



## Non-Fungible Token-Enabled Digital Certification, Provenance Verification, and Blockchain-Integrated Supply Chain Management Systems for Rare and Heritage Seed Variety Ownership and Traceability

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### Abstract

The conservation and sustainable management of rare and heritage seed varieties face critical challenges in ownership verification, provenance tracking, and supply chain transparency. Traditional paper-based certification systems are vulnerable to fraud, data loss, and lack real-time traceability across complex agricultural networks. Non-fungible tokens (NFTs) built on blockchain infrastructure offer unprecedented opportunities for immutable digital certification, transparent ownership transfer, and end-to-end supply chain monitoring of rare seed germplasm. This review examines the technical architecture, implementation strategies, and practical applications of NFT-based systems for rare seed variety management. We analyze tokenization protocols that encode genetic identity, geographic origin, and custodial history into unique digital assets, alongside smart contract mechanisms that automate verification, enforce breeding rights, and facilitate transparent marketplace transactions. Key applications include digital seed passports for heirloom varieties, blockchain-enabled seed bank registries, farmer-to-farmer exchange platforms, and regulatory compliance systems for plant genetic resources. Despite promising pilot deployments demonstrating enhanced traceability and stakeholder trust, significant barriers persist including scalability limitations, energy consumption concerns, interoperability gaps between agricultural databases and blockchain networks, legal ambiguities surrounding digital ownership of biological materials, and limited technical capacity among smallholder farming communities. Future development trajectories emphasize energy-efficient consensus mechanisms, mobile-accessible interfaces, integration with Internet of Things sensor networks for automated data capture, and harmonization of international legal frameworks governing NFT-based seed ownership rights.

**Keywords:** Non-fungible tokens; Rare seed varieties; Blockchain agriculture; Digital provenance; Smart contracts; Supply chain traceability

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### Introduction

#### Importance of Rare and Heritage Seed Varieties

Rare and heritage seed varieties represent irreplaceable repositories of agricultural biodiversity, embodying centuries of farmer selection, regional adaptation, and genetic diversity essential for food security and climate resilience <sup>[1]</sup>. These traditional cultivars possess unique traits including drought tolerance, pest resistance, and nutritional profiles often absent in modern commercial varieties <sup>[2]</sup>. The United Nations Food and Agriculture Organization estimates that 75% of crop genetic diversity has been lost since 1900, with thousands of locally adapted varieties disappearing annually due to agricultural intensification and market homogenization <sup>[3]</sup>. Conservation of these genetic resources extends beyond biological preservation to encompass

cultural heritage, indigenous knowledge systems, and socioeconomic sustainability of farming communities<sup>[4]</sup>. Despite their recognized value, rare seed varieties face systematic marginalization within contemporary agricultural systems dominated by proprietary hybrid seeds and centralized distribution networks. Traditional seed saving practices have declined precipitously, replaced by annual purchasing from commercial suppliers<sup>[5]</sup>. This transition threatens both genetic diversity and farmer autonomy, creating dependencies that undermine agricultural resilience and local food sovereignty<sup>[6]</sup>. Heritage seed conservation now relies heavily on seed banks, botanical gardens, and grassroots seed-saving networks, yet these efforts struggle with limited funding, fragmented databases, and inadequate linkages between ex-situ collections and farming communities<sup>[7]</sup>.

### Limitations of Traditional Ownership and Traceability Methods

Conventional systems for documenting seed ownership, variety identity, and supply chain history depend predominantly on paper certificates, physical labels, and disconnected databases vulnerable to multiple failure modes<sup>[8]</sup>. Physical documentation deteriorates over time, becomes separated from seed lots during handling, and offers no mechanism for real-time verification or automated authentication<sup>[9]</sup>. Fraudulent labeling represents a persistent problem, with studies revealing that 15-30% of seeds sold through informal markets are mislabeled regarding variety, origin, or quality parameters<sup>[10]</sup>. Such deception undermines farmer investment decisions, biodiversity conservation efforts, and consumer confidence in heritage food products<sup>[11]</sup>.

Current digital databases maintained by seed banks and regulatory agencies operate as isolated silos without interoperability standards or synchronized updating protocols<sup>[12]</sup>. Researchers seeking specific accessions must navigate fragmented information systems, while farmers attempting to verify seed authenticity lack access to authoritative reference data<sup>[13]</sup>. International exchange of plant genetic resources encounters additional complications from divergent national regulations, inconsistent phytosanitary certification procedures, and opaque tracking mechanisms that obscure benefit-sharing obligations under the Nagoya Protocol<sup>[14]</sup>. The absence of transparent provenance documentation particularly disadvantages indigenous communities and smallholder farmers whose traditional varieties may be appropriated without recognition or compensation<sup>[15]</sup>.

