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RESEARCH PAPER

Enhancing Sustainability in Agricultural Supply Chains Through a Blockchain-IoT Framework for Environmental Footprint Tracking: A Tunisian Citrus Case Study

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Abstract. Environmental demands on modern agriculture are increasing, particularly with respect to energy efficiency, greenhouse gas reduction, and water scarcity. Consequently, transparent and trustworthy identification of the environmental footprint across agri-food supply chains has become essential. Although blockchain and Internet of Things (IoT) technologies offer promising solutions, their combined application for sustainability monitoring, especially in citrus production, remains insufficiently explored. This study proposes an integrated digital platform for monitoring and disseminating key environmental footprint indicators across the citrus supply chain, including water consumption, energy usage, and CO_2 emissions. The system adopts a modular architecture that combines IoT-based environmental sensing, blockchain-secured data management using cryptographic hashing and digital signatures to ensure data integrity and immutability, and a web-based dashboard for real-time visualization and decision support. Throughout the product lifecycle, all stakeholders, from farmers to consumers, can contribute to and access tamper-proof sustainability records. Environmental performance was monitored during production, storage, and transportation phases on a medium-sized citrus farm in Tunisia using IoT sensors. The results demonstrate that environmental footprint metrics are reliably captured and securely recorded, while QR-code-based access enables consumers to retrieve verified environmental information. This allows purchasing decisions to consider not only product quality and origin but also environmental impact. By combining reliable sensing, cryptographically secured blockchain records, and transparent user interfaces, the proposed platform empowers consumers, supports national and international sustainability objectives, and promotes eco-responsible agricultural practices within digital and sustainable food systems.

Keywords: Environmental Traceability, Citrus Supply Chain, IoT, Blockchain, Sustainability Metrics

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1 Introduction

The sustainable management of water resources, energy efficiency, and the mitigation of greenhouse gas emissions, particularly CO_2 [Chin *et al.*, 2022; Moshood *et al.*, 2022; Cao *et al.*, 2022; Esmaeilian *et al.*, 2020], represent some of the most pressing challenges facing modern agriculture. According to the Food and Agriculture Organization (FAO), agri-food systems account for approximately 30% of global greenhouse gas emissions and nearly 70% of global freshwater withdrawals, while also exerting significant pressure on energy resources and ecosystems [Food and Agriculture Organization of the United Nations and Ziadat, 2021]. In response to these pressures, the agricultural sector is increasingly required to adopt more sustainable, transparent, and accountable practices, driven by global climate commitments, stricter regulatory frameworks, and growing consumer demand for reliable environmental information [Sharma *et al.*, 2025; Bosona and Gebresenbet, 2023; Lv *et al.*, 2023].

These challenges are accelerating the transition toward *Digital Agriculture* and *Agriculture 4.0*, which emphasize the integration of connected sensing technologies, data-driven decision support, and digital platforms to improve sustainability, traceability, and operational efficiency across agri-food systems [Klerkx *et al.*, 2019]. Within this paradigm, environmental traceability has emerged as a strategic mechanism for monitoring, reporting, and verifying the environmental footprint of agricultural supply chains, including water use, energy consumption, and greenhouse gas emissions. However, many existing digital traceability solutions remain limited by fragmented data acquisition, insufficient interoperability between sensing and data management layers, and the absence of trusted mechanisms ensuring data integrity and long-term verifiability.

To address these limitations, this work proposes a unified digital environmental traceability platform that integrates Internet of Things (IoT)-based environmental sensing, blockchain-secured data management, and user-facing web and mobile interfaces. The proposed system enables real-time acquisition, secure storage, and transparent dissemination of sustainability indicators across the product lifecycle, thereby supporting informed decision-making and enhancing trust among supply chain stakeholders.

The feasibility of the proposed architecture is demonstrated through a real-world pilot deployment in the Tunisian citrus sector, a major Mediterranean production context characterized by high water and energy demands, particularly during irrigation and post-harvest storage operations [Tang *et al.*, 2024; Jerbi *et al.*, 2022]. With an annual citrus production exceeding 600,000 tons, Tunisia provides a representative environment to assess how digital traceability can support environmentally responsible agricultural practices under real operational constraints [Sharma *et al.*, 2025; Azmi, 2024;

Ammar *et al.*, 2025].

Despite the growing body of research on blockchain-based agricultural traceability, existing systems primarily emphasize product provenance, food safety, or transaction transparency. Limited attention has been paid to the continuous monitoring and verification of multi-dimensional environmental sustainability indicators, particularly in crop-specific supply chains such as citrus production. Furthermore, many frameworks lack edge-aware data acquisition mechanisms, resilience to connectivity constraints, or validation under real-world operational conditions.

To address these limitations, our framework integrates multi-dimensional environmental footprint indicators (water, energy, and CO_2 emissions) within a unified end-to-end IoT–blockchain architecture, incorporating edge-aware data acquisition and role-specific user interfaces.

To clearly highlight the originality of this work, the main contributions are summarized as follows:

- We propose a unified end-to-end IoT–blockchain architecture enabling continuous, batch-level monitoring of water consumption, energy usage, and CO_2 emissions across multiple stages of the citrus supply chain.
- We develop an edge-aware data acquisition and buffering mechanism that ensures resilience to intermittent connectivity while preserving verifiable real-time environmental data integrity.
- We design a hybrid blockchain-based data management strategy combining on-chain integrity anchoring with off-chain storage to ensure scalability, traceability, and role-based access control.
- We implement a role-specific user interface, including a consumer-facing QR-code mechanism, that translates raw environmental measurements into contextualized and verifiable sustainability indicators.
- We validate the proposed architecture through a real-world pilot deployment in the Tunisian citrus sector, demonstrating technical feasibility, operational robustness, and practical usability.

The remainder of this paper is organized as follows: Section 2 reviews related work on IoT- and blockchain-based agri-food traceability. Section 3 presents the proposed system architecture. Section 4 describes the implementation and experimental setup. Section 5 discusses the results and evaluates system performance. Finally, Section 6 concludes the paper and outlines future research directions.

2 Related Works

Digital Agriculture and Agriculture 4.0 have emerged as central paradigms for advancing sustainability in agri-food systems through the integration of sensing technologies, data analytics, and digital platforms. Within this context, the monitoring of environmental indicators, particularly water consumption, energy use, and greenhouse gas emissions, has become a core research focus, as these metrics directly reflect the ecological footprint of agricultural activities and support more responsible resource management and policy making.

A growing body of literature addresses the use of digital technologies to monitor environmental performance across agri-food supply chains. Numerous studies emphasize the importance of tracking CO_2 emissions, water use, and energy consumption as key sustainability indicators for evaluating environmental impacts and guiding decision-making by producers and regulators [Sharma *et al.*, 2025; Awan *et al.*, 2021; Pang *et al.*, 2024; Azmi, 2024; Bhat *et al.*, 2025].

These works mainly provide surveys, conceptual frameworks, or technology overviews highlighting the importance of digital monitoring, but they generally do not propose integrated traceability platforms combining real-time sensing, trusted data management, and user-facing sustainability interfaces. While these works demonstrate the relevance of digital monitoring for sustainable agriculture, they also highlight persistent challenges related to data fragmentation, lack of trust, limited interoperability, and restricted access to verified information by non-expert stakeholders.

In Mediterranean and semi-arid regions, such as North Africa and Southern Europe, these challenges are particularly pronounced. Citrus production in these areas is characterized by high irrigation demand, energy-intensive post-harvest storage, and increased vulnerability to climate variability [Tang *et al.*, 2024; Jerbi *et al.*, 2022].

Recent research from Africa and South America highlights the growing adoption of IoT and blockchain technologies to address these challenges to address these challenges. Studies report their potential for improving traceability, sustainability, and food safety in African agri-food systems, while bibliometric analyses show increasing research activity led by South African institutions. Complementary work in West Africa and South America further demonstrates the use of IoT-based environmental monitoring and blockchain-enabled traceability across diverse agricultural contexts [Apeh and Nwulu, 2025; Dossou *et al.*, 2025; Ordo nez *et al.*, 2024]. These studies mainly analyze technological trends, adoption drivers, or conceptual architectures rather than implementing operational systems with real-time environmental monitoring and end-user accessibility. Studies report their potential for improving traceability, sustainability, and food safety in African agri-food systems, while bibliometric analyses show increasing research activity led by South African institutions. Complementary work in West Africa and South America further demonstrates the use of IoT-based environmental monitoring and blockchain-enabled traceability across diverse agricultural contexts [Apeh and Nwulu, 2025; Dossou *et al.*, 2025; Ordo nez *et al.*, 2024].

Despite the economic importance of citrus crops, exceeding 600,000 tonnes annually in Tunisia alone, with oranges accounting for more than 70% of production, digital agriculture applications explicitly targeting environmental performance monitoring in citrus supply chains remain scarce. Existing studies in this domain predominantly focus on food safety, yield optimization, or logistics efficiency, with limited attention to continuous, transparent monitoring of environmental indicators across the entire citrus product lifecycle.

Blockchain technology has been widely investigated as an enabler of transparency, trust, and traceability in agri-food systems [Kamble *et al.*, 2020; Chin *et al.*, 2022; Kumar *et al.*, 2023; Sakthivel *et al.*, 2024]. When combined with Internet of Things (IoT) technologies, blockchain enables the real-time acquisition and immutable storage of environmental data, thereby supporting verifiable sustainability reporting and auditability [Miller *et al.*, 2025; Hasan *et al.*, 2024]. Several studies demonstrate the feasibility of such integrations for logging water and energy consumption [Siddiqui *et al.*, 2024; Panwar *et al.*, 2023] or for estimating carbon footprints across processing and logistics stages [Menon and Jain, 2021; Vern *et al.*, 2025]. However, these studies typically focus on single indicators, conceptual frameworks, or specific supply chain stages, without providing integrated multi-indicator environmental monitoring combined with user-oriented traceability interfaces.

