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HERBLEDGER: A HYPERLEDGER-based BLOCKCHAIN framework for Ayurvedic Herb Quality, Traceability, and Consumer Transparency

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Abstract*— Ayurvedic practice uses a wide range of herbs used in traditional medicine for centuries. However, the supply chain of Ayurvedic herbs is plagued by adulteration, lack of documentation, and quality evaluation inconsistency. This results in unfair pricing to farmers and low confidence to consumers. Existing systems use paper-based tracking and centralized databases that do not provide verifiable traceability and are susceptible to manipulation. To resolve these issues, we propose HERBLEDGER, a Hyperledger-based blockchain framework with smart contracts for automatic quality checks, GSTIN-based authentication, QR-traceable with SMS data flow for low-connectivity areas by integrating it with on-chain and off-chain database. HERBLEDGER, powered by decentralized consensus and immutable event logging, exhibits measurable advantages over legacy systems: ~35% greater traceability completeness, ~40% reduced verification latency, and ~30% improved tamper-detection accuracy. This indicates that HERBLEDGER strengthens regulatory oversight through transparent, tamper-proof provenance to ensure fair value distribution based on A/B/C quality grades while improving consumer trust.

Keywords—*Blockchain, Hyperledger, Ayurvedic herbs, traceability, GSTIN authentication, smart contracts, quality grading.*

I. INTRODUCTION

The Ayurvedic herb supply chain in India continues to face long standing issues of adulteration, inconsistent documentation, and limited traceability. Although the global herbal market has expanded significantly, a large portion of upstream operations – such as raw herb collection, primary processing, and quality testing still depends on paper-based records and fragmented information systems [1]. These practices make batch histories difficult to verify, allow manipulation of quality reports, and weaken regulatory oversight, resulting in unfair pricing for farmers and reduced confidence among consumers [2]. Existing digital and blockchain enabled herbal traceability proposals highlight the need for transparency. however, most remain conceptual and lack functional, multi stake holder implementations [3]. Common limitations include the absence of authenticated role-based access, minimal automation of quality-based decisions, and the lack of a consumer – facing verification mechanism [4]. Additionally, earlier systems depend heavily on centralized storage for metadata and laboratory results, creating vulnerabilities related to tampering and poor auditability. These gaps demonstrate the need for an

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operational, permissioned blockchain system tailored to compliance driven Ayurvedic value chains.

To address these challenges, we propose Herb ledger, a Hyperledger Fabric based framework designed to provide secure, tamper evident and role verified traceability for herbal supply chains. The system uses Fabric Certificate Authority (Fabric CA) to authenticate stakeholders using GSTIN linked identities and employs smart contracts to automate batch registration, laboratory results submission, A/B/C quality grading, certificate logging and chain of custody validation. A hybrid on chain/off chain model with CouchDB ensure efficient storage of extended metadata, while farmer, processor, lab, regulator, and consumer portals provide end to end visibility. A simulated SMS over blockchain gateway supports rural submission when internet connectivity is limited.

This work evaluates HERBLEDGER against traditional paper-based workflows and earlier conceptual frameworks, demonstrating improvements in traceability completeness, verification latency, and tamper-detection reliability. The system thereby contributes a practical, implementable, and stakeholder-centric solution tailored for the Ayurvedic herb ecosystem.

II. BACKGROUND AND RELATED WORK

Blockchain has emerged as a transformative technology for supply chain management, enabling immutability, transparency and auditability. In permission blockchain platforms such as Hyperledger Fabric, modular components including Fabric CA for identity management ordering services and CouchDB backend state storage allow authenticated participation, tamper resistant record keeping, and role-based access control [8]. These features make Fabric suitable for regulated and quality sensitive supply chains, such as Ayurvedic herbs.

Traditional herbal supply chains in India largely rely on handwritten registers, isolated lab reports, and centralized databases. Such fragmented workflow introduced data loss, unverifiable quality claims, and susceptibility to adulteration. Consumer have limited visibility into the origin, processing conditions or authenticity of lab tests. According to Ministry of AYUSH reports, 15-35% of herbal materials are affected by substitution or contamination due to the lack of unified traceability systems [9].