### Scope and Objectives of the Article

This review systematically examines how NFT technology integrated with blockchain infrastructure can address critical gaps in rare seed variety ownership verification and supply chain traceability. We focus specifically on the unique properties of NFTs—their non-fungibility, cryptographic uniqueness, and capacity to embed rich metadata—that distinguish them from fungible cryptocurrency tokens and make them particularly suitable for representing individual seed accessions or distinct variety batches<sup>[16]</sup>. Our analysis encompasses technical architectures for tokenizing seed germplasm, smart contract protocols for automating ownership transfers and breeding rights management, and integration strategies connecting blockchain networks with existing agricultural databases and Internet of Things

monitoring systems<sup>[17]</sup>.

The article explores practical applications across diverse contexts including digital certification for heirloom variety marketplaces, immutable registry systems for community seed banks, transparent tracking of rare seeds through research and development pipelines, and regulatory compliance mechanisms for international germplasm exchange<sup>[18]</sup>. We evaluate real-world pilot deployments to assess technical feasibility, stakeholder acceptance, and measurable impacts on traceability accuracy and fraud reduction. Finally, we critically analyze implementation challenges spanning technological scalability, energy efficiency, legal frameworks, and socioeconomic barriers that must be addressed for widespread adoption across diverse agricultural contexts globally.

### Blockchain and NFT Fundamentals for Agriculture NFT Tokenization and Digital Ownership Principles

Non-fungible tokens represent cryptographically unique digital assets recorded on distributed ledger systems, distinguished from fungible cryptocurrencies by their individuality and indivisibility<sup>[19]</sup>. Each NFT contains distinct metadata and ownership records maintained through decentralized consensus protocols that prevent unauthorized duplication or modification<sup>[20]</sup>. For agricultural applications, NFTs function as digital twins of physical seed accessions, encoding identifying information such as variety denomination, genetic fingerprint data, geographic origin coordinates, generation number, and custodial history within the token's immutable data structure<sup>[21]</sup>.

The tokenization process begins with creating a unique digital identifier linked to specific seed lot characteristics verified through genetic testing, phenotypic assessment, or documented provenance chains<sup>[22]</sup>. This identifier becomes embedded within a smart contract deployed on a blockchain network, establishing the NFT's initial ownership state and defining rules governing subsequent transfers, subdivisions, or derivative creations<sup>[23]</sup>. Cryptographic hash functions ensure data integrity, with any alteration to recorded information producing detectably different hash values that reveal tampering attempts<sup>[24]</sup>. Ownership transfers execute through digitally signed transactions that update the blockchain ledger, creating permanent records accessible for verification by any network participant while maintaining appropriate privacy protections for sensitive commercial information<sup>[25]</sup>.

### Smart Contracts and Decentralized Ledger Technology

Smart contracts are self-executing programs stored on blockchain networks that automatically enforce predefined conditions and trigger specified actions when predetermined criteria are satisfied<sup>[26]</sup>. In seed traceability applications, smart contracts can encode complex business logic including breeding rights restrictions, geographic distribution limitations, quality certification requirements, and benefit-sharing calculations mandated by access and benefit-sharing regulations<sup>[27]</sup>. When seed ownership transfers occur, smart contracts automatically verify that all conditions are met—such as phytosanitary certification, payment receipt, or recipient licensing—before executing the transaction and updating ownership records<sup>[28]</sup>.

Decentralized ledger technology eliminates single points of failure inherent in centralized databases by distributing identical copies of transaction records across multiple