More recent research has explored integrated frameworks combining IoT, blockchain, and Artificial Intelligence (AI) to enhance environmental monitoring and decision support in sustainable agriculture Chaker *et al.* [2026]. In these architectures, IoT is typically used for real-time data acquisition, blockchain for ensuring data integrity and traceability, while AI techniques are employed for predictive analytics, anomaly detection, or resource optimization. However, the majority of these solutions remain technically complex, often requiring substantial computational resources and expert-level interpretation. As a result, they are primarily designed for expert users and offer limited accessibility for non-expert stakeholders such as smallholder farmers, consumers, or supply chain operators. Moreover, many AI-enabled frameworks remain conceptual or simulation-based, with few real-world deployments validating their feasibility in operational agricultural environments.

Within this research line, [Mofatteh *et al.*, 2024] proposed a blockchain–IoT framework for tracking CO_2 footprints in agricultural logistics. While this study provides valuable conceptual insights into carbon emission monitoring, it focuses mainly on logistics-level CO_2 tracking and does not address multi-indicator environmental assessment, batch-level traceability across production stages, or consumer-facing transparency mechanisms. In addition, AI components are discussed at a conceptual level and are not validated through real-world deployment. In contrast, the present study emphasizes operational feasibility and usability by enabling integrated monitoring of water use, energy consumption, and CO_2 emissions across multiple stages of the agricultural lifecycle, and by validating the approach through a pilot deployment in citrus production.

Beyond traceability, several works have investigated sustainability improvements through logistics optimization and simulation-based approaches. For example, [Jerbi *et al.*, 2022] explored transportation pooling strategies to reduce emissions, while [Jmaa *et al.*, 2025] reviewed optimization techniques for greener agri-food logistics. Although effective for strategic planning, these approaches typically rely on offline data analysis and do not provide continuous, verifiable environmental monitoring integrated with traceability mechanisms or accessible to multiple stakeholders along the supply chain.

Overall, despite significant advances in IoT-, blockchain-, and AI-enabled agricultural systems, existing solutions remain largely fragmented and system-centric. Many platforms prioritize producer-side monitoring, optimization, or regulatory compliance, while offering limited transparency, interoperability, and usability for downstream stakeholders such as distributors and consumers. This limitation is particularly evident in citrus supply chains, where end-to-end, user-centered environmental traceability systems with real-world validation remain scarce [Camel *et al.*, 2024; Vitaskos *et al.*, 2024]. Recent studies emphasize the need for citrus-specific solutions capable of delivering intelligible and verifiable sustainability information to non-expert users, thereby supporting informed decision-making and environmentally responsible consumption [Yang *et al.*, 2021; Gurupatham *et al.*, 2025].

Table 1 summarizes representative blockchain–IoT traceability systems, comparing crop focus, monitored indicators, technological components, user interfaces, and application contexts. The comparison highlights a clear imbalance in the literature: while generic agri-food systems are widely studied, fully integrated digital traceability solutions explicitly addressing citrus production in Mediterranean and semi-arid environments remain limited.

In summary, existing studies demonstrate the potential of blockchain and IoT for sustainability monitoring; however, gaps remain. Most work focuses on isolated technical components rather than integrated, end-to-end solutions. Regional coverage is limited, particularly in African and Latin American contexts, and very few studies provide user-facing interfaces that allow both producers and consumers to access verified environmental information. These gaps motivate the present work, which develops a modular platform combining IoT sensing, blockchain security, and intuitive dashboards to support transparency and eco-responsible practices across the citrus supply chain.

3 System Architecture and Design

This section presents the conceptual architecture of the proposed IoT- and blockchain-based environmental traceability system for citrus supply chains. The architecture aims to provide a reusable and modular framework supporting environmental accountability across heterogeneous agricultural contexts.

Within the broader paradigm of Agriculture 4.0, the system adopts a cyber–physical approach that integrates physical sensing infrastructures with trusted digital data management and human-centered decision support. The architecture is structured around three core objectives: (i) continuous and reliable acquisition of environmental data across the supply chain, (ii) secure and verifiable management of sustainability indicators, and (iii) transparent and actionable dissemination of information to multiple stakeholder groups. These objectives are realized through a layered design that explicitly separates concerns between sensing, data management, and application-level interaction.

The proposed architecture is designed to be robust to partial failures, scalable across multiple farms and supply chains, and adaptable to different crops, regions, and regulatory environments. This is achieved through modular components, standardized interfaces, and the decoupling of conceptual design principles from implementation-specific choices.

Table 1. Comparative Overview of Blockchain and IoT-Based Traceability Systems in Agri-Food Supply Chains

Reference	Crop / Domain	Environmental Indicators	Technologies	Region	Advantages	Limitations
[Siddiqui *et al.*, 2024]	Fruits	CO_2, pesticide use	IoT, Blockchain	Pakistan	Blockchain + IoT for real-time supply chain transparency secure recording smart contracts for compliance and payments scalable for high-volume IoT data field-tested on value crops	Limited to CO and pesticide indicators No consumer QR interface No multi-stage monitoring No predictive analytics or edge intelligence.
[Menon and Jain, 2021]	Dairy	Energy, CO_2	Blockchain	India	Comprehensive analysis of blockchain-enabled transparency in agri-food supply chains links blockchain attributes (traceability, immutability, auditability) to supply chain functions	Conceptual/theoretical study No IoT integration or environmental monitoring No system implementation or pilot validation.
[Yang *et al.*, 2021]	Rice	Water, fertilizer	IoT, Blockchain	China	Blockchain-based traceability system with dual storage (on-chain/off-chain) secure data sharing via cryptography reputation-based smart contracts	No environmental sustainability indicators (CO, water, energy) Limited to traceability No consumer-oriented sustainability interface or analytics.
[Kumar *et al.*, 2023]	Fruits	CO_2, energy, water	IoT, Blockchain	India	Ethereum-based blockchain framework with real-time IoT monitoring immutable product journey tracking	Limited evaluation of environmental footprint metrics No real-world deployment validation
[Camel *et al.*, 2024]	Mixed crops	CO_2, water	IoT	UAE	Empirical study of blockchain-enabled Green Product Platforming (GPP) analyzes impact on carbon footprint and economic performance	No technical architecture or real-time monitoring system scalability and operational deployment not validated.
[Chin *et al.*, 2022]	Agri-food	CO_2	Blockchain, AI	Malaysia	Explores blockchain as a driver of green innovation in ecosystem-based business models	No technical blockchain implementation No supply chain traceability system or environmental data monitoring
[Benzidia *et al.*, 2021]	Perishable products	Cold chain metrics	IoT, Blockchain	Morocco	links blockchain adoption to innovation performance in buyer–supplier relationships	No technical blockchain architecture No IoT integration or environmental traceability system
[Moshood *et al.*, 2022]	Agri-food	Energy, CO_2	IoT, Blockchain	Nigeria	Identifies key environmental drivers across product life cycle	Not agriculture-specific blockchain study No traceability system No IoT or real-time monitoring
[Hasan *et al.*, 2024]	Various crops	CO_2, water, energy	IoT, Blockchain	Malaysia	Blockchain + IoT framework for trusted sustainable agriculture real-time monitoring of soil, air, and crops smart contracts with security validation consumer traceability for certification compliance	No explicit quantitative environmental footprint metrics Scalability and large-scale deployment not fully validated.
[El Hathat *et al.*, 2024]	Groundnut	CO_2 emissions	IoT, Blockchain, ML	Morocco	Blockchain-enabled off-chain machine learning for GHG traceability predictive analytics for emissions reduction Hyperledger-based smart contracts decision-support dashboard	Focused only on GHG emissions limited to groundnut supply chain No multi-indicator environmental monitoring
[Gurupatham *et al.*, 2025]	Mixed crops	CO_2, water, energy	IoT, Blockchain	India	Conceptual integration of blockchain-based IoT to enhance traceability, efficiency, and sustainability in Indian agricultural supply chains	No quantified environmental monitoring indicators
[.Indap and Tanyaş, 2023]	Cherries	CO_2, food safety	IoT, Blockchain	Turkey	Integrates SCOR model and AHP to prioritize digital investments	No implemented blockchain prototype no real-time IoT or environmental sustainability monitoring
[Chan *et al.*, 2019]	Agri-food	Water, fertilizer, logistics	IoT, Blockchain	Malaysia	Recommends permissioned blockchain for improved transparency	Conceptual framework without implementation No real-time environmental monitoring No pilot deployment
[Sriram *et al.*, 2024]	Mixed crops	Water, energy	IoT	India	Integrated mobile platform for smart farm management using ML, weather APIs, mapping, and analytics supports decision-making and resource optimization	No blockchain integration No supply chain traceability No environmental footprint tracking
[Eswaran *et al.*, 2024]	Mixed crops	Water, soil, energy	IoT, Sensors	N/A	details environmental monitoring, irrigation, and crop health applications	No blockchain integration No supply chain traceability framework No sustainability metrics quantification
[Apeh and Nwulu, 2025]	Agri-Food Supply Chain	Traceability, Sustainability Metrics	Blockchain	South Africa	identifies research trends, benefits, gaps, and sustainability challenges maps technological and disciplinary evolution	No system implementation or pilot validation No specific environmental monitoring framework
[Ordo nez *et al.*, 2024]	Agriculture	Traceability, Sustainability	Blockchain	South America	analyzes smart contracts, DApps, NFTs, and blockchain oracles for transparency	No technical architecture or deployment No quantified environmental monitoring indicators
[Dossou *et al.*, 2025]	Smart Agriculture	Water, Resource Efficiency	IoT Decision Support	Senegal, West Africa	highlights sustainability potential and adoption trends	No blockchain integration No supply chain traceability system or environmental footprint quantification
[Tang *et al.*, 2024]	Agri-Food Supply Chain	Traceability, Food Safety	Blockchain, IoT	Africa	Evaluates technical, economic, legal, and operational dimensions	No implemented system or pilot validation No multi-indicator environmental monitoring framework
This work	**Citrus**	**CO_2, water, energy**	**IoT, Blockchain**	**Tunisia**	Unified IoT–Blockchain across multi-stage supply chain Edge-aware data acquisition Real-time verifiable environmental data Role-specific user interface Validated in real-world pilot deployment	Limited to citrus supply chain pilot Large-scale deployment and long-term evaluation remain future work

