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RESEAPRO JOURNALS

REVIEW

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Blockchain enabled seed traceability for enhancing seed quality assurance

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ABSTRACT

Seed quality assurance is a critical component of the seed supply chain, ensuring the delivery of superior and viable seeds to farmers. Proper quality control measures at key stages of production, storage, and distribution are essential to meet the consistent standards expected by the end-users to ensure sustainable production. Blockchain technology, a decentralized and immutable ledger system, is transforming the agricultural supply chain by boosting traceability. Blockchain offers a strong foundation for traceability by guaranteeing the validity and integrity of product-related data, from seed sources to end consumers. Improved food safety, better accountability throughout the supply chain, and easier access to information are just a few of the benefits that make traceability so crucial. The article addresses the fundamental ideas of blockchain technology and how it may be used in seed traceability, emphasizing how it can revolutionize conventional methods and satisfy contemporary expectations for transparency. Our confined Meta-analysis compares blockchain solutions for seed traceability across various crops, using published research from Google Scholar, Scopus, and PubMed indicating its successful implementation possibilities for seed quality assurance. Furthermore, the reliability of blockchain as a digital ledger is explored, along with the implications of consensus protocols and smart contracts. The synergy of these technologies promises increased transparency, efficiency, and accountability, ultimately empowering stakeholders in the agricultural ecosystem.

KEYWORDS

Blockchain; IoT; Seed quality; Supply chain; Socioeconomic sustainability; Traceability

ARTICLE HISTORY

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Introduction

Seed quality assurance is a cornerstone of a robust and sustainable seed supply chain. High-quality seeds are essential for achieving optimal crop yields, ensuring food security, and protecting the environment [1,2]. Through maintaining strict quality standards, seed producers can ensure that farmers receive seeds that are genetically pure, free from diseases and pests, and have a high germination percentage. In addition to improving crop performance, this also reduces the risk of crop failures due to poor seed quality. Additionally, ensuring seed quality helps preserve genetic diversity, which is crucial for adapting crops to changing environmental conditions and developing new varieties with desirable traits. Ultimately, investing in seed quality assurance is an investment in the future of agriculture and food production [3].

Blockchain is a decentralized and distributed ledger technology that securely records and verifies transactions across a network of computers [4]. The groundwork of our current understanding of "blockchain" was laid by Haber and Scott Stornetta in 1991 in their article "How to Time-Stamp a Digital Document" [5]. Satoshi Nakamoto's paper in 2008 introduced the first blockchain database [6]. One defines blockchain as a distributed ledger that maintains a consistently extending list of data records, wherein each participating node verifies [7]. It ensures transparency, immutability, distributed information, and tamper-resistant data storage. A blockchain comprises a sequence of interconnected blocks, with each block containing a hash of the preceding one. The initial block, known as the genesis block, marks the beginning of the blockchain and subsequent blocks extend the chain to the latest one. Each block encompasses a set of transactions executed by network participants. Valid transactions create an interconnected series of blocks within a public ledger. Miners consolidate transactions into a block before incorporating it into the blockchain. This cryptographic hash links the current block to the preceding one, forming a chain. If data is tampered with, the hash changes, invalidating the chain due to the one-way function of hashing. The hash acts as a unique identifier for each block, a fundamental principle in blockchain architecture. The SHA256 hash algorithm, created and introduced by the National Security Agency "NSA" is commonly used for cryptography, offering a high level of security with 256 bits of memory. The SHA256 algorithm satisfies five basic requirements presented in (Table 1) [8].

Internet of Things "IoT" refers to the network of interconnected devices that communicate and share data. When combined, Blockchain and IoT create a powerful synergy, enabling secure and transparent data exchange between devices, ensuring integrity and trust in the digital ecosystem such as TraceX solution, BCI SeedTrack, AgriBlockIoT, Agri-ICT, Consortium blockchain approach, Blockchain SDSS scheme, etc. [9-13].

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Table 1. Five basic requirements in cryptography.