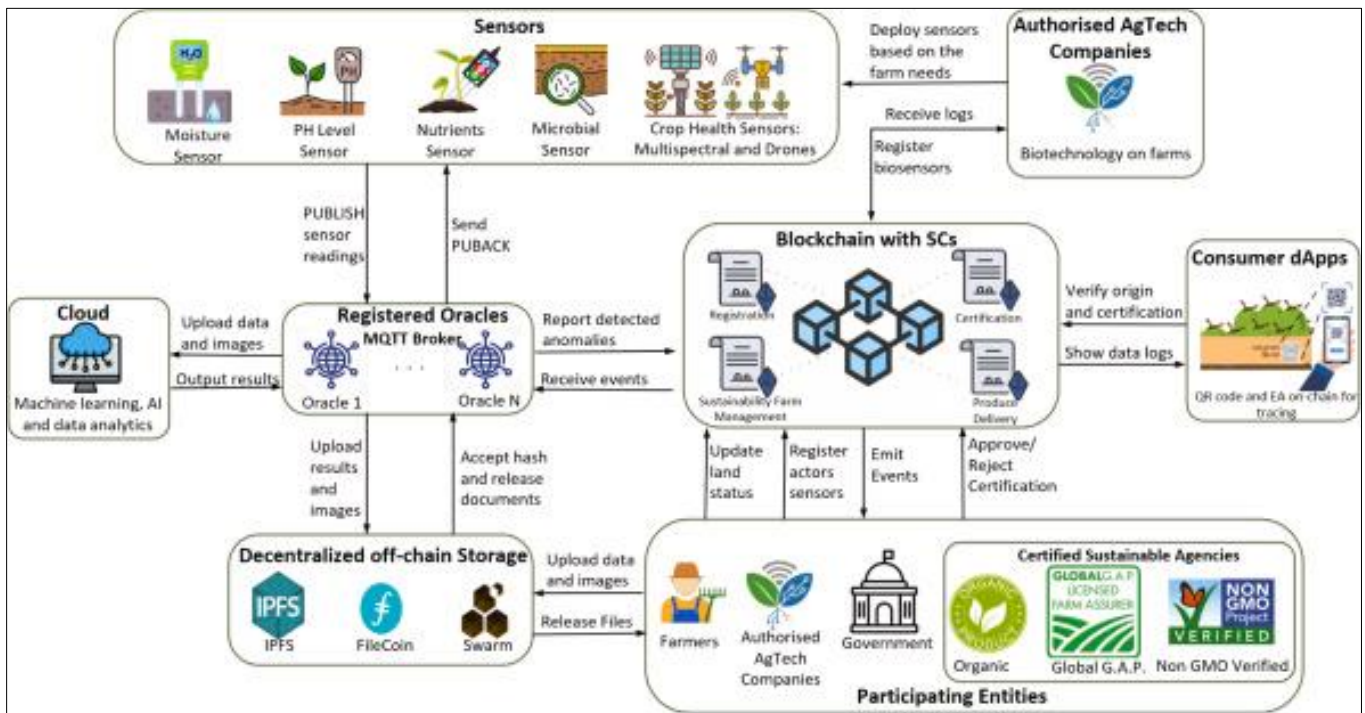
independent nodes [29]. Consensus mechanisms such as proof-of-stake or proof-of-authority protocols ensure that network participants agree on the valid state of the ledger without requiring trust in central authorities [30]. For agricultural supply chains, this architecture provides resilience against data loss, resistance to censorship or manipulation by individual actors, and transparent auditability that enhances accountability across complex multi-stakeholder networks. Different blockchain platforms offer varying tradeoffs between transaction speed, energy consumption, governance decentralization, and smart contract functionality, requiring careful selection based on specific agricultural application requirements.

**Integration with Agricultural Databases and IoT Systems**

Effective NFT-based seed traceability requires bidirectional data flows between blockchain networks and existing agricultural information systems including germplasm databases, variety registration portals, and supply chain management platforms. Application programming interfaces (APIs) enable automated data synchronization, allowing seed bank accession records to trigger NFT creation while blockchain ownership transfers update institutional

databases. Standardized data schemas such as the Multi-Crop Passport Descriptors ensure semantic interoperability, enabling different systems to correctly interpret variety characteristics, morphological traits, and geographic information encoded in NFT metadata.

Internet of Things sensor networks provide automated data capture capabilities that enhance NFT traceability accuracy while reducing manual documentation burden. Radio frequency identification (RFID) tags attached to seed containers enable automatic scanning during storage transfers, shipments, and planting operations, with transaction data cryptographically linked to corresponding NFTs. Environmental sensors monitoring temperature, humidity, and light exposure during seed storage generate verifiable data streams that can be anchored to blockchain records, providing tamper-evident documentation of handling conditions that affect germination viability. Satellite imagery and drone-based phenotyping systems deployed during variety multiplication create spatial and temporal records of seed production environments, enriching NFT provenance data with verified geographic origin information and cultivation practice documentation.