3.1 Architectural Objectives and Traceability Requirements

Environmental traceability in agricultural supply chains requires more than isolated data collection; it demands a coherent architectural framework capable of linking heterogeneous measurements to physical products, operational actors, and decision-making processes. The proposed system is therefore designed around three fundamental architectural objectives.

First, robustness is achieved through a layered and decoupled design in which data acquisition, trusted data management, and user-facing applications operate independently. This separation allows the system to tolerate sensor failures, intermittent connectivity, or partial subsystem outages without compromising data integrity or overall functionality.

Second, modularity enables the independent evolution of system components. IoT devices, blockchain services, and visualization interfaces can be extended, upgraded, or replaced without requiring structural redesign. This modularity is essential for adapting the architecture to different farm sizes, technological maturity levels, and crop types.

Third, transparency is structurally enforced through cryptographic verification mechanisms, immutable data records, and role-aware access policies. Environmental indicators such as water consumption, energy use, and CO_2 emissions are recorded in a tamper-resistant manner and exposed at batch level through accessible interfaces, ensuring consistent and verifiable visibility for authorized stakeholders.

From a traceability perspective, the architecture must support end-to-end linkage between physical citrus batches and their associated environmental footprint across cultivation, post-harvest storage, transportation, and distribution stages. This requirement implies clear stakeholder responsibilities, batch-level identification mechanisms, and trusted data flows across organizational boundaries.

3.2 Conceptual Multi-Layer Architecture

Building on these objectives, the proposed system adopts a conceptual multi-layer architecture that structures the flow of environmental information from physical measurement to decision support. The architecture monitors environmental indicators across five critical stages of the citrus lifecycle: cultivation, harvesting, post-harvest storage, transportation, and distribution or retail.

At a conceptual level, the architecture is organized into four functional layers, each defined by its intended role rather than by specific technologies:

1. **Sensing and Acquisition Layer**, responsible for capturing physical environmental measurements from the field and logistics infrastructure.
2. **Processing and Communication Layer**, which ensures data validation, buffering, and secure transmission under operational constraints.
3. **Trusted Data Management Layer**, which guarantees immutability, traceability, and decentralized trust.
4. **Application and Interaction Layer**, which exposes verified sustainability information through user-centric interfaces.

Figure 1 illustrates this conceptual organization and the interactions between layers. Importantly, this layered abstraction remains independent of specific communication protocols, blockchain frameworks, or user interface technologies, thereby preserving generalizability and reusability.

3.3 Data Lifecycle and System Workflow

While the architectural layers define the structural organization of the system, the data lifecycle describes the dynamic flow of information across these layers. Figure 2 presents the end-to-end workflow, from environmental data acquisition to visualization and decision support.

The lifecycle begins with continuous environmental monitoring at production and logistics stages. Measurements related to water use, energy consumption, and CO_2 emissions are timestamped at the point of acquisition and locally logged. Edge-level preprocessing includes noise filtering, aggregation, and consistency checks, ensuring that only validated data enter subsequent stages.

Validated data are then synchronized with the trusted data management layer, where cryptographic hashes and transaction timestamps provide immutable evidence of data ingestion, ordering, and provenance. As citrus batches move through the supply chain, additional environmental records are incrementally linked, enabling cumulative footprint assessment across lifecycle stages.

Finally, aggregated and verified indicators are exposed through the application layer. Supply chain actors access analytical dashboards for operational and strategic decisions, while consumers retrieve transparent sustainability information through QR-code-based interfaces. This workflow enables traceable, auditable, and decision-relevant environmental accountability.

3.4 Sensing and Data Acquisition Layer

The sensing and data acquisition layer constitutes the physical interface between the agricultural environment and the digital traceability system. Its primary objective is to ensure accurate, continuous, and resilient acquisition of environmental data across heterogeneous operational contexts, including fixed agricultural infrastructure and mobile transport assets.

To clarify how environmental data are collected and transmitted in the pilot implementation, Fig. 3 illustrates the concrete communication architecture adopted for the IoT layer. The diagram details the interaction between field sensors, communication networks, edge gateways, data management services, and the blockchain infrastructure, serving as an implementation-level instantiation of the conceptual acquisition layer.

During cultivation, distributed IoT sensor nodes monitor soil moisture, irrigation water flow, ambient temperature, and humidity. Energy consumption associated with electrically powered equipment, such as irrigation pumps, is captured through smart energy meters. Fuel consumption from agricultural machinery used for field operations is estimated through onboard diagnostics or structured operational reporting and subsequently converted into CO_2-equivalent emissions using standardized emission factors.

During the harvesting stage, operational data related to harvesting activities are collected to complement the environmental profile of each citrus batch. These data include harvesting dates, machinery usage duration, fuel consump-

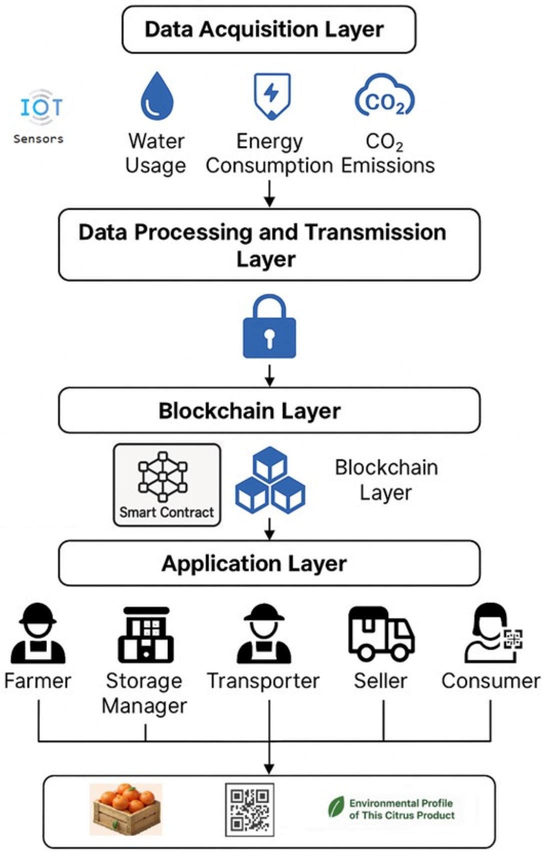


Figure 1. Conceptual multi-layer architecture of the proposed environmental traceability system.

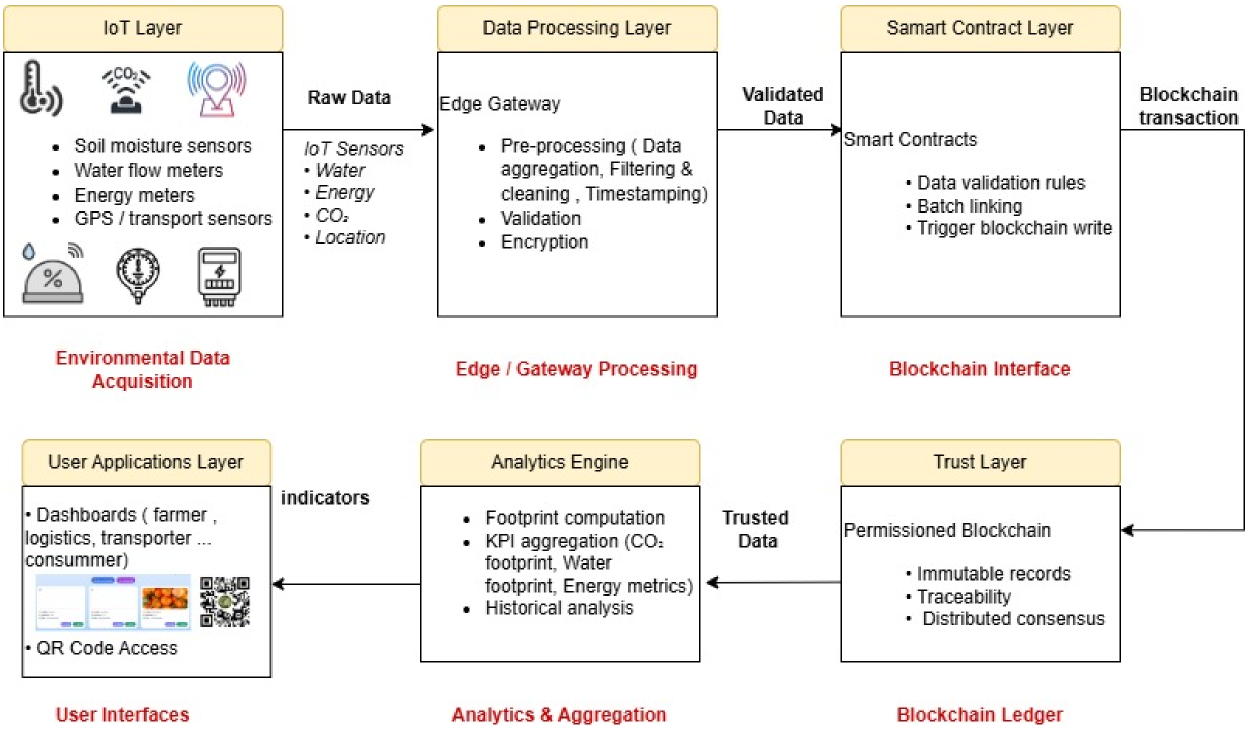


Figure 2. End-to-end data lifecycle and operational workflow.