S.N.	Key properties	Discussion
1	One-Way Decryption Algorithm	It is computationally infeasible to reverse the hashing process and retrieve the original input from the hash value
2	Deterministic	The algorithm produces the same hash output for the same input every time, ensuring consistency
3	Fast Computation	The hashing process is efficient and can be performed quickly, making it suitable for various applications
4	Avalanche Effect	A small change in the input results in a significantly different hash output, making it challenging to predict or manipulate
5	Withstanding Collisions	It is highly improbable for two different inputs to produce the same hash output, ensuring the integrity of the hashing process

Quality seed is one of the most important inputs for enhancing crop productivity. As seed is the carrier of any novel technology, the quality of the seed should be ascertained for the end users and farmers. Quality assurance is of utmost importance at all stages like seed production, seed processing, seed packaging, seed storage, and distribution stages. Seed traceability through modern technologies enables seed quality assurance at all the seed production stages and may be rectified easily if any mistake happens. The published manuscripts available on available on Google Scholar, PubMed, and Scopus libraries were used to represent the results in the present review paper.

Introduction to Traceability and Its Importance in Agricultural Supply Chain

According to the International Organization for Standardization "ISO", traceability is the ability to trace the path of a product through the supply value system, beginning from the production, processing, and validating to the final distribution phases [14]. This idea makes it easier to obtain in-depth details of a product (Figure 1). Traceability is frequently stated as the “one step back, one step forward” approach [15]. However, the capacity to access the product details over the course of its whole supply cycle through documented identifications is the formal definition of traceability [16]. In a similar manner, seed traceability is referred to as the capacity to trace the seed from the production, sticking to several classes (nucleus, breeder, foundation, certified) and encompassing all details from origin (seed material, variety) to final distribution. A comprehensive traceability system should combine both quantitative and qualitative details considering the supply chain system. Moreover, this system provides a complete track record of seed variety, its origin, seed purity, viability, vigorousity, and appearance assisting end-users. Information and Communication Technology "ICT" can provide a significant contribution to digitization for easy flow of information.

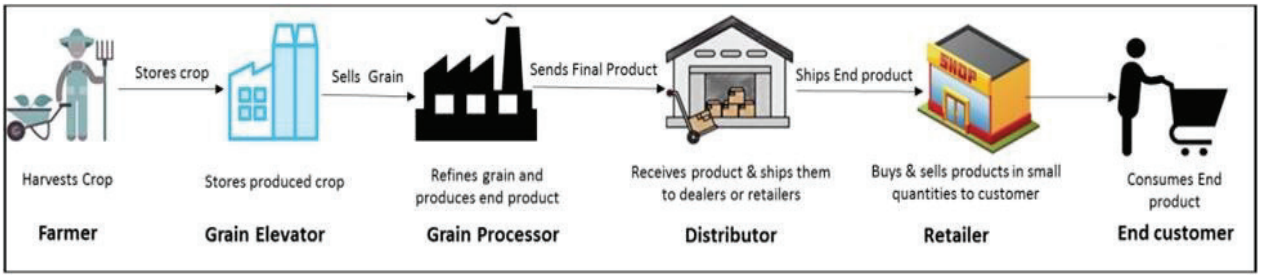

Figure 1. Farm to fork product supply chain system. Source: (https://cicr.org.in/wpcontent/uploads/CI-2024-2.pdf).

Categorization of Traceability

A traceability system enables users to track a product across various stages, including manufacturing, processing, distribution, and handling. When designing such a traceability system, collection of data type, information for ownership, tools (sensors and networks), and management strategies are the crucial key factors to consider [17]. The agriculture system includes product traceability (tracking the origin and movement of agricultural products), process traceability (monitoring various production stages), and supply chain traceability (tracing at each step, the entire product journey from farm to consumer) (Figure 2). Internal-level traceability is performed by a single entity, such as a company or organization, utilizing internal protocols. Intra-company traceability focuses on identifying the origins of a product’s ingredients, packaging, etc when queried from within the supply chain. Whereas, external traceability combines intra-company processes with a reconstructive process to outline the comprehensive history of a particular product [18]. Traceability levels are further categorized into mandatory and voluntary classifications. Mandatory traceability is often driven by financial considerations and may lack detailed information about product quality. In contrast, voluntary traceability allows supply chain factors to choose the data they collect independently. However, voluntary systems can be challenging due to their complexity, as varying standards and methods employed by each factor result in a wide range of data for tracking and tracing products [19].