**Fig 1:** NFT-enabled architecture for ownership and traceability of rare seed varieties geographic origin claims [42].

**NFT-based Ownership and Traceability Systems  
Seed Provenance Verification and Certification**

Digital provenance systems built on NFT infrastructure create immutable historical records documenting each seed lot's origin, breeding lineage, multiplication generations, and custodial transfers from initial collection through commercial distribution. Initial NFT minting requires establishing baseline authenticity through genetic fingerprinting using molecular markers, phenotypic characterization against reference descriptions, and documentation of traditional knowledge from originating communities. This foundational data becomes cryptographically sealed within the NFT, providing a permanent reference against which subsequent seed samples can be verified for genetic conformity and

Provenance verification protocols leverage the NFT's embedded metadata alongside physical seed testing to authenticate variety identity and trace custodial history. When farmers or researchers acquire seeds claiming rare variety status, they can scan associated QR codes or RFID tags to retrieve the linked NFT record, examining complete transfer history and comparing current genetic test results against the reference genome fingerprint stored in the token. Discrepancies trigger alerts indicating potential mislabeling or genetic drift, enabling early detection of quality issues or fraudulent substitutions. For indigenous and traditional varieties, provenance records can incorporate prior informed consent documentation and benefit-sharing agreements,

ensuring transparency regarding rights holder recognition and equitable compensation.

**Supply Chain Monitoring and Fraud Prevention**

NFT-enabled tracking systems create end-to-end visibility across complex seed supply chains involving multiple intermediaries including collectors, seed banks, plant breeders, multiplication farmers, distributors, and end-users. Each transfer point generates a blockchain transaction that updates the NFT ownership record while capturing contextual data such as transaction price, quantity transferred, quality assessments, and phytosanitary certifications. Smart contracts can enforce quality gates requiring independent verification before ownership transfers complete, preventing distribution of degraded seed lots that fail germination or genetic purity standards.

Fraud prevention mechanisms leverage blockchain's immutability and transparency to deter counterfeit seed production and mislabeling schemes that undermine market confidence. Because NFT ownership records are publicly verifiable and historically complete, buyers can independently confirm that sellers possess legitimate custody rights and that seed lots trace to authenticated sources. Counterfeiters cannot create convincing fake NFTs without access to private cryptographic keys controlled by legitimate rights holders, while attempts to duplicate existing NFTs are immediately detectable through ledger inspection. This cryptographic security combined with physical authentication through genetic testing creates multi-layered anti-counterfeiting protection far exceeding traditional paper

certificate systems.

**Platform Interoperability and Regulatory Compliance**

Interoperability between different blockchain platforms and existing agricultural regulatory systems requires technical standards and governance frameworks enabling seamless data exchange and mutual recognition of NFT-based certifications. Cross-chain bridge protocols allow NFTs minted on one blockchain to be transferred to or represented on alternative networks, preventing vendor lock-in and accommodating stakeholder preferences for specific platforms. Standardized metadata schemas aligned with international seed trade regulations ensure that NFT records contain all information required for phytosanitary certification, variety registration, and intellectual property documentation.

Regulatory compliance mechanisms embedded in smart contracts can automate enforcement of legal restrictions including geographic distribution limitations, breeding use restrictions, and export control regulations applicable to plant genetic resources. When international transfers occur, smart contracts automatically verify that required permits have been issued, material transfer agreements signed, and benefit-sharing calculations completed before executing ownership transfers. Integration with government seed certification agencies enables regulators to audit supply chains, verify varietal identity claims, and monitor compliance with quality standards through read-access to relevant blockchain records without requiring centralized data submission.

**Table 1:** Types of rare seed varieties and their NFT-enabled traceability attributes

Variety Category	Genetic Attributes	Provenance Requirements	NFT Metadata Elements	Authentication Methods
Heirloom vegetables	Stable open-pollinated lines	Family/community origin, cultivation history	Varietal name, breeding lineage, traditional knowledge holder, cultivation region	Phenotypic description, molecular markers
Landrace cereals	Heterogeneous populations	Geographic origin, farmer selection history	Collection location coordinates, environmental adaptation traits, custodial farmer records	Population genetic analysis, morphological characterization
Wild crop relatives	Native genetic diversity	Natural habitat documentation	Species identification, collection site, conservation status	Taxonomic verification, herbarium voucher linkage
Traditional varieties	Cultural significance	Indigenous community association	Traditional names, cultural usage, prior informed consent	Community verification, traditional knowledge documentation
Rare cultivars	Limited distribution	Historical breeding records	Breeder information, registration details, multiplication restrictions	Official variety registration, certified seed production records