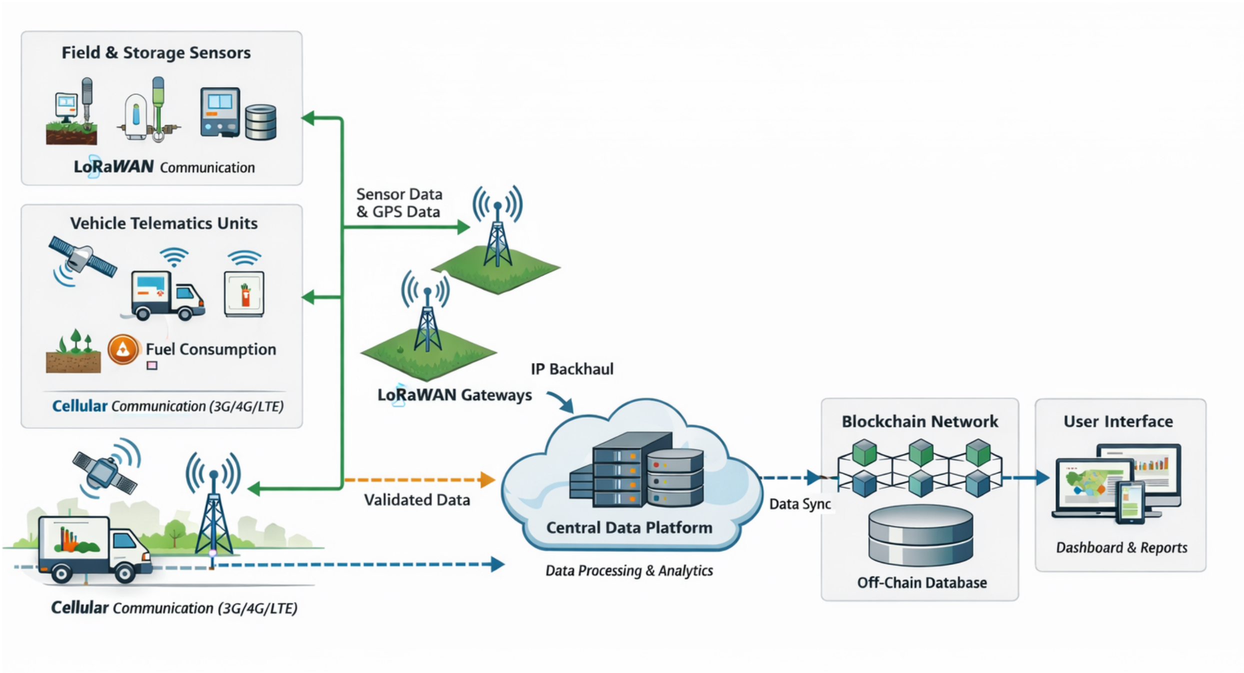


Figure 3. Communication architecture of the IoT-enabled citrus traceability system, illustrating data flows between sensors, gateways, data management services, and the blockchain layer.

tion associated with harvesting equipment, and labor-related logistics. Although harvesting is less sensor-intensive than cultivation, integrating these operational records ensures continuity of batch-level traceability and allows emissions linked to harvesting operations to be incorporated into the overall environmental assessment.

Post-harvest storage facilities are instrumented with sensors tracking temperature, humidity, and refrigeration energy use in cold storage units. Smart energy meters continuously monitor electricity consumption, enabling precise attribution of post-harvest energy demand and associated emissions to specific product batches during storage periods.

Transportation assets rely on telematics units integrating GPS positioning, transit duration, and aggregated fuel consumption. GPS data are transmitted using cellular networks (3G/4G), which provide continuous coverage along transportation routes and support the mobility and data rate requirements of vehicular tracking, which are less suited to low-power wide-area networks. These data enable the calculation of transport-related emissions and ensure spatiotemporal traceability of citrus batches during logistics operations.

At the distribution and retail stage, batch-level environmental indicators are consolidated and made accessible through digital interfaces. Environmental summaries, logistics metadata, and sustainability indicators are linked to each batch and exposed via QR codes, allowing distributors, retailers, and end consumers to access verified information on product origin, storage conditions, transportation history, and associated environmental impacts. This final stage closes the traceability loop by transforming raw environmental data into intelligible and actionable sustainability information.

To accommodate rural deployment constraints, the acquisition layer adopts a hybrid communication architecture designed to balance coverage, energy efficiency, and communication reliability across heterogeneous operational environments. LoRaWAN is particularly suitable for stationary agricultural sensors due to its low power consumption and long communication range, which enables battery-powered devices to operate for extended periods in sparsely connected rural areas. In contrast, transportation assets require higher mobility support and continuous connectivity along road networks, making cellular communication technologies more appropriate.

In the pilot deployment, end devices were typically located at distances ranging from 0.5 to 3 km from the nearest gateway, depending on field topology and line-of-sight conditions. Two LoRaWAN gateways were deployed at elevated positions near farm buildings, each providing an effective coverage radius of approximately 5–7 km.

Typical LoRaWAN payloads ranged from 20 to 50 bytes per message, encapsulating timestamped sensor readings and batch identifiers. Message transmission intervals varied between 5 and 15 minutes, depending on the monitored parameter and its expected temporal variability. These transmission intervals were selected to balance timely environmental monitoring with energy efficiency, ensuring that battery-powered sensor nodes could operate for extended periods without frequent maintenance.

Network performance during the pilot was characterized by RSSI values between –70 and –115 dBm and signal-to-noise ratios (SNR) between –5 and 10 dB, which are consistent with reliable LoRaWAN operation in rural settings. Observed packet loss remained below 5% under nominal conditions.

Several design choices were implemented to minimize message loss and ensure data integrity. These include adaptive data rates (ADR), local buffering at sensor nodes and edge gateways, acknowledgment-based retransmission for critical measurements, and store-and-forward mechanisms at the gateway level to handle intermittent backhaul connectivity.

Edge gateways constitute a core component of the system's edge computing layer. They perform initial validation, aggregation, and temporal batching of incoming data, enabling local processing, latency reduction, and autonomous operation in rural environments with intermittent connectivity, before securely forwarding the data to the trusted data management and blockchain layers.

While the pilot deployment validated the feasibility of the proposed communication architecture at farm scale, the modular design of the IoT layer allows for straightforward scaling by increasing the number of gateways or adjusting their placement according to farm size and terrain characteristics. A qualitative discussion of infrastructure cost and scalability considerations is provided in Section 5.

3.5 Trusted Data Management Layer

The trusted data management layer provides the system's core guarantees of integrity, traceability, and accountability. This layer relies on a permissioned blockchain infrastructure that records cryptographic commitments of environmental data and operational events.

Environmental measurements are hashed prior to registration, generating immutable digital fingerprints that are linked to batch identifiers, stakeholder identities, and lifecycle stages. Smart contracts automate validation rules, enforce role-based access control, and support compliance verification without exposing sensitive operational data.

To balance transparency and scalability, a hybrid on-chain/off-chain storage strategy is adopted. High-volume raw data are stored off-chain, while hashes and essential metadata are anchored on-chain. This approach preserves verifiability while avoiding excessive storage overhead.

By decoupling data integrity guarantees from data volume management, the trusted data layer establishes a reliable foundation for environmental traceability across multi-actor supply chains.

3.6 Application Layer: Visualization and Decision Support

The application layer translates verified environmental data into actionable knowledge for stakeholders and provides transparent, contextualized information for consumers and distributors. Role-based dashboards offer tailored access to sustainability indicators aligned with each actor's responsibilities.

Environmental indicators are presented together with contextual information to support informed interpretation. Historical performance data are visualized through time-series representations, enabling stakeholders to assess trends in water consumption, energy use, and CO_2 emissions at batch, plot, or farm level across successive production cycles. Comparative benchmarks derived from regional, crop-specific, or industry reference values allow users to position a batch's performance relative to typical citrus production practices under similar agro-climatic conditions. External contextual inputs such as climatic conditions (e.g., droughts or heat waves), soil characteristics, and regulatory thresholds further support responsible interpretation and prevent misleading conclusions.

All contextual data are processed at the application layer, while raw measurements and their provenance remain immutably recorded on the blockchain. This separation preserves data integrity while ensuring that end-users are provided with intelligible, responsible, and decision-relevant sustainability information.

