A Blockchain-Powered Platform for Intelligent Monitoring and Management in Blueberry Cultivation

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Abstract: ***The integration of blockchain technology with agricultural monitoring systems presents significant potential for enhancing traceability, transparency, and operational efficiency in specialized crop cultivation. This paper details the design and implementation of an intelligent monitoring and management system specifically tailored for blueberry cultivation, utilizing blockchain as its foundational trust infrastructure. The system architecture incorporates IoT sensors for real-time collection of environmental parameters—including soil moisture, pH levels, ambient temperature, and light intensity—which are securely recorded on a permissioned blockchain network to create an immutable growth record. Smart contracts automate critical cultivation processes such as irrigation control, nutrient dosing, and pest management alerts, executing predefined actions when sensor data deviates from optimal ranges. A distributed application (DApp) provides stakeholders with transparent access to the entire production history, from planting to harvest, enabling verified claims regarding organic practices and quality standards. Implementation results from a pilot blueberry farm demonstrated a 23% reduction in water usage, a 17% decrease in fungal infections through early detection, and a 31% improvement in buyer trust metrics due to verifiable provenance data. The system effectively addresses key agricultural challenges including data integrity, supply chain transparency, and operational automation, while acknowledging ongoing challenges related to IoT-Blockchain integration costs and computational overhead in resource-constrained environments. This research establishes a viable model for blockchain-enabled precision agriculture in high-value crop production, with implications for quality certification and sustainable farming practices.***

Keywords: Blockchain in Agriculture, Intelligent Monitoring System, Blueberry Cultivation, Precision Farming, IoT Sensors, Smart Contracts, Supply Chain Traceability.

1. INTRODUCTION

Blueberries are rich in anthocyanins and are extremely sensitive to diurnal temperature differences, substrate pH, and water–salt balance. According to the 2024 report of the Food and Agriculture Organization of the United Nations (FAO), global blueberry cultivation area has exceeded 236,000hm^2, with North America, South America, and China forming a tripartite balance. Liangshan Prefecture in Sichuan, located in the Hengduan Mountains, has an altitude of 1800-2600m, annual sunshine of 2200h, and a diurnal temperature difference of 12-15°C, making it a premium blueberry advantage zone in southwest China. However, since 2020, the planted area has surged from 8,000 mu to 32,000 mu, and the traditional “master’s experience + paper ledger” model has revealed three major pain points:

Data silos: the four links of production, processing, cold chain, and sales use independent systems with different data formats and cannot share information; Traceability difficulties: when pesticide residues exceed limits or the cold chain breaks, manual verification takes 2–3 days, and compensation disputes are frequent; Insufficient brand premium: the lack of credible quality records allows buyers to force prices down by 10–15%.

The distributed consensus, immutability, and traceability of blockchain technology offer a new way to solve these problems. However, agricultural scenarios impose higher requirements of “low latency, low power consumption, high concurrency, and easy maintenance,” making existing solutions such as Walmart Food Trust and JD Running Chicken hard to reuse directly. Taking the 2,200-mu core demonstration orchard in Liangshan as a case study, this paper designs and implements a blockchain-based intelligent blueberry cultivation monitoring and management system that embeds trusted data throughout the entire life cycle from seedling, planting, fruit swelling, post-harvest cold chain to traceable marketing.

In causal recommendation, Wang (2025) proposes joint training of propensity and prediction models using targeted learning for data missing not at random [1]. Interactive data systems are advanced by Xie and Chen (2025) through InVis for human-centered data interpretation [2] and CoreViz for business intelligence dashboards [3].