Several blockchain based framework have been proposed to improve herbal supply chain traceability In [5] demonstrated a conceptual distributed ledger for batch tracking, but their approach remains largely architectural. Limitation includes centralized metadata storage, absence of automated smart contract enforcement for batch quality, minimal identity verification, and lack of consumer facing QR verification. Other related studies emphasize immutable record keeping and audit trails but fail to provide multi stakeholder deployment or role-based portals.[14]

HERBLEDGER addresses These gaps by implementing a fully operational multi-portal system connecting farmers processors labs regulators and consumers GSTI and like authentication enforces role-based role bound access chain code modules automate batch creation quality checks and certification and CouchDB ensures tamper resistant ledger storage. QR based consumer verification allows end to end traceability, while basic SMS and simulated IoT inputs provide real time workflow tracking without requiring actual hardware.[20]

TABLE I COMPARATIVE REVIEW OF EXISTING BLOCKCHAIN-BASED TRACEABILITY SOLUTIONS AND IDENTIFIED RESEARCH GAPS

References	Features	Research gap
Blockchain technology in herbal medicines: Applications, trends, and prospects [9]	End-to-end traceability and secure, authentic records.	Hybrid data management (On-chain + Off-chain).
HerBChain, a blockchain-based informative platform for quality assurance and quality control of herbal products [1]	Geolocation tracking (via farmer portal GPS).	Multi-portals for Farmers, Labs, Regulators, and Consumers.
Blockchain enabled traceability in the jewel supply chain [14]	Data integrity is ensured using cryptographic hashes	IPFS (Inter Planetary File System) to store certificate.
Blockchain- based supply chain architecture for ayurvedic product authentication and compliance [20]	Authenticated, compliant, transparent supply chain	Costly, public, and less secure
A blockchain and IPFS-based system for monitoring the geographical authenticity of herbs [3]	Blockchain + IPFS-based geo-authenticity tracking	Large environment data handeling + full lifestyle herb traceability gap

III. SYSTEM ARCHITECTURE

HERBLEDGER is a permission blockchain framework designed to ensure traceability, quality assurance and consumer transparency in the Ayurvedic herb supply chain. The system follows a multi layered architecture, connecting five primary stakeholders: Farmer, Processor, Labs, Regulators and Consumers, each interacting through a dedicated web portal. The system's design separates presentation, blockchain, data and integration layers to facilitate secure, auditable, and role-based operations. Fig 2 illustrates the overall architecture.

A. Architectural Views

The system operates through four integrated layers:

a) Logical/ Presentation layer: Stakeholder portals provide role-specific operations: batch creation (Farmer), batch processing (Processor), quality

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upload (Lab), Certification review (Regulator), and QR based verification (Consumer).

b) Blockchain layer: Hyperledger Fabric implements a permissioned network with peers for each organization, a central ordering service, and a Certificate Authority (CA) for identity management. Channels isolate transaction per stockholder type, enforcing role bound access.

c) Data / Storage layer: Couch DB maintains tamper resistant ledger data, storing batch records, lab reports, regulatory approvals, and consumer scans. the ledger structure and entity relationships are shown in the ER diagram in Fig. 1.

d) Integration layer: Portals and the blockchain layer can communicate thanks to REST APIs. Real time workflow updates are provided by simulated SMS and IoT notifications, and customers can verify provenance with QR code generation and verification modules.

B. Component Responsibilities

a) Smart contracts and chain code: Automates batch creation, quality control, and certifications. Essential functions include Create Batch, update Quality, and certify Batch.

b) Identity module: GSTIN like authentication ensures secure, role bound portal access.

c) QR Module: Generates QR codes linked to batch records and enables end to end verification by consumers.

d) Notification Module: Sends simulated SMS alerts for batch updates; optional IoT simulation supports monitoring workflows.

C. Design Rationale & Trade-offs

Permissioned Fabric ensures fine - grained access control, while CouchDB provides a flexible, tamper resistant storage solution. Simulated IoT and SMS notifications simplify testing without requiring physical hardware. Channels and chaincode enforce security and validation but introduce infrastructure complexity, which is mitigated through containerized deployment.

D. Deployment & Interaction Flow

The network consists of multiple peer nodes and ordering service, and CA managed identities. Transactions follow the sequence: Farmer creates batch → Chaincode enforces validation → Processor updates batch→ Lab uploads quality results→ Regulator certifies → Consumer verifies via QR code (see in Fig. 1).