Interactive visualizations support temporal analysis, batch-level comparisons, geospatial exploration, and trend assessment. Contextual interpretation is enabled through these historical, comparative, and external reference layers, ensuring that indicators are both :meaningful and actionable.

Beyond visualization, the interface facilitates decision-making through alerts, sustainability reporting tools, and the generation of verifiable digital eco-labels. Security and authentication are enforced through cryptographic credentials, digital signatures, and auditable access logs, ensuring trust at both the data and interface levels.

3.7 Cross-Cutting Properties: Interoperability and Scalability

Interoperability and scalability are treated as cross-cutting architectural properties rather than isolated features. Standardized protocols, open data formats, and modular APIs enable seamless integration with external farm management systems, certification platforms, and regulatory infrastructures.

The architecture supports horizontal scalability at the IoT level through edge-based processing and at the data management level through batch-oriented blockchain transactions. New stakeholders and supply chain segments can be onboarded without disrupting existing operations.

Although the proof-of-concept deployment validated the architecture under pilot-scale conditions, large-scale performance benchmarking remains a direction for future work. Nevertheless, the underlying design principles ensure adaptability to diverse agricultural contexts and future technological evolution.

4 Implementation and Experimentation

This section delineates the technical implementation of the proposed environmental traceability system and presents the preliminary results from its deployment in a real-world citrus farming context. The primary objectives are to validate the architectural feasibility of the system, evaluate its performance, and demonstrate the end-to-end pipeline for capturing, securing, and visualizing environmental data across the supply chain.

4.1 Experimental Setup

The pilot deployment was implemented across multiple citrus-producing regions in Tunisia to ensure data representativeness, with a focus on the Cap Bon area—the country's primary citrus basin. Tunisia cultivates approximately 26,000–28,000 hectares of citrus orchards, nearly 70% of which are concentrated in the Cap Bon region. This area features diverse citrus varieties, including Maltaise, Valencia, Thomson, and Navel, cultivated under both traditional and semi-intensive irrigation systems.

Across these zones, IoT sensor networks were deployed to monitor key environmental indicators throughout cultivation, irrigation, and post-harvest stages. This setup was designed to capture variability in water use, energy consumption, and carbon emissions across representative Tunisian citrus supply chain conditions.

4.2 Data Acquisition and Carbon Footprint Modeling

The deployed IoT infrastructure incorporated several sensors and data sources for environmental monitoring. These included soil moisture sensors (capacitive probes) for real-time monitoring of field-level irrigation efficiency, flow meters integrated into drip irrigation lines to quantify water consumption per plot and per irrigation cycle, and temperature and humidity sensors in both open fields and cold storage facilities to track ambient conditions. Crucially, for energy and emission accounting, the system employed smart energy meters on irrigation pumps and cold storage units to measure electricity consumption, and fuel trackers for on-farm machinery supplemented by manual logging to estimate emissions from fuel combustion. Sensor data from stationary assets, including field sensors and storage facilities, were transmitted via a LoRaWAN (Long Range Wide Area Network) to a local edge gateway. In contrast, data generated by mobile assets, such as GPS-equipped machinery and transport vehicles, were transmitted using cellular networks. The edge gateway performed initial data aggregation, preprocessing, and secure transmission to the blockchain-backed data layer, enabling unified handling of heterogeneous communication streams. This hybrid communication approach reflects practical deployment constraints in rural agricultural environments and ensures reliable data acquisition for both fixed and mobile assets. This setup provided low-power, wide-area coverage while minimizing latency for near real-time monitoring. To provide a consolidated overview of the sensing infrastructure, Table 2 summarizes the deployed sensors, their measured parameters, deployment locations, and measurement frequencies.

Leveraging this data stream, a computational model for estimating the carbon footprint was implemented directly on the edge gateway. The model quantified CO_2-equivalent emissions from three primary on-farm sources, utilizing the acquired sensor data as detailed in Table 3. All emission factors used in the calculations were derived from the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006), including updates from the 2019 Refinement, which are widely adopted in agricultural carbon accounting studies.

Emissions from fuel usage were calculated as $E_{\text{fuel}} = Q_{\text{fuel}} \times \text{EF}_{\text{fuel}}$, where Q_{fuel} was provided by machinery fuel trackers and EF_{fuel} is a fuel-specific emission factor. Similarly, emissions from electricity consumption were derived as $E_{\text{elec}} = E_{\text{cons}} \times \text{EF}_{\text{grid}}$, where E_{cons} was measured by smart energy meters and EF_{grid} corresponds to the electricity grid emission factor.

For fertilizer application, the model accounted for both direct nitrous oxide (N2O) emissions from soil and indirect emissions related to fertilizer production, calculated as $E_{\text{fert}} = (Q_{\text{fert}} \times F_{\text{N}} \times \text{EF}_{\text{direct}} \times \text{GWP}_{\text{N}_2\text{O}}) + (Q_{\text{fert}} \times \text{EF}_{\text{prod}})$. The system's overall carbon footprint was obtained by aggregating all emission sources as $E_{\text{total}} = E_{\text{fuel}} + E_{\text{elec}} + E_{\text{fert}}$.

As an illustrative example, if the electricity consumption recorded by the smart meter is 0.47 kWh per kilogram of citrus produced and the grid emission factor is 1.34 kg CO_2-eq/kWh (IPCC), the resulting electricity-related emissions are computed as

$$E_{\text{elec}} = 0.47 \times 1.34 = 0.63 \text{ kg CO}_2\text{-eq kg}^{-1}.$$

The same calculation principle applies to fuel and fertilizer-related emissions.

Uncertainty in the estimated emissions mainly arises from the use of generalized emission factors and variability in local operational conditions, such as energy mix, fuel characteristics, and fertilizer composition. While a full uncertainty or sensitivity analysis is beyond the scope of this pilot implementation, these limitations are acknowledged and will be addressed in future work through the integration of localized emission factors and uncertainty propagation methods.

By executing these calculations at the edge, the model enabled real-time, field-level carbon accounting. Finally, the system quantified key environmental indicators per kilogram of citrus produced, providing a functional unit-based assessment of the orchard's eco-efficiency. The carbon footprint was normalized against the total yield (Y) from the monitored area, expressed as $\text{CF} = E_{\text{total}}/Y$ (kg CO_2e kg^{-1} fruit). This granular metric, derived from continuous IoT data streams, enabled a meaningful analysis of how specific activities, such as irrigation or harvesting, contributed to the overall environmental impact per unit of production.

4.3 Blockchain Deployment

The system was implemented using a private, permissioned blockchain network built on *Hyperledger Fabric*. This framework was selected for its modular architecture, support for fine-grained access control, and efficient transaction processing capabilities. Each stakeholder, including farmers, storage managers, and transporters, was assigned a unique digital identity with role-specific permissions, ensuring secure and authenticated participation in the network.

This choice was motivated by the need to balance transparency with controlled data access in multi-stakeholder agri-food supply chains. Unlike public blockchains, a permissioned architecture allows the definition of role-based permissions and ensures that sensitive operational data remain accessible only to authorized participants while preserving data integrity and auditability.

Smart contracts (chaincode), developed in Go, were deployed to automate data validation and enforce access policies. A *CouchDB* state database was integrated to enable rich querying of environmental records, while RESTful APIs ensured seamless interoperability with the front-end dashboard and mobile applications. All sensor data were encoded into blockchain transactions and indexed by batch ID. To enhance traceability, QR codes were generated and linked to corresponding product batches, allowing end-users to retrieve the full environmental history directly from the immutable ledger.

4.4 User Interface and Data Visualization

A responsive web application, developed using the *React* framework, served as the primary interface for the platform. The system provided role-specific dashboards tailored to the operational needs of different stakeholders:

- **Farmers** could access interactive dashboards displaying irrigation metrics, energy consumption trends, and CO_2

Table 2. Summary of deployed IoT devices and their roles in environmental monitoring

Device Type	Measured Parameter	Deployment Location	Measurement Frequency
Soil Moisture Sensor	Volumetric Water Content	Root zone across fields	Every 15 minutes
Flow Meter	Water flow rate	Drip irrigation lines	Every minute
Temperature/Humidity Sensor	Air temperature, Relative humidity	Open fields, Cold storage	Every 10 minutes
Smart Energy Meter	Active power, Energy consumption	Irrigation pumps, Cold storage units	Every 5 minutes
Fuel Tracker	Fuel consumption	Agricultural machinery	Real-time (engine on)
GPS Tracker	Machinery movement and location	Tractors, Harvesters	Every 30 seconds

Table 3. Data utilization for carbon footprint calculation

Emission Source	Primary Data Source	Calculation Method
Fuel Combustion	Fuel tracker, GPS data	$E_{\text{fuel}} = Q_{\text{fuel}} \times \text{EF}_{\text{fuel}}$
Electricity Consumption	Smart energy meter	$E_{\text{elec}} = E_{\text{cons}} \times \text{EF}_{\text{grid}}$
Fertilizer Application	Manual log + spreader sensor	$E_{\text{fert}} = (Q_{\text{fert}} \times F_{\text{N}} \times \text{EF}_{\text{direct}} \times \text{GWP}_{\text{N}_2\text{O}}) + (Q_{\text{fert}} \times \text{EF}_{\text{prod}})$

emission estimates at the plot and batch levels, facilitating data-driven resource management.