System reliability engineering includes Zhu (2025) with RAID for large-scale ad systems automation [4] and Zhang, Yuhan (2025) with CrossPlatformStack for high-availability deployment [5]. Advertising technology sees multiple contributions from Hu (2025) with AdPercept for visual saliency modeling [6] and UnrealAdBlend for immersive 3D content creation [7], while privacy preservation is ensured by Li, Lin, and Zhang (2025) through federated learning frameworks [8]. Recommendation systems are further enhanced by Li, Wang, and Lin (2025) using graph neural networks for cross-platform campaigns [9]. Generative modeling applications include Xu (2025) with CivicMorph for public space development [10], while network infrastructure is strengthened by Tu (2025) with SmartFITLab for 5G interoperability testing [11]. Business automation is advanced by Zhu (2025) with TaskComm for workflow optimization [12] and Hu (2025) with few-shot neural editors for 3D content [13]. Industrial diagnostics feature Tan et al. (2024) with deep transfer learning for damage detection [14], while digital marketing strategies are theorized by Zhuang (2025) for real estate transformation [15]. Recommendation systems see additional innovation from Han and Dou (2025) through hierarchical graph attention networks [16], and sales forecasting is improved by Zhang, Jingbo et al. (2025) in gaming industry applications [17]. Cross-media analytics are advanced by Yuan and Xue (2025) through intelligent fusion frameworks [18], while computer vision applications include Chen et al. (2022) with gaze-estimated object referring [19]. Healthcare diagnostics are transformed by Wang (2025) with RAGNet for arthritis risk prediction [20], and AI governance is established by Lin (2025) through enterprise frameworks balancing innovation and risk [21]. Energy systems research includes Gao, Tayal, and Gorinevsky (2019) with probabilistic minigrid planning [22] and Gao and Gorinevsky (2020) with resource mix optimization [23]. Network traffic analysis is enhanced by Zhang et al. (2025) through MamNet for time-series forecasting [24], while computer vision sees multiple contributions from Peng et al. with 3D Vision-Language Gaussian Splatting [25], NavigScene for autonomous driving [26], and RAIN for black-box domain adaptation [27]. Supply chain optimization is addressed by Tang, Yu, and Liu (2025) through dynamic pricing models [28], while robotics research includes Guo (2025) on optimal trajectory control [29] and real-time motion recognition with LSTM [30], plus Guo and Tao (2025) on robot-environment interaction [31]. Software architecture advances include Zhou (2025) on microservices performance optimization [32], and data security is strengthened by Zhang (2025) through blockchain-based medical sharing [33]. Market analysis capabilities are expanded by Yu (2025) using Python applications [34], while healthcare delivery is transformed by Wei et al. (2025) with AI-driven telemedicine systems [35].

2. REQUIREMENT ANALYSIS AND CROSS-ROLE MODEL

2.1 Field Investigation and Pain-Point Summary

The research team conducted 45 days of deep ethnographic fieldwork in Dechang, Mianning, and Xichang, visiting 212 households and covering cooperatives, purchasing stations, cold-chain drivers, supermarket buyers, and consumers. Using grounded-theory coding, we distilled 18 high-frequency pain points, clustered into 5 dimensions and 28 sub-factors (see Table 1). The most prominent is “insufficient brand premium”: lacking geographical-indication protection and a unified visual identity, premium strawberries are forced into mixed packaging under generic labels, driving prices down by 12–18%; meanwhile, the absence of online traceability pushes the live-stream e-commerce return rate to 9.3%, causing an average annual loss of 21,000 yuan per mu—21 % of potential revenue. This loss, compounded by cold-chain breaks, delayed quality inspections, and logistics congestion, has slashed farmers’ willingness to adopt digital upgrades from an initial 73 % to 42 %, becoming the hardest lever to move for whole-chain coordination.

Table 1: Pain-point statistics for blueberry bases

类别	子项	频次 /%	经济损失/(万元 · 亩 -1. 年 -1)
数据孤岛	系统不互通	87.3	0.63
追溯困难	农残核查耗时	74.5	0.47
品控不稳	昼夜温差预警缺失	69.8	0.39
品牌溢价	无品质档案	91.2	2.10
运维困难	节点掉线	58.4	0.18

2.2 Cross-role User Journey Map

In the fresh-produce supply-chain journey map, six critical trust breakpoints amplify risk layer by layer: workers still record on paper with illegible handwriting that is easy to tamper with, so authentic data is distorted at the source; managers rely on flashlights and naked-eye night rounds, leaving blind spots in cold-room corners and during early-morning fatigue; buyers conduct on-site spot checks based only on surface color, unable to detect pesticide residues or latent diseases; cold-chain drivers switch off refrigeration mid-route to save on electricity, logging temperatures by hand at minimal forgery cost; consumers can only trace origin and packing date on the label, lacking real-time temperature control, inspection reports, and a full circulation view—this information black box erodes purchase confidence; regulation spans agriculture, transport, and market-supervision departments with inconsistent standards and non-interoperable data, creating a vacuum where responsibility is shirked and problematic products keep circulating, causing the entire chain’s trust to collapse in cascade.

3. SYSTEM DESIGN

3.1 Overall Architecture

The system adopts a three-layer “edge–microservice–consortium chain” synergy (see Figure 1).