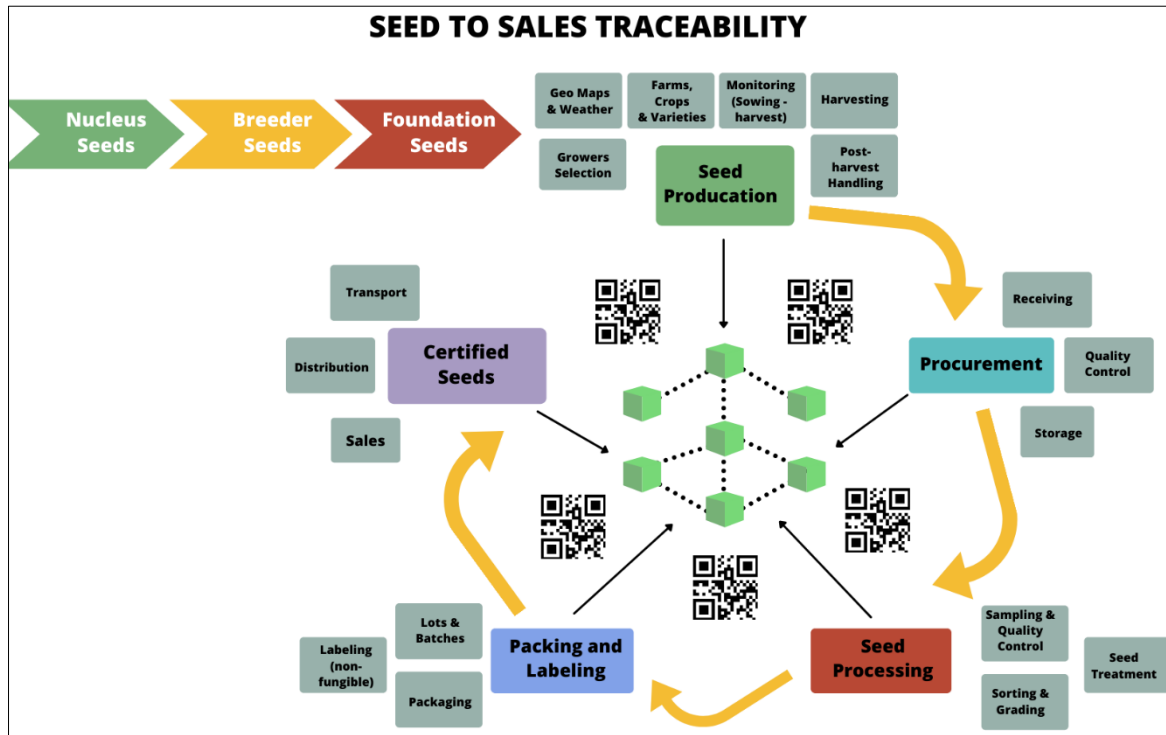


Fig 2: Workflow of seed tokenization, smart contract registration, and provenance verification

## Applications and Case Studies

### Rare Seed Marketplaces and Farmer Adoption

Digital marketplaces leveraging NFT infrastructure enable direct transactions between heritage seed producers and buyers while providing transparent provenance documentation and quality assurance mechanisms. Several pilot platforms have demonstrated feasibility of NFT-based seed commerce, with farmers minting tokens representing specific heirloom variety seed lots and listing them for sale with complete cultivation history and genetic purity certifications. Smart contracts escrow payments until buyers confirm seed receipt and quality, while automatically transferring ownership records and triggering benefit-sharing payments to traditional knowledge holders when applicable. Farmer adoption studies reveal mixed results, with technically sophisticated producers embracing NFT systems for premium heirloom varieties commanding price premiums from quality-conscious buyers, while smallholder farmers in resource-limited settings face barriers including limited internet connectivity, digital literacy gaps, and transaction costs. Successful implementations provide mobile-accessible interfaces requiring minimal technical expertise, integrate with existing farmer cooperative structures, and demonstrate clear economic benefits through price premiums or reduced fraud losses that offset system participation costs. Community seed banks have pioneered participatory NFT systems where collective governance determines tokenization standards and benefit distribution, enhancing social acceptance through culturally appropriate institutional arrangements.

### Conservation Programs and Seed Banks

International seed banks and genetic resource collections are exploring NFT systems to enhance accession management, improve data accessibility, and streamline material transfer processes [65]. Digital passport systems assign unique NFTs

to each accession, encoding passport data including species, origin, collection date, donor information, and available evaluation data within the token metadata. Researchers requesting germplasm samples interact with smart contracts that automatically verify their institutional affiliation, confirm material transfer agreement acceptance, and generate shipment documentation while updating distribution records on the blockchain.

These systems improve conservation efficiency by creating transparent audit trails for safety duplicate storage agreements between institutions, automating inventory reconciliation, and facilitating germplasm repatriation to countries of origin when requested. Pilot deployments at regional gene banks demonstrated 40-60% reductions in administrative processing time for germplasm requests, improved data quality through automated validation against international descriptors, and enhanced user satisfaction through self-service access to accession information and real-time request tracking. Integration with cryopreservation facilities enables automated recording of storage condition monitoring data, providing evidence of proper maintenance and supporting quality assurance protocols.

