways and user input interfaces. Built with Express.js, the server exposes a RESTful endpoint (/api/submit) where incoming data is received in JSON format. Upon reception, the server invokes a dedicated validation module that checks the consistency, type, and range of critical parameters such as pH, bicarbonate levels (mg/L and meq/L), electrical conductivity (salinity), and organic matter percentage (MO). If the data is valid, it is timestamped, normalized, and stored temporarily in an in-memory data store for further use. This module plays a crucial role within the Application Layer of the decentralized architecture by bridging raw input with intelligent off-chain validation mechanisms. Figure 3 exposes a snippet of code of the validator in the node.js server.
2. The Validation Engine Component is a modular and extensible Java-based rule engine that encapsulates the domain-specific business logic for evaluating the suitability of agricultural land—particularly for olive tree planting. This component operates at the Application Layer of

```

1 export function validateSoilData(data) {
2   const errors = [];
3
4   // Validate pH
5   if (typeof data.pH !== "number" || data.pH < 3 || data.pH > 10) {
6     errors.push("Invalid pH value");
7   }
8
9   // Validate bicarbonate
10  if (typeof data.bicarbonateMg !== "number" || data.bicarbonateMg < 0) {
11    errors.push("Invalid bicarbonateMg");
12  }
13
14  if (typeof data.bicarbonateMeq !== "number" || data.bicarbonateMeq < 0) {
15    errors.push("Invalid bicarbonateMeq");
16  }
17
18  // Validate salinity
19  if (typeof data.ce !== "number" || data.ce < 0) {
20    errors.push("Invalid salinity (CE)");
21  }
22
23  // Validate organic matter
24  if (typeof data.mo !== "number" || data.mo < 0 || data.mo > 100) {
25    errors.push("Invalid organic matter (MO)");
26  }
27
28  return {
29    valid: errors.length === 0,
30    errors
31  };
32 }
33

```

Figure 3: Snippet code of validator in the node.js server.

the decentralized platform, specifically within the Off-Chain Intelligence and Preprocessing sub-layer. It encodes expert-verified agronomic thresholds—such as the acceptable range for NDVI as rule conditions that are programmatically evaluated. When land data is received, the engine validates each parameter, determines its compliance status, and compiles a structured evaluation report. The output is serialized to JSON, hashed for blockchain anchoring. Designed for interoperability, the engine ensures that only compliant and traceable data proceeds to the smart contract layer, reinforcing the platform's integrity and trustworthiness.

3. The Off-Chain Storage Module is a key component of the decentralized application's Application Layer, responsible for storing detailed land and soil data in a secure and tamper-proof manner using IPFS. Implemented in Node.js, this module leverages services like Web3.Storage, which abstracts and simplifies interaction with the IPFS network and Filecoin storage layer. Upon receiving a file, the module first validates and formats it, then uploads it to IPFS using the Web3.Storage API. Once the upload is successful, the system returns a Content Identifier (CID)—a unique hash representing the content. This CID serves as a permanent and verifiable reference to the stored data and is later anchored on-chain in a smart contract. By separating large or rich data from the blockchain and storing only the CID on-chain, the module maintains scalability while guaranteeing the authenticity of off-chain resources. Figure 4 exposes a JSON validation report on the console generated by the Application Layer.

```
{
  "location": "Farm 001",
  "pH": 7.1,
  "mo": 2.3,
  "ce": 1.8,
  "bicarbonateMgl": 180,
  "suitable": true,
  "validatedAt": "2025-07-22T08:30:00Z"
}
```

Figure 4: Validation report generated by the Application Layer.

5.1.3 Smart Contract Layer: Certification Logic and Storage

The smart Contract Layer is composed of four smart contracts. Smart contracts are developed using Solidity and deployed on a permissioned Ethereum-compatible blockchain, ensuring transparency and immutability while maintaining governance and access control. It consists of four main smart contracts:

- **Storage Contract.** This contract store metadata and content hashes (CIDs) from IPFS onto the blockchain. Each data set is represented by a hash and associated metadata. An example of the data set used is available online.¹ This ensures the verifiability and integrity of off-chain data without overloading the blockchain. Furthermore, it minimizes gas consumption by recording only lightweight transactions instead of large data-heavy ones.
- **Certification Contract (NFT-Based).** This contract implements the certification logic. When a plot of land meets the eligibility criteria (validated off-chain), a non-fungible token (NFT) is minted to serve as a digital certificate. The NFT adheres to the ERC-721 standard, ensuring uniqueness and traceability. The full implementation of this contract is available online². The certificate includes:
 - Link to the off-chain PDF report (IPFS hash),
 - land information,
 - Certification metadata (e.g., MDVI, eligibility status).