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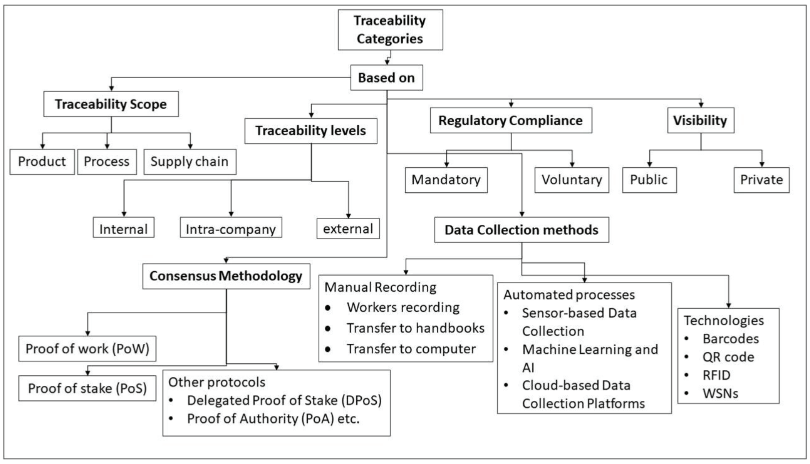

Figure 2. Categorization of traceability on different aspects.

The reliability of any digital ledger, including blockchain, is contingent upon the organization responsible for its maintenance. Issues can arise if the cryptographic link is compromised due to malicious alterations or system errors. Blockchain operates on peer-to-peer "P2P" networks where blocks are replicated across interconnected computers through the utilization of cryptographic keys, thereby enhancing security and resilience [20]. Each block in the blockchain encompasses the block number, stored data, and hash of the preceding and current block. Additionally, the "nonce" field, which stands for "number used only once", plays a crucial role in the mining process and creation of new blocks. Moreover, the difficulty adjustment mechanism ensures that the mining process remains consistent over time, irrespective of fluctuations in the number of users or the speed of their hardware.

Decentralized applications "Dapps" are programs that operate and can be kept on the peers' computers inside a blockchain network instead of a centralized server. Using distributed blockchain technology, the fundamentally innovative idea is to create a global supercomputer where all data, including programs and transactions, is permanently recorded, tracked, and saved. Ethereum introduced the concept of smart contracts to address limitations in the visibility of network peers within certification access mechanisms. Smart contracts envision a distributed ledger for contract storage. Contracts are digital agreements stored on the blockchain with tamper-proof code. These contracts execute automatically based on predefined rules, providing transparency and security beyond traditional contract methods. Various consensus protocols such as Proof of Work "PoW" and Proof of Stake "PoS" address blockchain network security and chain resolution. PoW incentivizes individuals with superior equipment by offering higher rewards, leading to mining pools and potential centralization, making it susceptible to a 51% Attack, wherein a single entity controls the majority of hashing power [21]. In contrast, PoS fosters decentralization by encouraging node setup instead of mining.

Public blockchain networks are specified as permissionless, allowing anybody to access, update data, and create smart contracts, assuring complete transparency and a high degree of privacy [13]. On the other hand, private networks create a closed ecosystem through access restriction. Businesses often opt for private blockchain networks to leverage technology benefits without compromising autonomy [22]. Private blockchains often employ consensus mechanisms other than Proof of Work "PoW". In short, public blockchain networks prioritize decentralization, while private ones emphasize configurational flexibility. Hybrid approaches, known as permissioned blockchain systems, also exist [23].

In the agricultural supply chain, integrating blockchain-distributed ledgers and IoT technology enhances information exchange efficiency among network participants, offering a reliable data source accessible to all stakeholders. This transparent supply chain has the capability to enhance productivity and lower production costs. Within this system, the blockchain ledger dynamically updates by analyzing and evaluating data as objects progress through the facility. Upon product acceptance at its destination, an electronic notification triggers a blockchain smart contract, facilitating a pay agreement for the products.