### Operational Metrics and Real-World Deployments

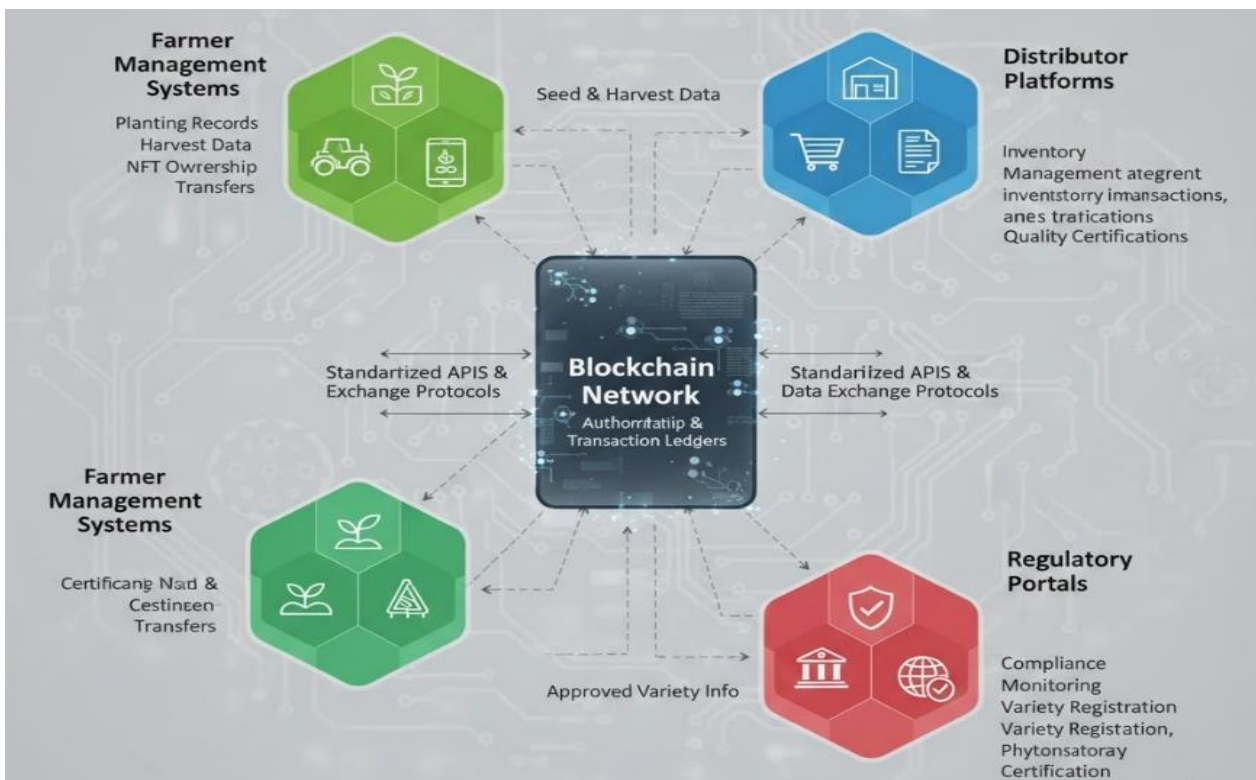
Early-stage deployments provide preliminary evidence of NFT system performance across key operational metrics including traceability accuracy, transaction costs, user engagement, and fraud reduction. A consortium of organic seed companies implementing blockchain traceability for heirloom tomato varieties reported 95% reduction in mislabeling incidents detected through customer genetic testing, alongside 25% price premiums for NFT-certified seeds reflecting enhanced consumer confidence. Transaction costs averaged \$2-5 per NFT minting on energy-efficient blockchain platforms, representing 1-3% of typical seed lot values for rare varieties but potentially prohibitive for low-value commodity seeds.

User engagement metrics from farmer-facing platforms show 60-70% continued participation rates among initial adopters after 18-month pilot periods, with retention strongly correlated with tangible economic benefits and responsive technical support. Challenges include blockchain network congestion during peak planting seasons causing transaction delays, interoperability failures between different platforms

preventing seamless data exchange, and limited integration with government certification systems requiring parallel documentation processes. Energy consumption analyses using proof-of-stake consensus mechanisms indicate environmental footprints orders of magnitude lower than proof-of-work systems, with per-transaction energy use comparable to traditional database operations.