- **Storage managers** could monitor real-time environmental conditions and maintain digital inventory records linked to sustainability metrics.
- **Transporters** were provided with access to delivery logs and vehicle emissions data, enhancing operational transparency and accountability.
- **Consumers** could retrieve the environmental profile of individual fruit batches by scanning QR codes on product packaging, empowering informed and sustainable purchasing decisions.

Data visualization incorporated dynamic line graphs, bar charts, and geospatial maps to intuitively represent water consumption and CO_2 emissions. These visual tools greatly enhanced the interpretability of environmental performance indicators across all user groups.

4.5 Evaluation Methodology and Metrics

The proposed system was evaluated using a combination of technical performance metrics and user-centered evaluation criteria. This section describes exclusively the evaluation procedures, metrics, and protocols adopted during the pilot deployment, without reporting or interpreting results.

Data Accuracy Validation. Data accuracy was assessed by comparing IoT sensor measurements with manually recorded reference values collected during the pilot deployment. Standard error metrics were employed, including absolute error and percentage deviation, to quantify discrepancies between automated and manual measurements. The deviation range was used to assess sensor consistency and identify potential calibration limitations.

Blockchain Performance Evaluation. Blockchain performance was evaluated through transaction-level metrics, including data submission latency and block confirmation time. Latency was defined as the elapsed time between data submission by the IoT gateway and confirmation on the blockchain ledger. To ensure end-to-end data integrity, sensor data packets are cryptographically hashed at the edge gateway prior to submission. Only the hash and metadata are recorded on-chain, while raw data remain off-chain. Any modification at the acquisition or transmission stage results in a hash mismatch, enabling a posteriori verification of data authenticity and immutability. Data integrity was therefore assessed through systematic hash verification of stored records.

Usability Evaluation Protocol. Stakeholder interviews were conducted with twelve participants (n=12), including farmers, storage managers, transporters, and consumers, using a semi-structured interview protocol. The interviews combined open-ended questions and Likert-scale items designed to assess interface usability, clarity of environmental metrics, and perceived practical utility of the platform.

Likert-scale responses were recorded on a five-point scale ranging from 1 (poor) to 5 (excellent). Qualitative responses from open-ended questions were analyzed using thematic coding to identify recurring patterns and user perspectives. All interviews were conducted anonymously, and participants were informed of their right to withdraw at any time.

Traceability Assessment. Finally, traceability capabilities were evaluated by verifying the system's ability to uniquely identify and track citrus batches across multiple supply chain stages, from production to distribution, while maintaining continuous linkage with associated environmental indicators.

This evaluation methodology provides a structured and reproducible framework that supports the quantitative and qualitative findings presented in the Results and Discussion section.

5 Results and Discussion

This section presents a comprehensive analysis of the results obtained from a pilot implementation of the proposed environmental traceability system. The system's performance, usability, and impact on sustainability awareness across the citrus supply chain are evaluated, followed by a discussion of comparative advantages and limitations.

The results reported herein correspond to a pilot deployment conducted on a limited number of citrus farms and are primarily intended to validate the practical feasibility and operational coherence of the proposed architecture rather than to establish statistically representative environmental benchmarks.

While the experimental scale does not allow for robust quantitative comparison with regional or industry-wide averages, the system architecture is explicitly designed to support the integration of historical performance baselines, external benchmark datasets, and contextual reference values. These comparative elements are therefore considered at the architectural and interface levels, but their large-scale empirical validation is identified as an important direction for future work.

5.1 Environmental Performance Metrics

This subsection analyzes the environmental indicators monitored during the pilot deployment of the proposed system. The evaluation focuses on CO_2 emissions, water consumption, and energy usage, which are widely recognized as core sustainability metrics in agricultural systems.

The selection of these indicators is motivated by their direct relevance to citrus production in Mediterranean and semi-arid regions, where irrigation demand and energy-intensive operations such as pumping, cold storage, and transportation represent the dominant sources of environmental impact. Moreover, these metrics are commonly used in sustainability assessment frameworks, enabling meaningful interpretation and comparison.

The IoT sensor network successfully captured real-time environmental metrics with high reliability across three monitored plots, encompassing field irrigation, post-harvest storage, and transportation activities. These results stem from a real-world pilot deployment conducted over a four-week period on multiple citrus farms and associated logistics operations in Tunisia. The objective of this deployment was to validate the technical feasibility, functional scalability, and practical usability of the proposed IoT- and blockchain-based traceability platform rather than to establish statistically representative benchmarks.

The experimental deployment involved three citrus-producing farms located in the Cap Bon region, selected to reflect diverse irrigation practices, plot sizes, and operational conditions. Within each farm, a single representative plot was monitored, resulting in a total of three monitored plots. Each plot was equipped with a set of low-cost IoT devices, including digital flow meters for irrigation water, smart energy meters for electricity consumption, and environmental sensors for temperature and humidity monitoring. Depending on local infrastructure and monitoring requirements, between six and nine sensors were deployed per plot.

The pilot implementation focused on monitoring three core environmental indicators, CO_2 emissions, water consumption, and electricity usage. Nevertheless, the proposed system architecture is inherently extensible: additional environmental indicators can be integrated through new sensing devices or analytical modules without altering the underlying blockchain-based traceability mechanisms.

The observation campaign spanned a continuous four-week period during the active irrigation season. Data were sampled at intervals ranging from 5 to 15 minutes depending on the sensor type. This configuration enabled the capture of fine-grained temporal variations in resource usage while maintaining low communication overhead and energy consumption, which is essential in rural agricultural settings. While this observation period does not cover a full production cycle, it provides representative insights into resource-intensive phases of citrus cultivation, particularly irrigation and post-harvest cooling. Seasonal variability and long-term trends are further discussed as limitations in Section 5.7.

As summarized in Table 4, the system quantified key environmental performance indicators per kilogram of citrus produced. Water consumption was primarily associated with irrigation activities, electricity usage was dominated by irrigation pumps and cold storage systems, and CO_2 emissions accounted for fuel usage in agricultural machinery, electricity consumption, and emissions from fertilizer application. These results demonstrate the system's ability to generate granular, batch-level environmental indicators that support both operational decision-making and sustainability reporting.

Table 4. Environmental performance indicators per kilogram of citrus produced

Indicator	Value
Water consumption	4.3 L/kg ($\pm$0.2 L)
Electricity usage	0.47 kWh/kg ($\pm$0.05 kWh)
CO_2 emissions	0.63 kg CO_2-eq/kg

The observed values are consistent with the operational characteristics of citrus production systems in Mediterranean climates. Water consumption is largely driven by irrigation requirements during the dry season, while electricity usage reflects the combined energy demand of irrigation pumps and post-harvest cold storage. Similarly, CO_2 emissions are primarily influenced by fuel-powered agricultural machinery and electricity-related emission factors. These patterns confirm that the monitored indicators accurately capture the dominant environmental impact sources in the studied supply chain.

To ensure the reliability of the collected environmental data, a calibration and validation protocol was applied prior to and during the pilot deployment. Water consumption was measured using low-cost digital flow meters installed on irrigation lines, while electricity usage was monitored through smart energy meters connected to irrigation pumps and cold storage units. These sensor types were selected due to their affordability, low power consumption, and suitability for deployment in smallholder and medium-scale agricultural contexts.

Sensor calibration was conducted using reference measurements obtained from certified mechanical water meters and calibrated handheld power analyzers compliant with IEC standards. Initial calibration was performed before deployment, followed by weekly verification checks to account for potential sensor drift caused by environmental factors such as temperature variations, humidity, and prolonged outdoor exposure. Calibration adjustments were applied when deviations exceeded predefined thresholds.

Manual validation was performed by comparing sensor readings against ground-truth reference measurements collected under normal operational conditions across irrigation, storage, and transportation stages. A total of 45 paired reference measurements (15 per monitored plot) were collected over the four-week observation period by trained technicians. Sensor performance was evaluated using deviation-based criteria, and accuracy was considered acceptable when deviations remained below 5% for both water and energy metrics, a threshold commonly adopted in applied agricultural monitoring systems. Under these criteria, the sensor-derived measurements achieved an accuracy exceeding 95%, confirming their suitability for the intended environmental performance assessment.

To illustrate operational variability, Table 5 compares environmental performance across different citrus batches, highlighting how cultivation practices and post-harvest handling influence sustainability indicators. The observed variations reveal opportunities for targeted improvements in irrigation efficiency and energy management.

The variability observed across batches can be attributed to differences in irrigation scheduling, soil moisture conditions, and cold storage duration following harvest. For instance, batches with slightly higher water consumption correspond to plots where irrigation events occurred closer to harvesting periods, while lower energy usage reflects shorter storage times or more efficient pump operation. These results illustrate how operational practices directly influence environmental performance indicators.

To further illustrate the impact of irrigation optimization on environmental performance, Figure 4 presents a comparison of water consumption per kilogram of citrus before and after the implementation of the optimized irrigation strategy. The observed reductions in water usage across all monitored batches demonstrate the practical benefits of data-driven resource management while maintaining stable energy consumption and CO_2 emission levels. This improvement can be explained by the use of sensor-based irrigation monitoring, which allowed farmers to better align irrigation volumes with crop water requirements. By reducing unnecessary irrigation events, the system helped optimize water usage without increasing energy demand or affecting other operational parameters.