Data collection methods and data processing

In the realm of supply chain traceability, gathering a substantial volume of data is imperative. Previously, manual data recording by field workers was the norm, but this method posed risks of inaccuracies and inefficient resource utilization during data transfer. However, in recent decades, the advent of automated processes and communication technologies, epitomized by the IoT, has revolutionized traceability. Technologies like barcodes, Quick Response "QR" codes, Radio Frequency Identification "RFID" and Wireless Sensor Networks "WSNs" have become ubiquitous in supply chains [24]. For instance, RFID facilitates the swift identification of the source of food safety issues. WSNs, an alternative or complement to RFID, employ sensors and actuators to communicate wirelessly with an external system, providing data in real-time on variables such as temperature, humidity, and plant diseases while conserving energy [25]. Augmenting WSNs with advanced technologies like the Global Positioning System "GPS" enhances their functionality. Traceability systems leveraging these technologies offer numerous advantages, including expedited product recalls for public health safety, heightened consumer confidence, and the promotion of transparency and reliability in the intricate modern food supply chain. Data processing entails the analysis and interpretation of collected data to derive meaningful conclusions. Subsequently, this processed information is recorded on the blockchain, creating an immutable and transparent record.

Application of Block Chain and IoT in Agricultural Traceability System

Blockchain technology offers a clear and reliable traceable record of the tracked products in real-time, enabling the creation of a more efficient and robust supply chain. Through a collaborative blockchain network, associated members can create and exchange traceability information. This information must be maintained safely and immutably. Blockchain and IoT revolutionize

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agricultural traceability by ensuring data accuracy, transparency, and security. In this system, sensors and devices collect real-time data from farms, processing units, and distribution channels (Table 2). This data is then recorded on a blockchain, creating a decentralized and tamper-proof ledger. Below are some highlights of the key advantages of this integration:

- Enhanced Transparency
- Improved Data Integrity
- Real-time Monitoring
- Secure and Immutable Records
- Increased Trust in the Supply Chain

Table 2. Application of blockchain technology in agriculture supply chain management.

Topic	Description	Reference
TA chain and Zero-Knowledge proof	The study presents the Trusted Auditing Chain (TA chain), a blockchain-based prototype designed for secure and comprehensive traceability data storage. It tackles scalability and privacy issues using Schnorr-style Zero-knowledge proofs for enhanced security. Capable of auditing over 1000 transactions in under 1ms with minimal error, the TA chain ensures reliable and fair traceability. The study also proposes a framework for incorporating blockchain technology into supply chain management.	[26]
Pandemic and blockchain	This study explores how blockchain technology can enhance agricultural supply chains during the COVID-19 pandemic. It highlights blockchain's role in improving shipment tracking, data management, fraud prevention, and addressing supply chain inflexibility. Interviews with agricultural companies in Pakistan show unanimous support for blockchain as a solution to these challenges.	[27]
Solana blockchain	The proposed software architecture utilizes the Solana blockchain, a prototype combined with an IoT device to execute supply chain processes and manage business logic through digitization.	[28]
Sustainability within the food supply chain	This study suggests a blockchain-enabled architectural framework to enhance the sustainability in the supply chain by ensuring reliable communication of food product characteristics.	[29]
Fantom network	This paper presents a peer-to-peer blockchain architecture that incorporates self-sovereign identity (SSI) and a decentralized key management system (DKMS) to establish a reliable traceability service for agricultural products. Built on the Fantom network, it demonstrates superior transaction and verification speeds than the Ethereum network.	[30]
Petri net theory	This study developed a blockchain-based e-commerce cold chain traceability model using stochastic Petri net theory to improve the reliability and validity of logistics traceability systems.	[31]
Q-methodology	This study utilized Q-methodology to assess the agri-food supply chain and improve organizational infrastructure, facilitating successful blockchain implementation across the agri-food supply chain. It proposes the 3T's (Traceability, Transparency and Trust) framework to highlight blockchain's benefits for enhancing stakeholder value.	[32]
Two-level fresh supply chain	This article examines how blockchain technology can address false freshness reporting in a two-level fresh supply chain involving a rural cooperative and a supermarket. It analyzes the impact of product freshness and blockchain investment levels on market demand and identifies thresholds where blockchain adoption might lead to reduced cooperation or contract effectiveness.	[33]

IoTs and blockchain devices and protocols revolutionized the agricultural tracking and tracing system with the utilization of smart sensors for continuous monitoring of prevailing conditions to ensure quality standards and GPS trackers, and tags for precise tracking. Various Blockchain and IoT solutions have been implemented in supply chain and seed tracing systems globally [9-11,13,34].