**Table 2:** Blockchain and NFT platforms suitable for agricultural supply chain applications

Platform	Consensus Mechanism	Transaction Speed	Energy Efficiency	Smart Contract Support	Agricultural Deployments
Ethereum	Proof-of-stake	15-30 TPS	Moderate	Full Turing-complete	Seed marketplaces, carbon credits
Polygon	Proof-of-stake	7,000+ TPS	High	EVM-compatible	Food traceability, land registries
Algorand	Pure proof-of-stake	1,000+ TPS	Very high	Layer-1 smart contracts	Sustainability verification, supply chain
Hedera Hashgraph	Proof-of-stake	10,000+ TPS	Very high	Smart contract service	Carbon tracking, commodity provenance
Hyperledger Fabric	Pluggable consensus	3,500+ TPS	High	Chaincode	Enterprise food safety, permissioned networks
Tezos	Liquid proof-of-stake	40+ TPS	High	Michelson contracts	Art and collectibles, emerging agriculture use



**Fig 3:** Integration of NFT-based seed tracking with farmer, distributor, and regulatory platforms

**Challenges and Future Perspectives**  
**Scalability, Energy Consumption, and Cost**

Scalability limitations represent fundamental constraints on NFT system deployment across global agricultural supply chains processing billions of seed transactions annually. Current blockchain platforms achieve transaction throughput ranging from tens to thousands of transactions per second, potentially insufficient for peak-period demand during global planting seasons when millions of seed purchases occur within concentrated timeframes. Layer-2 scaling solutions including state channels, sidechains, and rollup protocols offer promising approaches to increase effective throughput by processing transactions off the main

blockchain and periodically settling aggregated results. Energy consumption remains controversial despite proof-of-stake mechanisms reducing environmental impact by 99% compared to proof-of-work systems. Critics argue that even energy-efficient blockchains introduce unnecessary computational overhead compared to centralized databases, while proponents counter that decentralization benefits justify modest energy costs equivalent to conventional cloud computing infrastructure. Life cycle assessments should compare total system energy use including data center operations, network transmission, and user device energy against traditional paper-based certification and physical documentation transportation.

Economic sustainability requires transaction costs compatible with diverse agricultural contexts ranging from high-value rare seed commerce to subsistence farming systems [83]. Current per-transaction fees of \$1-10 on public blockchains may be acceptable for premium heirloom varieties but prohibitive for everyday seed transactions in developing countries where farmers operate on minimal cash budgets. Subsidized infrastructure, transaction fee pooling across farmer cooperatives, and hybrid architectures utilizing free public verification layers with paid premium services offer potential pathways toward economically accessible systems.

### Legal and Intellectual Property Considerations

Legal frameworks governing NFT-based seed ownership remain underdeveloped, creating uncertainties regarding the relationship between digital token ownership and physical seed custody rights, breeding rights, or intellectual property protections. Fundamental questions persist about whether NFT transfers automatically convey associated plant variety protection rights, farmer's privilege exemptions, or benefit-sharing obligations under the International Treaty on Plant Genetic Resources for Food and Agriculture. Smart contracts encoding breeding restrictions or geographic use limitations may conflict with farmer's rights provisions protecting seed saving and exchange, requiring careful legal analysis and stakeholder consultation.

Intellectual property conflicts arise when traditional varieties subject to customary governance systems are tokenized without proper community consent or benefit-sharing arrangements. NFT systems must incorporate robust prior informed consent protocols, recognize indigenous data sovereignty principles, and implement equitable benefit distribution mechanisms compliant with the Nagoya Protocol and relevant national access and benefit-sharing legislation. Some indigenous organizations reject commodification of traditional seeds through NFT marketplaces, viewing digital tokenization as incompatible with cultural values of communal stewardship and non-commercial exchange.

Cross-border legal harmonization poses additional challenges as different jurisdictions adopt inconsistent approaches to blockchain technology regulation, digital asset classification, and agricultural biotechnology oversight.

International seed trade requires mutual recognition of NFT-based certifications, standardized legal templates for smart contract material transfer agreements, and coordinated regulatory frameworks preventing fragmentation that would undermine interoperability.

### User Adoption and System Standardization

Widespread adoption depends on overcoming sociotechnical barriers including limited digital literacy among farming populations, inadequate rural internet infrastructure, and cultural resistance to new recordkeeping practices. User-centered design principles emphasize simplifying interfaces to essential functions, providing multilingual support, accommodating low-bandwidth connectivity, and integrating with existing social structures such as farmer cooperatives or agricultural extension services. Successful implementations demonstrate clear value propositions addressing tangible problems farmers face—such as fraud losses, market access barriers, or certification costs—rather than emphasizing technical novelty.