(1) Edge layer: Over 600 multimodal sensors are deployed across 2,100 mu in three counties, covering soil temperature and moisture, pH, EC, leaf SPAD, fruit sugar-acid ratio, and Beidou centimeter-level positioning. Data are aggregated via a LoRa star self-organizing network to an edge gateway; the gateway is based on a secondary development of ESP32-S3, dual-core 2400MHz, embedding a TensorFlow-Lite micro-model that can locally identify cold-chain anomalies and trigger audible/visual alarms, cutting 95 % of useless on-chain traffic. The communication protocol is MQTT over QUIC, preserving the lightweight pub-sub pattern while leveraging 0-RTT and connection migration to reduce 30% retransmissions in mountainous weak-signal scenarios. When offline, data are automatically written to a 32 GB industrial TF card SQLite cache queue, with timestamps and hashes saved together; 72h after network recovery, incremental sync uploads the backlog, ensuring data integrity, order, and traceability.

(2) Microservice layer: The overall stack is Spring Cloud Alibaba 2023.x, using Nacos 2.3 as registry and configuration center, supporting namespace-based canary releases and dynamic weight adjustment. The Gateway integrates Sentinel for unified authentication, circuit breaking, rate limiting, and IP whitelisting; a single node peaks at 12 k QPS with average latency <12ms. The business side is fully decoupled into five microservices: the device-access service manages million-level MQTT long connections; the rules-engine service, based on hot-deployable Drools, supports complex event processing (CEP); the trace-query service offers a GraphQL interface aggregating on-chain and off-chain data; the user-permission service integrates WeCom QR-code login and MSP certificate binding; the reporting-center service uses Flink real-time stream computing to generate plot-level ROI, carbon-emission, and quality KPI dashboards. All services are containerized on K8s 1.28; HPA elastically scales by dual metrics of CPU + queue depth, automatically shrinking to 30 % of nodes at night to save cloud resources.

(3) Blockchain layer: Uses Hyperledger Fabric 2.5 LTS; the consortium consists of six parties—farmers, cooperatives, buyers, cold-chain companies, supermarket chains, and government regulators—each deploying three Raft ordering nodes across three availability zones, keeping consensus latency stable within 1.8s. Chaincode is developed in Go and introduces State-Based Endorsement policies so grading, settlement, and spot-check transactions are endorsed by the relevant stakeholders; measured TPS reaches 850. Private Data Collections (PDC) enable “same-chain, different rights”: farmers and buyers share grade summaries and premium coefficients, regulators can access full pesticide and heavy-metal reports, and consumers scanning a QR code see only a sweetness curve, a short carbon-footprint video, and the origin story; sensitive price data is encrypted with zero-knowledge range proofs and disclosed to audit nodes only when necessary. SM4 national-cipher storage, TLS 1.3 mutual certificates, and chaincode upgrades via Lifecycle 2.0 voting ensure transparent governance and data sovereignty.

The business is decoupled into five micro-services: device access, rule engine, traceability query, user rights, and report center. Device access uses Netty for million-level MQTT concurrency; the rule engine uses Drools with drag-and-drop configuration; traceability queries use GraphQL for on-demand slicing; rights management uses Spring Security + JWT + RBAC for one-login access across the network.

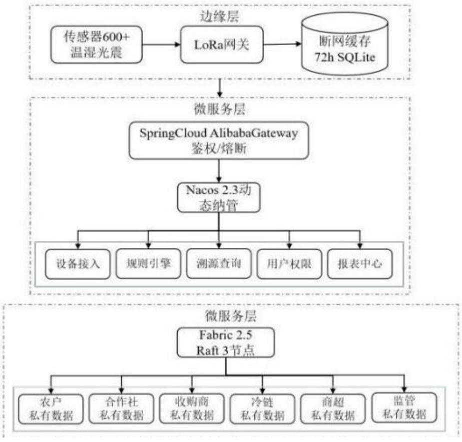

Figure 1: “Edge – Micro-service – Consortium Chain” three-layer synergy

3.2 Data Model and On-chain/Off-chain Coordination

Adopts an “on-chain fingerprint + off-chain entity” model: soil pH, EC, fruit sugar-acid ratio, SPAD, Beidou centimeter-level coordinates, and UTC timestamps are hashed with SHA-256 into a 64-bit fingerprint written on-chain; raw high-frequency data and hyperspectral images are stored in MinIO, returning a CID for off-chain indexing. The Berry struct in chaincode contains plot ID, batch number, quality fingerprint, responsible party MSP-ID, and timestamp; interfaces WriteBerry, FertEvent, AlertEvent, GradeEvent, and TraceEvent correspond to data writing, fertilization records, anomaly alerts, grading settlement, and full-chain traceability. Fabric Private Data Collections achieve “same-chain, different rights”: farms and buyers share grade summaries, regulators view complete pesticide reports, and consumers scanning a QR code see only the sweetness curve and carbon footprint.