General agricultural supply chain and implementation of blockchain

Blockchain projects aim to increase accountability, efficiency, and safety from farm to fork are highlighted by Kim and Laskowski in their analysis of the supply chain for agriculture [35]. In order to address the issues marginalized supply chain

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participants face, Tripoli and Schmidhuber investigate Distributed Ledger Technologies "DLTs" [36]. They address institutional and technical adoption barriers as well as the role DLTs play in achieving Sustainable Development Goals "SDGs". In order to improve product supply chains, Hua et al. 2018, suggest a blockchain-based agricultural provenance system that combines dependable data management with decentralization [37]. Designed for food provenance, Malik et al. 2018, present Product Chain, a permissioned blockchain framework with a three-tiered architecture to control data access and ensure guarantee [38]. Arsyad et al. 2019, propose a two-factor blockchain system that links documentation and watermarking to trace cocoa and chocolate manufacture [39]. Awan et al. 2020, combine blockchain technology with IoT to maximize energy efficiency and routing in dispersed networks, while Zhang et al. 2020, describe an architecture for storing agricultural breeding data via the blockchain [40,41]. Traceability is the most important component of blockchain adoption in agriculture [42]. Various research demonstrates the applicability of blockchain in supply networks, assuring safety and quality, and proposed new frameworks for improving transparency in supply chains. Overall, blockchain is presented as a transformative tool for enhancing traceability, security, and efficiency across agricultural supply chains.

Introduction To Seed Supply Chain and Role of Traceability in Seed Supply Chain

Seed supply chain is an organized and sometimes informal system of seed production, processing, distribution, marketing, and lifting the lots in concern of related management units and agencies. This system of supply chain has configured the quality assurance of produced seeds and products for a long time (Figure 3). However, the era has changed in recent years; the degradation in the quality, nutritional value, and purity of supplied seeds and products has become the main concern to the managing authorities. The reasons are many including the vast and sophisticated structure of the supply chain, mishandling during the quality testing and allocation of seed lots, imbalanced chemical use, fraudulence and spurious seed mixing, incomplete information flow and access to the data, etc. In the context of seed quality assurance and safety, there is a need of transparency and authenticity in the supply chain. Traceability with digital interventions is the solution to all these limitations [43].

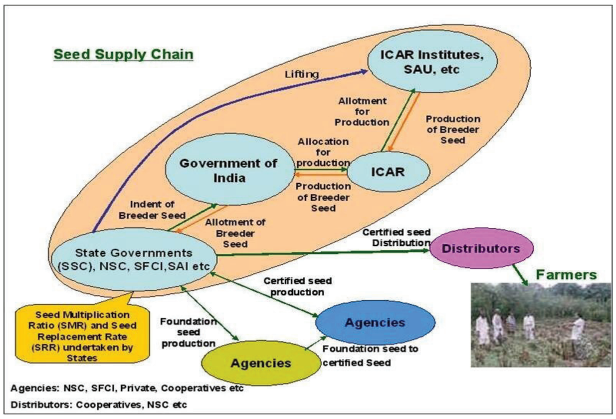

Figure 3. Protocol design of seed supply chain and its executing authorities in India. Source: (SeedNet India portal; https://vikaspedia.in/agriculture/agri-inputs/seeds/classes-of-seeds)

Importance of Seed Traceability in Seed Quality Assurance

Spurious seed identification

Digitization and traceability have become essential in the seed industry due to the requirement to identify and exclude low-quality and spurious seeds from the quality seed lot for promising seed quality assurance. The low quality is due to mishandling, manual record keeping, inappropriate information during seed production, and malicious mixing of faulty seeds into a lot of quality seeds. These factors also have an impact on the farmer's income, the cost of processing, the grading and sorting process, the seed value chain, and other related factors. Digitization and traceability provide complete transparency of the operational process (i.e., seed treatment, grading, sorting, packaging) and assure a full proof verification of the quality in the seed industry that will raise the seed prices and improve end-user benefits [2].

Digital identification of breeder foundation certified seeds

Tracing the production process of nucleus seed (parental source), breeder seed, foundation seed, registered seed, certified seed, and labeled seed ensures authentic and quality seed production leading to high-yielding cultivars. This can be achieved by digitally indicating the seed classes. Seed traceability provides a more convenient solution to this tracking system. The primary step is to indent the seed generation unit (for different seed classes) and register these seed production centre. The secondary step is allocation for seed production, verification of seed class, and issuing the labels to the seed lots for identification. Maintenance of the samplings, proper inspection, testing, and registering the tags or QR coding are the further steps (SATHI portal).