This NFT acts as an immutable, verifiable, and transferable proof of compliance and can be used in audits or loan/insurance applications.

¹<https://github.com/MedAmine221/NDVI-Certificates-Blockchain/tree/main/certificates>

²<https://github.com/MedAmine221/NDVI-Certificates-Blockchain>

- **Access Control Contract.** Security is enforced through a role-based access model. It uses Solidity's AccessControl features to assign roles like Farmer_ROLE and ADMIN_ROLE.

- **Retrieval Contract.** The Retrieval Contract provides read-only access to stored data. This contract allows:
 - The visualization of stored land and soil information on an interactive map using GPS coordinates,
 - The access to the generated certification, lands are linked to a PDF certificate if their NDVI falls within the acceptable range.

These smart contracts are developed and tested using the Truffle framework, and their state is verified using Etherscan tools.

5.1.4 Execution Layer: Blockchain and Network Infrastructure

The Execution Layer serves as the core trust engine of the AgriTrustChain platform. This layer is exposed in Figure 5 and leverages a private Ethereum blockchain, smart contracts written in Solidity, and a decentralized storage system (IPFS) to provide verifiable, tamper-proof certification records. Our smart contracts are deployed on the Ethereum blockchain. A PoA (Proof-of-Authority) private Ethereum network is set up with validators representing different stakeholders. Smart contracts are optimized using Solidity features like struct packing, mapping-based data access, and off-chain computation to minimize gas usage.

5.2 Experiments

In this section, we will expose the experimental setup and results.

5.2.1 Experimental Setup

We deployed the AgriTrustChain platform on a local private Ethereum network using Geth configured with PoA consensus. Table 1 exposes technical Infrastructure of the AgriTrustChain Platform.

5.2.2 Test Case Scenarios

To validate the AgriTrustChain platform, we designed experiments focusing on its main functionalities: (1) the decentralized storage of land and soil data, (2) real-time retrieval and visualization on an interactive map, and (3) automated certification generation using NFTs.

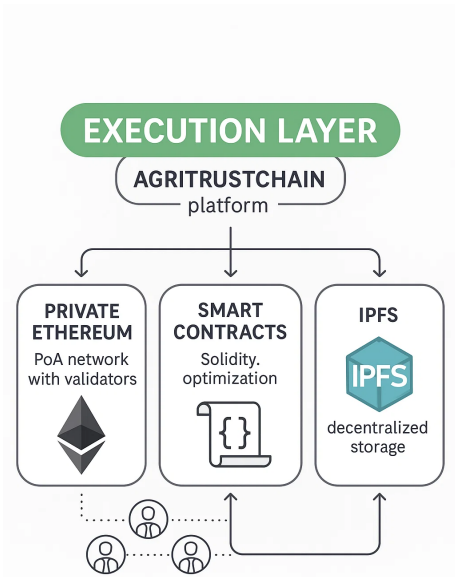


Figure 5: AgriTrustChain Execution Layer.

Table 1: Technical Infrastructure of the AgriTrustChain Platform.