Standardization efforts require multi-stakeholder coordination to establish interoperable data schemas, common smart contract templates, and shared governance frameworks. Industry consortia including seed companies, technology providers, farmer organizations, and research institutions are developing open standards for agricultural NFT metadata, but fragmented initiatives risk creating incompatible systems that reduce network effects [98]. International bodies such as the Food and Agriculture Organization and international seed trade associations can facilitate standardization through convening processes, reference implementation development, and capacity building programs.

Long-term sustainability requires transitioning from donor-funded pilots to economically self-sustaining business models based on service fees, premium certifications, or value-added data services. Public-private partnerships combining government support for basic infrastructure with private sector innovation in application development offer promising institutional arrangements. Open-source software frameworks reduce vendor lock-in risks and enable localized customization by community developers.

**Table 3:** Smart contract mechanisms and validation strategies for seed ownership

Mechanism Type	Validation Strategy	Application Context	Technical Implementation	Governance Requirements
Ownership transfer	Multi-signature authorization	High-value germplasm exchanges	Require approval from both transferor and designated authority	Institutional oversight, audit trails
Breeding rights	License verification	Controlled variety multiplication	Check active breeder license before transfer approval	Plant variety protection office integration
Quality certification	Third-party verification	Commercial seed sales	Require independent quality test results before transaction	Certified seed agency accreditation
Benefit-sharing	Automated calculation	Traditional variety commercialization	Calculate payments based on sales volume, transfer to rights holders	Community governance, payment protocols
Geographic restrictions	Location validation	Regulated germplasm movement	Verify recipient location against permitted distribution zones	Regulatory compliance database access

**Table 4:** Advantages, limitations, and adoption challenges of NFT-based seed traceability systems

Dimension	Advantages	Limitations	Adoption Challenges	Mitigation Strategies
Technical	Immutable records, automated verification, tamper resistance	Scalability constraints, interoperability gaps, technology complexity	Infrastructure requirements, technical expertise gaps	Layer-2 solutions, standardization, capacity building
Economic	Fraud reduction, price premiums for certified seeds, market efficiency	Transaction costs, initial investment requirements	Cost barriers for smallholders, uncertain ROI	Fee subsidies, cooperative models, demonstrated value
Social	Transparency, stakeholder trust, farmer empowerment	Digital divide, cultural appropriateness concerns	Limited awareness, resistance to change	Participatory design, culturally adapted interfaces
Legal	Automated compliance, clear ownership records	Legal uncertainty, IP conflicts, jurisdictional gaps	Regulatory ambiguity, enforcement challenges	Policy development, legal harmonization
Environmental	Reduced fraud-driven waste, efficient resource allocation	Energy consumption (platform-dependent)	Sustainability concerns	Energy-efficient platforms, life-cycle assessment
Governance	Decentralized control, multi-stakeholder participation	Coordination complexity, standard-setting challenges	Institutional fragmentation, power imbalances	Industry consortia, inclusive governance

## Conclusion

Non-fungible token technology integrated with blockchain infrastructure offers transformative potential for addressing critical deficiencies in rare and heritage seed variety ownership verification, provenance documentation, and supply chain traceability. The immutable, transparent, and decentralized characteristics of NFT systems create unprecedented capabilities for combating fraud, enabling direct farmer-to-farmer transactions, automating regulatory compliance, and preserving traditional knowledge associated with indigenous crop varieties. Demonstrated applications spanning digital seed marketplaces, gene bank accession management, and conservation program coordination provide proof-of-concept for technical feasibility and stakeholder value creation across diverse agricultural contexts.

However, realizing this potential at scale requires concerted efforts to overcome substantial barriers spanning technological, economic, legal, and social dimensions. Scalability improvements through layer-2 protocols and efficient consensus mechanisms must reduce transaction costs while maintaining security and decentralization properties. Legal frameworks clarifying the relationship between NFT ownership and biological resource rights, harmonizing international regulations, and protecting indigenous data sovereignty require urgent development through multi-stakeholder policy processes. User adoption depends on culturally appropriate system designs, accessible interfaces accommodating limited digital literacy and infrastructure, and clear economic value propositions addressing tangible farmer needs rather than technological novelty.

Future research priorities include long-term impact evaluations measuring effects on genetic diversity conservation outcomes, comparative analyses of alternative blockchain platforms for agricultural suitability, integration strategies connecting NFT systems with emerging technologies including artificial intelligence for variety identification and satellite monitoring for origin verification, and participatory governance frameworks ensuring equitable benefit distribution and community control. As climate change intensifies pressure on agricultural systems and biodiversity loss accelerates, NFT-enabled tools for preserving and sustainably managing rare seed genetic resources represent important innovations worthy of continued development, critical evaluation, and responsible deployment aligned with principles of food sovereignty,

environmental sustainability, and social justice.

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