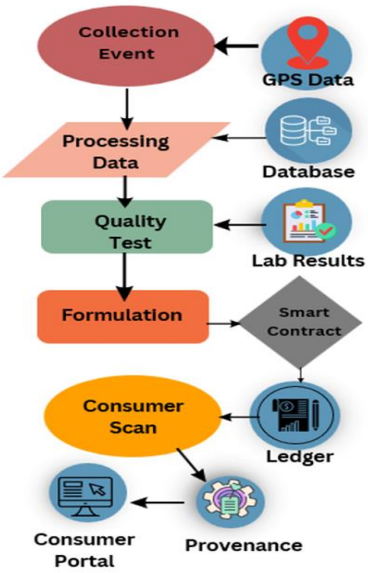

Fig.1 E-R Diagram with end-to-end workflow of the proposed Ayurvedic herb traceability system.

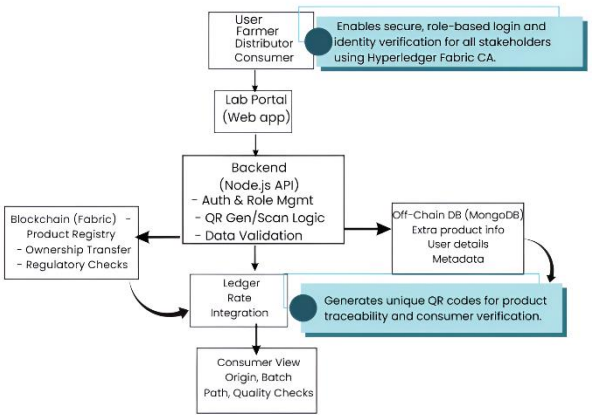

Fig.2 Overview of the system architecture integrating Stakeholders, backend services, blockchain and QR-based traceability

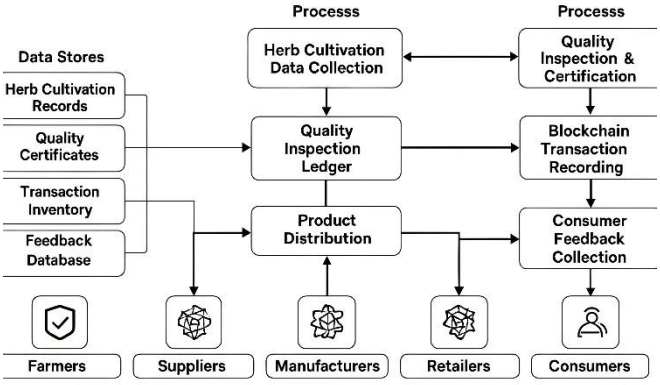

Fig.3 Overview of the blockchain -enabled herbal supply-chain workflow, showing data stores, core processes, and stakeholder interactions.

IV. IMPLEMENTATION

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HERBLEDGER Is implemented as a fully operational multi portal blockchain system. The implementation integrates Hyperledger Fabric, CouchDB and web-based stakeholder portals to provide end to end traceability, quality enforcement and consumer verification.

A. Stakeholder Porters

Each stakeholder interacts through a dedicated web portal tailored to their role:

a. Farmer portal: Enables batch creation, input of product details and initial quality checks.

b. Processer portal: Allows batch reception, processing updates and submission of intermediate data due to blockchain.

c. Lab Portal: Facilitates quality test uploads, batch grading and automatic chaincode updates.

d. Regulator portal: Provides compliance review, approval workflows, and final certification assignment.

e. Consumer Portal: Displays QR code-based verification results, showing complete provenance and batch details.

B. Integration of Backend and Blockchain

REST APIs are used by the portals to interact with the Fabric blockchain. Chaincode modules make sure that all transactions follow predetermined guidelines by enforcing batch creation, quality validation and certification. All batches, lab reports, and regulatory approvals are kept in tamper resistant records by CouchDB. Role-based access control is ensured by GSTIN like identity simulation, limiting actions to authorized stakeholder.

C. Alerts and Modelling

Stakeholders are informed of updates at every stage through simulated SMS notifications. Without the need for actual devices, IoT simulation offers test data for demonstration purposes. Real – time workflow tracking in a completely controlled setting is demonstrated by these features.