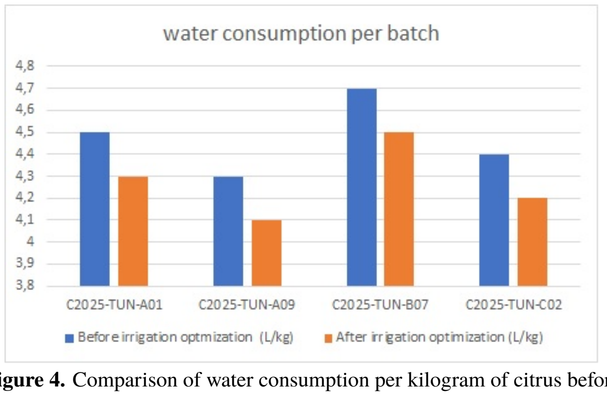


Figure 4. Comparison of water consumption per kilogram of citrus before and after irrigation optimization across monitored batches.

Sensor calibration and validation were conducted using a mixed laboratory and in-field approach. Water flow sensors were calibrated against certified mechanical flow meters, while energy consumption measurements were validated using portable reference power analyzers compliant with IEC standards. Environmental sensors were cross-checked using calibrated handheld instruments under controlled conditions.

Validation was performed on a total of 45 reference samples collected across the three plots during different operational conditions (irrigation events, storage cooling cycles, and transportation phases). The comparison between sensor readings and ground-truth measurements yielded a mean absolute error (MAE) below 5% for both water and energy metrics, with root mean square error (RMSE) values consistently below operational thresholds. The coefficient of determination (R^2) exceeded 0.93 across validated indicators, indicating strong agreement between measured and reference values.

Carbon footprint estimates were validated indirectly by comparing computed emissions against standard IPCC-based emission factor ranges reported for similar citrus production systems. While this approach does not constitute direct measurement, it ensures consistency with internationally accepted accounting frameworks.

5.2 System Performance Evaluation

Technical performance testing demonstrated the system's efficiency in managing real-time data transmission and recording with minimal latency. Key metrics included an average blockchain transaction time of 1.8 seconds, a block creation interval of approximately 5 seconds, and figure execution for data validation taking less than 200 milliseconds.

These observed performance metrics are largely attributable to the use of a lightweight, permissioned blockchain network with a limited number of validator nodes, which reduces consensus overhead compared to public blockchains. Additionally, local edge buffering and efficient data aggregation minimize network congestion and transmission latency, ensuring timely recording of environmental measurements. The modular software architecture further allows parallel processing of incoming sensor streams, which contributes to the observed scalability and responsiveness.

No data loss or corruption was observed during the testing period. The permissioned blockchain infrastructure ensured complete immutability and non-repudiation of all environmental records. The modular architecture also facilitated seamless integration of new sensors and stakeholders, confirming the system's scalability and adaptability for diverse agricultural contexts.

5.3 System Interface and Visualization

To complement the quantitative environmental performance metrics, we present the user-facing interfaces of the proposed system. These interfaces illustrate how stakeholders interact with real-time sustainability data and make informed decisions based on product quality and environmental impact.

Figure 5 presents two main views of the platform:

- **Storage Manager Dashboard (Figure 5a)**: This interface enables the storage manager to monitor product quality, track key environmental indicators, and make compliance decisions regarding batches. Data from IoT sensors are aggregated and visualized in real time, highlighting deviations or anomalies that require attention.

Table 5. Environmental performance comparison across citrus batches

Batch ID	Water (L/kg)	Energy (kWh/kg)	CO_2 (kg CO_2-eq/kg)	Eco Score
C2025-TUN-A01	4.3	0.47	0.63	4.0
C2025-TUN-A09	4.1	0.50	0.65	3.5
C2025-TUN-B07	4.5	0.45	0.60	4.2
C2025-TUN-C02	4.2	0.48	0.62	4.0

- **Consumer Dashboard via QR Code (Figure 5b)**: Consumers can scan a QR code on citrus products to access verified information about the environmental footprint of the batch, including water consumption, energy usage, and CO_2 emissions. This interface also displays the product history, ensuring transparency and empowering eco-responsible purchasing decisions.

By integrating these dashboards, the platform demonstrates its practical usability and provides tangible evidence of how blockchain-secured, sensor-driven data can be presented intuitively for different stakeholders. The combination of technical robustness (from IoT and blockchain) and user-centric design enhances trust, transparency, and sustainability awareness across the citrus supply chain.

5.4 Usability and Stakeholder Engagement

Stakeholder interviews were conducted with 12 participants, including farmers, storage managers, transporters, and consumers, using a semi-structured protocol. The interviews consisted of open-ended and Likert-scale questions designed to assess usability, clarity of environmental metrics, and practical utility of the platform. Responses were coded thematically to identify common patterns and insights.

Quantitative usability metrics were derived from the Likert-scale questions, with scores ranging from 1 (poor) to 5 (excellent). The overall mean usability rating across all participants was 4.6 ($\pm$0.3), indicating high satisfaction. Farmers particularly valued irrigation tracking tools and dashboards for resource planning. Storage managers highlighted the system's role in monitoring energy efficiency and maintaining temperature compliance. Transporters appreciated improved delivery tracking and fuel consumption reporting. Among consumers, over 80% indicated that access to product-specific environmental data via QR codes would influence their purchasing decisions.

These findings confirm the platform's practical usability and engagement potential across all stakeholder groups. The high satisfaction and positive feedback are likely due to the intuitive, role-specific interface design, which presents environmental indicators in a clear and contextualized manner. Farmers could easily interpret irrigation and energy data for operational decisions, while consumers accessed verifiable sustainability information through QR codes, fostering trust and informed choices. By combining quantitative ratings with qualitative thematic insights, the study demonstrates that the system effectively supports informed decision-making from production to consumption, and illustrates how transparent, actionable environmental metrics can enhance stakeholder awareness and adoption of sustainable practices.

5.5 Impact on Sustainability Practices

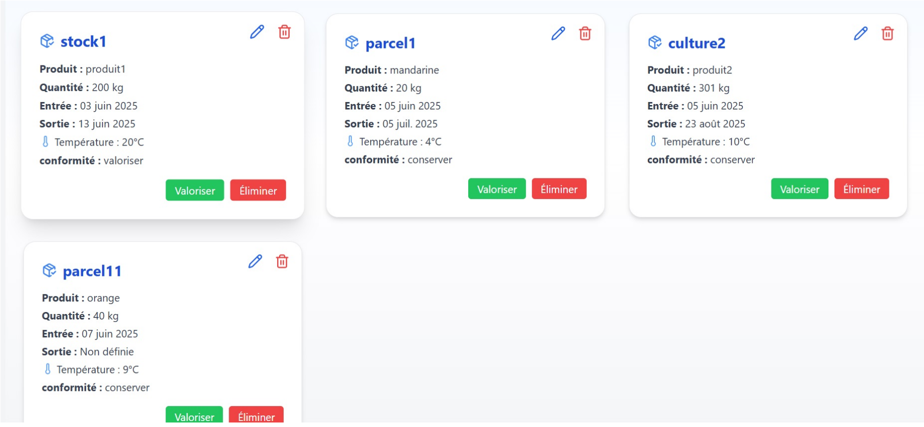
The integration of blockchain-secured environmental data with intuitive visualizations led to measurable behavioral changes across multiple stakeholder groups. Farmers reduced irrigation frequency by approximately 15% after analyzing real-time water consumption trends, while storage managers optimized cold-room operations during off-peak hours, resulting in a 12% reduction in energy use. In parallel, consumers showed a clear preference for citrus batches with lower environmental footprints when transparent sustainability indicators were made accessible.

These outcomes highlight the system's role as a catalyst for eco-responsible decision-making throughout the supply chain, by translating heterogeneous environmental measurements into actionable and verifiable insights. However, the functional role of real-time data differs across stakeholder categories.

For primary producers, real-time data acquisition is critical to enable timely operational decisions such as irrigation adjustment, energy load shifting, or early detection of inefficiencies. In contrast, for downstream stakeholders such as distributors and consumers, the value of near real-time environmental information lies not in second-level immediacy, but in the availability of up-to-date, event-synchronized, and immutable sustainability indicators at key decision points, including logistics handling, quality control, and product selection.

For distributors and retailers, access to recently updated environmental metrics facilitates the rapid identification of deviations from expected operating conditions, such as excessive energy consumption during cold storage or abnormal emissions during transportation. This enables corrective actions including batch-level verification, delayed release, or logistics reconfiguration. Similar approaches have been reported in highly traceable and high-value supply chains, such as cold-chain logistics, pharmaceuticals, and premium food products, where near real-time monitoring supports accountability and risk mitigation.

For consumers, instantaneous access to environmental information through QR codes ensures that sustainability indicators reflect the most recent verified state of the product rather than static or post hoc declarations. This timeliness reduces information asymmetry, enhances trust in sustainability claims, and strengthens informed purchasing decisions at the point of sale. Consequently, the real-time aspect of the proposed system should be understood as a mechanism for continuous data synchronization and transparency across the supply chain, rather than as a requirement for sub-second decision making for all stakeholders.



(a) Storage manager dashboard for product quality monitoring.

(b) Consumer view accessed via QR code, displaying product history and environmental metrics.

Figure 5. Illustration of the user interfaces in the proposed system.

5.6 Comparative Analysis

Table 1 summarizes a comparative analysis between the proposed platform and representative traceability systems reported in the literature. From a technical standpoint, several baseline functionalities are shared across these systems, including IoT-based data collection, basic environmental monitoring, and batch-level traceability. However, important differences emerge when considering system architecture, domain specificity, and user interaction.