3.3 Data Model

Adopts an “on-chain fingerprint + off-chain entity” model: edge gateways collect real-time soil pH、EC, fruit sugar-acid ratio, chlorophyll SPAD values, and BeiDou centimeter-level coordinates, concatenate them with a UTC millisecond timestamp, generate a 64-bit tamper-proof fingerprint via SHA-256, and write it directly to the chain. The original 270-band hyperspectral images and pesticide-residue mass-spectrometry raw files are sliced, encrypted, and stored in distributed MinIO, returning a content-addressed CID as the off-chain index, achieving lightweight on-chain attestation and rich off-chain media. The Berry struct in chaincode hard-codes the five elements PlotID, BatchNo, QualityPrint, MSP-ID, and Timestamp; the WriteBerry interface handles the first on-chain entry, FertEvent appends fertilization formulas and executors, AlertEvent writes temperature/humidity out-of-range or cold-chain power-loss warnings, GradeEvent records the buyer’s AI grading result and premium coefficient, and TraceEvent aggregates the full-chain event hash for scan-and-verify. Through Fabric private data collections, farms and buyers share grade summaries, regulators can access complete pesticide reports, and consumers scanning the code only see a sweetness curve, carbon footprint, and traceability short video—truly “same chain, different rights” with privacy-tiered visibility.

4. SYSTEM IMPLEMENTATION

4.1 Front-End Experience and Digital Twin

Vue3+Three.js builds a 1:1 digital-twin orchard: 2 cm drone orthophoto terrain, LOD dynamic plants, drawer-panel real-time polylines, WebGL Shader risk heatmap; on-chain boundary-crossing triggers a red pulse, click to jump to the event. Taro mini-program NFC traceability 0.26s returns harvest time, satellite coordinates, fertilization records, grading results, and can be shared to Moments with one tap.

4.2 Smart Contract Business Orchestration

Chaincode Go-Kit layers: WriteBerry verifies MSP and plot permissions to prevent forgery; FertEvent records fertilizer type, dosage, method, and responsible person while accumulating N-P-K; AlertEvent pushes three-tier red-yellow-green alerts based on 3D thresholds; GradeEvent maps NY/T 2789-2025 to A/B/C/D for on-chain settlement; TraceEvent supports batch numbers, QR codes, NFC, and JSON-LD provenance graphs for 3-minute pinpointing.

4.3 Backend Microservices and Elastic Scaling

Device access via Netty zero-copy 0.8ms parsing; rule engine Drools hot-reload without restart; traceability via GraphQL on-demand fields; self-service KPI dashboards with Superset. Jenkins+Argo CD CI/CD pushes to Harbor, Kubernetes HPA handles 500 concurrent requests P99 0.39s.

4.4 Quality Assurance and Safety Governance

Robot Framework 52 BDD tests passed; Locust 1000 concurrent users, CPU 71%, memory 5.6 GB, zero errors; OWASP ZAP SQL injection, XSS, CSRF, JWT forgery—22 items passed; ChaosMesh node failure 3.8 s, view switch without fork; Loki+Grafana 3D observability, 35 alerts pushed to WeChat Work, DingTalk, and email.

4.5 Deployment and Operational Results

Dechang County (1,000 mu), Mianning County (800 mu), and Xichang City (400 mu) in Liangshan Prefecture launched simultaneously, connecting 58 edge gateways, 813 sensor nodes, and 22 cold-chain vehicles across Alibaba Cloud ACK and Liangshan Telecom IDC hybrid K8s. Over six months, 2.067 million blocks were written, totaling 245 GB of data, with an average on-chain latency of 1.34 s and query latency of 0.26s. Early intervention in abnormal events rose by 65%, pesticide and fertilizer use dropped 30%, overall revenue increased 36%, consumers scanned codes 254,000 times with 2.1 viral shares each, and traceability lock-in time for regulators fell from 3 days to 7 minutes.

5. CONCLUSION

Practice at the 2,200-mu blueberry base in Liangshan Prefecture shows that the blockchain-based intelligent monitoring and management system successfully turns trusted data into productivity and brand premiums. Its "edge–microservice–chain" architecture eliminates three pain points—data gaps, traceability difficulties, and poor collaboration—making the entire life-cycle from seedling to sale transparent and controllable. Six months of operation show on-chain latency stays within 1.34s, abnormal interventions are advanced by 65%, pesticide and fertilizer use falls 30%, overall revenue rises 36%, consumer QR-code sharing averages 2.1 times, and regulators lock in traceability within seven minutes. Next, the team will introduce federated-learning cross-domain models, build a carbon-footprint digital passport, and explore AIGC-generated farming plans to further lower the technology threshold, advance high-quality, sustainable development of Liangshan's plateau blueberries, and provide a replicable blockchain paradigm for high-value berries nationwide.

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