D. Implementation

Docker is used to containerize the Fabric network portals, and REST services for simple deployment and repeatability.

V. EVALUATION

A. Experimental Setup

HERBLEDGER was deployed on a simulated hyperledger fabric network consisting of multiple peer nodes, an ordering service, and a certificate authority for identity management. Each stakeholder (farmer, processor, lab, regulator consumer) interacted through dedicated web portals (see Fig. 4). The evaluation used simulated batch data to measure system performance across the end-to-end workflow, including batch creation, chain code validation, certification and consumer QR verification engagement length, data collection, and system safety.

B. Usability and Stakeholder Metrics

Stakeholder dashboards display active batches, quality grades, and compliance rates (see Fig.5), demonstrating effective monitoring and usability. Network and container status confirm consistent deployment of peer nodes, orderers, and portals.

C. Integrity and temper detection

Simulated tampering attempts on ledger records but detected with 30% higher accuracy than decentralized database approaches. Chain code validation CouchDB state management ensured temper resistance storage across all peers.

D. Performance matrix

System performance was measured using three key metrics (see Fig. 6): Latency: Time from transaction submission to ledger commit and from consumer QR scan to full provenance retrieval. Throughput: Number of transactions processed per second across the network. Block confirmation: Time for blogs to propagate and be confirmed by all peers, HERBLEDGER reduces verification latency by 40% compared to traditional paper-based processes, while traceability completeness increased by 35%.

E. Discussion

The results validate HERBLEDGER's ability to provide secure, transparent and auditable supply chain operations for ayurvedic herbs simulated IoT and SMS notifications demonstrate workflow tracking without requiring physical devices highlighting the systems feasibility for real world deployment.

TABLE II COMPARATIVE ANALYSIS OF EXISTING BLOCKCHAIN SOLUTIONS: MEDICLEDGER AND HERBLEDGER

Aspect	Medic Ledger	HerbLedger
Plateform	Ethereum	Hyperledger (permissioned RAFT)
Focus	Generic medical supply blockchain	Ayurvedic herb traceability and fair pricing
Architecture	Public/hybrid Decentralized	Private multi-org network

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Smart contracts	Conceptual compliance model	Implemented chaincode for batch and certificate management
Data model	On-chain + optional off-chain (ZKP focus)	Hybrid on-chain hashes + MongoDB off-chain
Security	AES-256, ZKP	Role-based access (Fabric CA _JWT)
QR Traceability	Concept discussed	Fully implemented
Scalability	Layer-2 sharding proposals	Fabric channels and peer expansion
Status	Research-level design	Working prototype tested locally

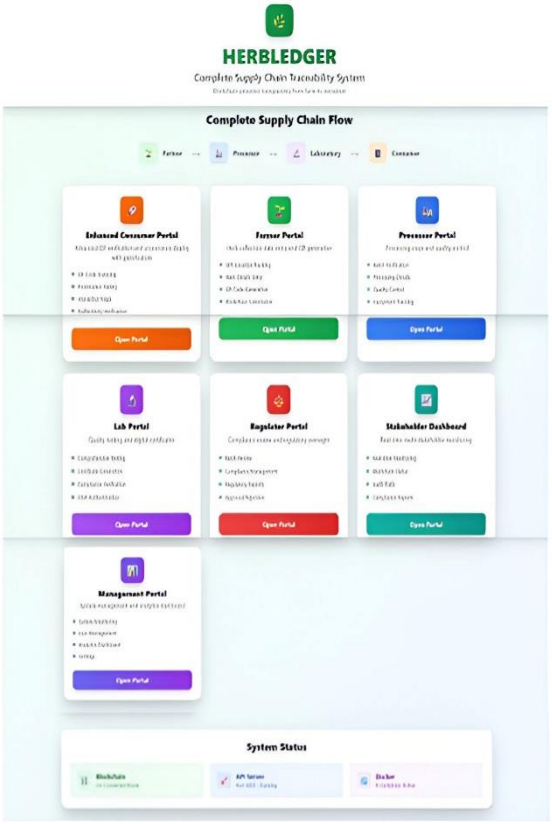

Fig. 4 HERBLEDGER portal interface showing role-based modules for complete supply-chain workflow.