Compared to AgriSense [Eswaran *et al.*, 2024], which primarily provides historical monitoring data for post-analysis, the proposed system enables near real-time data acquisition and feedback loops at the field level. This capability supports operational interventions such as dynamic irrigation adjustment, which in the pilot deployment resulted in a water consumption reduction of up to 10% per batch. The observed improvement is attributable to the integration of fine-grained IoT sensing with automated data aggregation and visualization, allowing farmers to make timely and informed decisions that directly impact resource efficiency.

FarmTrack [Sriram *et al.*, 2024] relies on a centralized data management architecture, which simplifies deployment but limits transparency and trust across stakeholders. By contrast, our platform integrates a permissioned blockchain layer to ensure data immutability, non-repudiation, and controlled access among producers, logistics operators, and downstream actors. This architectural choice not only secures the data but also motivates stakeholder engagement and adherence to sustainability practices, as actors can trust the recorded environmental metrics, which explains the high acceptance and reported impact on decision-making.

Beyond architectural differences, the proposed system distinguishes itself through its citrus-specific design and user-centric features, which are not explicitly addressed in most general-purpose traceability platforms listed in Table 1. These include crop-tailored monitoring indicators (e.g., irrigation water per kilogram of citrus), batch-level environmental footprint aggregation, and a consumer-facing interface based on QR codes. In the pilot study, approximately 80% of surveyed consumers reported that access to environmental traceability information influenced their purchasing decisions. This impact arises from the combination of accurate, real-time environmental data and a clear, actionable presentation, demonstrating how technical design choices directly contribute to both operational performance and stakeholder engagement.

Overall, this comparative analysis indicates that while the proposed system builds upon common technological foundations found in existing platforms, it extends the state of the art by combining real-time operational support, citrus-specific environmental accounting, and end-user transparency within a unified architecture. The observed improvements in water efficiency, energy monitoring, and user engagement can thus be directly linked to the integrated IoT–blockchain infrastructure, role-specific interfaces, and targeted design choices for citrus production.

5.7 Limitations

While the proposed system demonstrated promising results during the pilot deployment, several technical and operational limitations should be acknowledged, particularly regarding large-scale adoption and long-term deployment.

First, the use of low-cost sensing devices, while essential for affordability and scalability, requires regular calibration to maintain acceptable data accuracy over time. Although calibration and validation procedures were applied during the pilot, long-term deployments would benefit from automated calibration mechanisms or adaptive correction models to reduce maintenance effort.

Second, connectivity constraints were observed in rural environments across the monitored citrus-producing areas, occasionally affecting data transmission reliability. While edge computing and local buffering mitigated part of this issue, intermittent network availability remains a challenge. More advanced synchronization strategies and redundancy mechanisms would be required to ensure uninterrupted operation under highly variable connectivity conditions.

Third, the current carbon footprint assessment relies on generalized emission and conversion factors derived from international standards. While appropriate for comparative and exploratory analysis, this approach does not fully capture region-specific agricultural practices, machinery characteristics, or energy mixes. Future work should therefore incorporate localized emission factors to improve the accuracy and contextual relevance of carbon impact estimates.

Although the pilot deployment covered multiple citrus-producing sites in Tunisia, including the Cap Bon region, the system has not yet been evaluated under large-scale cooperative or nationwide operational conditions. Scaling the platform to support a higher number of farms and heterogeneous stakeholders would require more advanced data governance, access control, and coordination mechanisms to preserve trust, efficiency, and data ownership.

Furthermore, the environmental dataset used in this study remains context-specific to Tunisian citrus production. While the collected IoT measurements provide reliable insights for the case study, broader comparative environmental benchmarking across different agricultural regions, climatic conditions, and crop types has not yet been conducted. Expanding benchmark datasets in future implementations would strengthen cross-context sustainability assessment, improve generalizability, and enable standardized environmental performance comparisons.

In addition, the four-week observation period, while sufficient to validate system functionality, data consistency, and measurement reliability, does not capture the full seasonal variability of an entire citrus production cycle. Resource consumption patterns may differ substantially during flowering, fruit development, and harvest phases, as well as under varying climatic conditions. Consequently, the reported environmental indicators should be interpreted as indicative rather than fully representative of annual performance. Extending monitoring to cover complete production cycles constitutes an important direction for future research.

Finally, although the blockchain infrastructure was designed as a lightweight, permissioned network relying on energy-efficient consensus mechanisms, its own energy and environmental impact was not quantitatively assessed in this study. Design choices such as the absence of energy-intensive mining, a limited number of validator nodes, controlled transaction frequency, data aggregation at the edge, and the use of off-chain storage substantially reduce the environmental footprint when compared to public blockchain networks. Nevertheless, the cumulative energy impact of the digital infrastructure remains an important consideration when scaling the system to larger supply chains or broader geographic deployments.

The adoption of an IoT- and blockchain-based traceability platform may also raise accessibility concerns, particularly for smallholder farmers. While low-power communication technologies such as LoRaWAN help limit connectivity and energy costs, initial investments in sensing devices, gateways, and basic digital infrastructure may still constitute barriers for resource-constrained stakeholders. In addition, effective use of the platform requires a minimum level of digital literacy and training, which may result in uneven adoption and potential digital inequalities. Addressing these challenges will require complementary measures such as shared infrastructure models, cooperative deployment strategies, public or institutional support, and targeted capacity-building initiatives in future implementations.

From a data availability and reproducibility perspective, raw sensor logs and system-level data streams cannot be made publicly available due to confidentiality agreements with participating farms. Nevertheless, the logging mechanisms, sampling rates, calibration protocols, validation procedures, and aggregated performance indicators are fully documented to ensure methodological transparency and reproducibility.

6 Conclusion and Future Work

This paper presented a novel environmental traceability system designed for citrus supply chains, integrating IoT-based environmental sensing, blockchain-secured data storage, and an intuitive user interface. The proposed platform enables real-time monitoring and transparent sharing of key sustainability indicators, including CO_2 emissions, water consumption, and energy usage. It empowers stakeholders across the supply chain with verifiable insights into the environmental footprint of citrus products.

Experimental deployment confirmed the technical feasibility, scalability, and usability of the system in a real-world agricultural context. By ensuring tamper-proof data collection and transparent visualization, the platform supports eco-responsible practices and informed consumer decision-making. From a scientific perspective, this work contributes to digital agriculture by demonstrating the value of combining IoT and blockchain technologies for environmental traceability in horticultural supply chains.

Beyond its technical contributions, this work highlights important socio-technical considerations related to data ownership, inclusivity, and environmental responsibility. By prioritizing producer data sovereignty, lowering adoption barriers for smallholder farmers, and minimizing the energy footprint of the blockchain infrastructure, the proposed platform aims to balance technological innovation with social and environmental accountability.

In future work, building upon the limitations identified in this study, several directions can be explored to further improve the robustness, scalability, and intelligence of the proposed system:

- Integration with third-party certification bodies and eco-labeling schemes to align blockchain-based traceability with regulatory requirements and market-driven sustainability standards.
- Incorporation of lightweight AI-based analytics at the edge and processing layers for anomaly detection, predictive irrigation scheduling, environmental footprint forecasting, and energy optimization in cold storage. Resource-efficient machine learning models deployed on IoT gateways would enable real-time predictive capabilities while maintaining low computational overhead. All AI outputs will remain traceable through blockchain registration to ensure transparency and trust.
- Expansion toward multi-farm, cooperative, and cross-regional deployment models, enabling scalable data aggregation, federated governance, and comparative environmental benchmarking across agricultural sites.
- Development of mobile-first, low-bandwidth, and low-literacy-friendly user interfaces to improve accessibility and adoption by smallholder farmers and non-expert stakeholders in rural environments.
- Comprehensive economic and socio-technical evaluation of adoption scenarios, including cost–benefit analysis, infrastructure constraints, incentive mechanisms, and stakeholder acceptance.

These extensions aim to enhance the system's intelligence, scalability, and inclusiveness, while maintaining its core principles of transparency, robustness, and environmental accountability. Ultimately, they position the proposed framework as a foundation for next-generation, climate-aware digital agriculture systems applicable beyond the citrus sector.

Declarations

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Authors' Contributions

RF contributed to the conception and design of the study, developed the proposed framework, and was the primary writer of the manuscript. RF also performed the system implementation and data processing. MHA contributed to the methodological validation, supervised the research activities, and participated in reviewing and editing the manuscript. MHA also supported the field deployment and data collection. Both authors read and approved the final version of the manuscript.t.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

This work focuses on the design and implementation of a Blockchain–IoT framework for environmental traceability in citrus supply chains.

In line with open science and reproducibility principles, all software artifacts developed in this study—including smart contract templates, edge-layer data acquisition scripts, system architecture documentation, and sample datasets—are publicly available in the GitHub repository: `https://github.com/RimFakhfakh/citrus-traceability`. The repository provides sufficient technical details to enable transparency, reuse, and replication of the proposed framework.

Due to confidentiality agreements with participating farms, the full raw environmental datasets cannot be shared publicly. However, the repository contains anonymized and simulated datasets that closely reflect real sensor readings and deployment configurations. These resources allow other researchers to reproduce the experimental setup, validate system functionalities, and explore further extensions of the framework.

All procedures, parameters, and system-level settings used during the pilot deployment are documented in the repository to facilitate reproducibility and ensure methodological transparency.

Further relevant information

Ethics Approval: The authors declare that generative Artificial Intelligence tools were used exclusively for language editing and stylistic refinement of the manuscript. These tools did not contribute to the study design, data analysis, interpretation of results, or scientific conclusions. The authors take full responsibility for the content of this work.

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