Component	Details
Blockchain Network	3 validator nodes (Ministry, certifier, expert), 1 client (farmer)
Smart Contracts	Deployed via Hardhat
Frontend	ReactJS + MetaMask
Backend	PHP or Java via web3.php
Off-chain Storage	IPFS via web3.storage
Testing Wallets	Generated with MetaMask

- Scenario 1: Storage of Land and Soil Data on Blockchain with IPFS.** The objective of this scenario is to verify that land and soil data can be securely stored on IPFS and its reference immutably recorded on the blockchain. Figure 9 presents a screenshot of the front-end interface of the Storage Contract, where stakeholders can submit data through the form, which is then automatically displayed on the interactive map in real time. **Steps:**
 - A farmer submits land coordinates and soil data (pH, EC, GPS, organic matter) via the React frontend.
 - The backend uploads the data file to **IPFS** and obtains the corresponding **CID**.
 - The backend invokes the smart contract function `storeSoilData` to save the CID and meta-

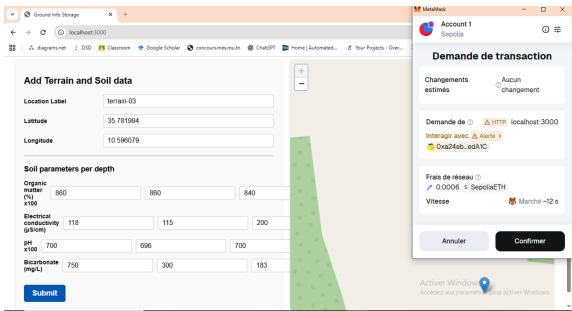


Figure 6: Screenshot of the front-end interface of the Storage Contract.

- data on-chain.
- The contract emits a `SoilDataStored` event.
- Table 2 exposes key Metrics of the Storage of Land and Soil Data on Blockchain with IPFS Process. **Metrics Measured:**

Table 2: Key Metrics of the Storage of Land and Soil Data on Blockchain with IPFS Process.

Metric	Value
Gas Cost (Storage)	~ 100,000 units
IPFS Upload Time	≤ 2 seconds
Event Emission Rate	100%

2. Scenario 2: Real-Time Retrieval and Interactive Map Visualization.

The objective of this scenario is to ensure accurate retrieval of stored land and soil data from the blockchain and its visualization on an interactive map. Figure 7 illustrates an example of our interactive map, where NDVI data is retrieved from the blockchain and displayed in real time.

Procedure:

- The React frontend queries the blockchain for soil data using the land ID.
- The platform fetches the corresponding IPFS CID and retrieves the full data file.
- The data is processed and displayed on an **interactive map** with soil layers (pH, EC, NDVI).
- The user can select or filter data points on the map.

Table 3 exposes key metrics of data retrieval and visualization. **Metrics Measured:**

- Scenario 3: Automated Certification and NFT Generation.** The objective of this senario is to validate that the certification process is automatically triggered and the certificate is issued as an NFT stored with IPFS metadata. Figure 9 illustrates our interactive maps, where a marker of a

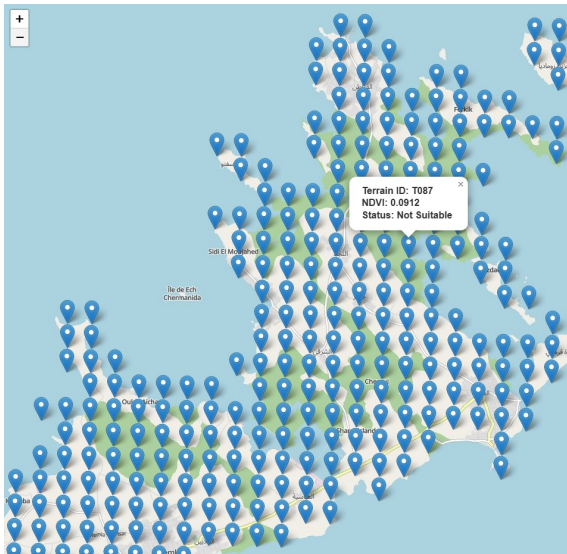


Figure 7: Blockchain-Based NDVI Data Visualization on an Interactive Map.

Table 3: Key Metrics of Data Retrieval and Visualization.

Metric	Value
Blockchain Query Time	≤ 1.5 seconds
IPFS Retrieval Time	≤ 1.5 seconds
Map Rendering Time	≤ 1 second
Data Accuracy	100% match with input

suitable land contains a button that opens the PDF certification.