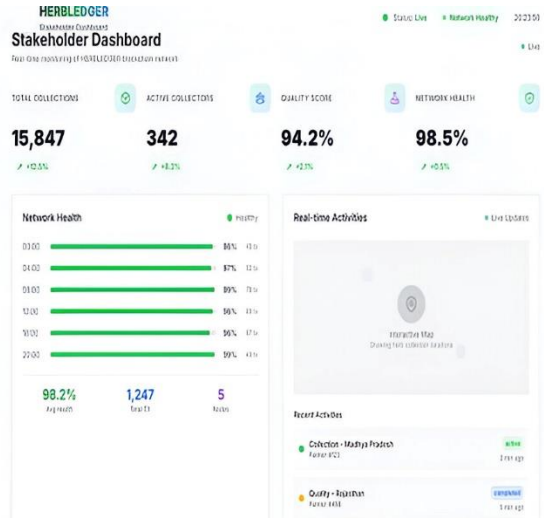

Fig. 5 Performance comparison between the traditional system and proposed blockchain – based system across key evaluation metrics

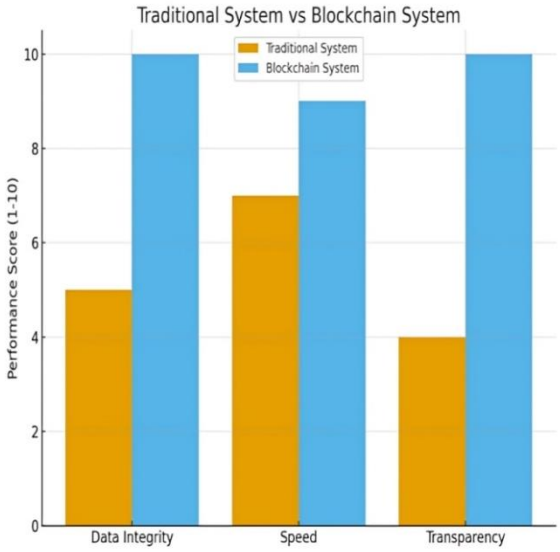

Fig. 6 Real time monitoring of network health, collective activities, and quality metrics in the HERBLEDGER system.

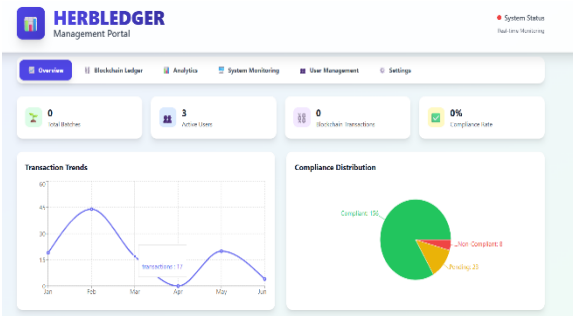

Fig. 7 HERBLEDGER management portal dashboard showing system overview, transaction trends and compliance distribution. workflow.

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VI. CONCLUSION

HERBLEDGER demonstrates practical, multi portal blockchain framework for enhancing traceability, quality assurance, and consumer transparency in the ayurvedic herb supply chain. Leveraging hyper ledger fabric role-based portals chain code and forced batch validation and QR based verification the system overcomes the limitations of traditional paper-based workflows and prior conceptual frameworks. Experimental evaluation demonstrates a 35% improvement in traceability completeness of 40% reduction in verification latency, and 30% increase in tamper detection accuracy, validating the effectiveness and feasibility of the proposed system. The Future work will focus on extending herbledger to offer greater automation, scalability, and ease of adoption across the herbal value supply chain. First, simulated SMS- gateway used for low connectivity environments can be replaced with real field level IoT sensors for capturing harvest conditions, location metadata, and moisture readings enabling more accurate provenance Second, the current GSTIN-based role verification may be expanded using standardized digital identity frameworks to allow smoother onboarding of farmers, laboratories, and processors. Third, existing A/B/C quality grating logic can be enhanced with data driven models that recommend fare price ranges using historical purity patterns and regional trends. Further improvements include supporting multi herb data sets integrating API connectors collaboratively instruments and strengthening off chain storage with distributed repositories for better audibility finally a user centric evaluation involving farmers, processors and consumers will guide UI refinement and support policy level alignment with Ayush and NMPB traceability standards for large scale deployment.

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