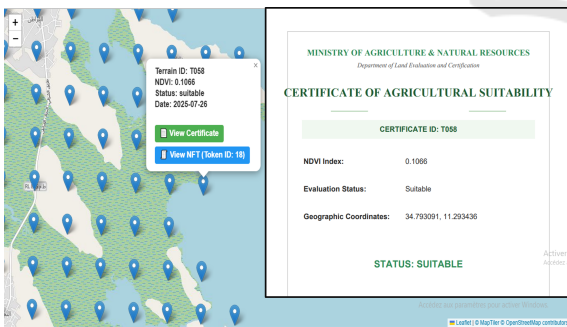


Figure 8: Interactive Map Displaying Markers with Online PDF Certifications.

Procedure:

- The platform analyzes NDVI data based on pre-defined eligibility rules.
- If the land meets the criteria, the smart contract function `generateCertification` is triggered.
- The contract mints a **Soulbound NFT** contain-

ing certification metadata (land ID, owner address, NDVI value, IPFS CID).

- The certification appears on the interactive map and can be verified publicly in a PDF format.

Table 4 exposes keys metrics for certification and NFT generation.

Metrics Measured:

Table 4: Keys Metrics for Certification and NFT Generation.

Metric	Value
NFT Minting Time	≤ 5 seconds
Gas Cost (Minting)	$\sim 150,000$ units
Certification Retrieval	≤ 2 seconds
Integrity Verification	100% success

Figure 9 depicts the interactive maps, where each terrain marker provides detailed soil data information.

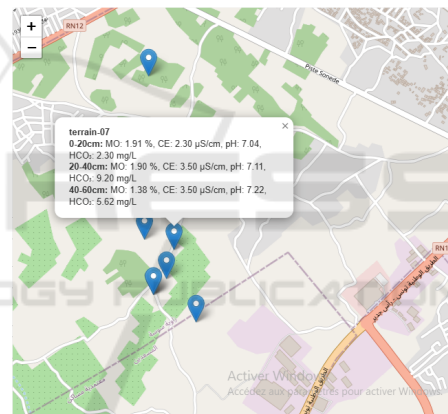


Figure 9: Terrain soil data displayed on a carte.

5.2.3 Discussion

The experimental evaluation of AgriTrustChain demonstrated its efficiency, security, and transparency for decentralized agricultural certification. Table 5 exposes a Summary of experimental results for AgriTrustChain platform. Data storage on IPFS and anchoring on the blockchain were completed in less than 3 seconds with consistent event emission. Real-time data retrieval and visualization on the interactive map were accurate and responsive, while automated NFT-based certification ensured 100% data integrity and immutability. Public verification confirmed full transparency and auditability of certification records. Although minor delays in IPFS retrieval and the need for simplified identity onboarding were observed, the platform showed promising scalability and usability. These results confirm that

AgriTrustChain is a viable and trustworthy solution, with future improvements planned for AI-driven validation, gasless transactions, and enhanced privacy through zero-knowledge proofs.

Table 5: Summary of experimental results for AgriTrustChain platform.

Scenario	Execution Time (s)	Gas Cost (units)	Success Rate	Integrity
Data Storage (IPFS + Blockchain)	2.8	100,215	100%	100%
Data Retrieval & Map Visualization	2.7	–	100%	100%
Certification & NFT Minting	4.9	156,900	100%	100%

6 CONCLUSION

Computer science has brought transformative advances to the agricultural sector by enabling data-driven decision-making, automation, and intelligent resource management. Distributed systems, particularly blockchain, offer a robust solution by providing tamper-resistant data storage, enhanced traceability of land and soil records, and decentralized access control. By integrating these technologies, agriculture can reach a higher level of trust, accountability, and efficiency. In this paper, we introduced a blockchain-based platform called AgriTrustChain combining IPFS for decentralized storage, interactive soil data visualization, and NFT-based land certification. The implemented platform confirm its potential to ensure efficient data management, accurate visualization, and transparent certification. Future work will focus on large-scale validation, integration of advanced analytics for automated soil assessment, and interoperability with multi-chain ecosystems. Further enhancements will target security, scalability, and usability to facilitate broader adoption by agricultural stakeholders. Finally, developing standardized frameworks and interoperability protocols will be crucial to ensure seamless data exchange across stakeholders, paving the way for a transparent and sustainable agricultural ecosystem.

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