Visibility of seed chain

Seed traceability systems can provide complete transparency of seed supply and value chain. In order to make the seed supply chain more transparent and reliable, seed traceability systems assist with data at each level and make the process responsive. This also assists the relevant agencies to collect profits and ensure a good quality product to robust the national and international seed market. Promoting transparency in the seed chain through the digitalization of traceability solutions makes it possible to minimize waste, ensure timely distribution, and permit effective management of inventory. Furthermore, blockchain technology for the seed supply and value chain empowers a single platform to obtain validated information that promotes traceability and transparency at all times [13].

Management of Seed Value Chain Through Seed Traceability

The seed value chain is a broad, intricate system that includes several stages of execution, including seed development, multiplication, processing, distribution units, farmers and consumers [44]. The broad and problematic supply chain extending from the raw materials to the final customer makes it very difficult and time-consuming to trace the source of a product. Therefore, a secure framework must be designed to track information about the product's origin, production methods, and safety throughout its supply chain cycle restricting

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third-party and centralized control [45]. Integration of digital solutions throughout the seed value chain has configured a smooth system of traceability process with complete transparency of the information. This also ensures a quality assurance of seeds and enhanced productivity. The value-chain analysis paradigm has been used to design better alternatives where the contribution of the private sector is fruitful in reducing poverty, enhancing human nutrition, and considering gender equity [46]. The traceability process comprises the steps as per design by PJTSAU-TraceX, IoT, BCI seedtrack, and several adopted solutions. The information of every step is recorded within linked traceability and web design. The process begins by determining the seed quantity to be produced, following the farmer's registration, and allotting classes of seed to them for cultivation. These allotted farms are geo tagged and surveyed for the field conditions. Guidelines as indicated in the solutions are provided regarding the package of practices to be followed. Scientific assistance, crop mapping, progress, and data recording are simultaneously done during the crop period. Individually harvested seed batches are dispatched for germination and quality testing. Following treating, grading, and sorting, high quality seeds meeting the standards of the certification agency are selected and stamped. Certified seeds are distributed for multiplication as per the requirement. Using Trace X, each certified sample is bagged, stamped, labeled, and sealed with a unique QR-coded tag. Scanning the QR code provides all the details of seeds in the bag from source to certification.

Different Technologies Applied for Seed Traceability

Some related work has been discovered by researchers in their findings, analysis and designing of traceability solution to combat the limitation of supply chain systems. Using blockchain technology and the IoT, Tian et al., 2017 propose a system for food supply tracking based on Hazard Analysis and Critical Control Points (HACCP) [34]. Tian et al., 2016 already addressed the benefits and drawbacks of RFID and blockchain technology for agricultural supply chain traceability [47]. AgriBlockIoT, a blockchain-based traceability system that incorporates information obtained from IoT devices across the agricultural supply chain is described by Caro et al., 2018 [9]. They designed an application model that compared implementations using Ethereum and Hyperledger, tracing food from farm to fork. In their discussion of using blockchain technology in the food supply chain, they contrasted traditional solutions with blockchain-based ones and additionally emphasized significant aspects of reliability, transparency, and security [48]. In order to improve productivity and give traceability in the agricultural sector, a study has explored the use of distributed ledger technology "DLT" and smart contracts [36].

Blockchain Enabled System for Seed Traceability

According to researchers, blockchain technology facilitates the tracking process and guarantees reliable proof of an item's source and subsequent alterations. In addition, product ownership specifies the process of management for being capable of recognizing fake once and the supply chain is made safer by recognizing potential locations [49,50]. It improvises the structure of the agricultural supply line by functioning as an intermediary [51]. These reviews state that blockchain based traceability provides an authentic value addition to the supply chain system. Startups such as AgriBlockIoT, SATHI, TraceX, AgriICT, etc. have successfully implemented the characteristics of blockchain technology to the seed supply chain (Table 3).

Table 3. Utilization of various blockchain platforms and traceability solutions.

S.No.	Traceability solutions	Utilization	References
1	Blockchain	Seed supply chain tracing	[52]
2	Blockchain	Seed supply chain information traceability and credit enhancement	[53]
3	Blockchain	In automotive industry; waste management; seed traceability	[54]
4	Blockchain platform (TRST01)/ TraceX solution	Tracingthe classes of seed (Nucleus seed to Certified seed)	https://trst01.com/blockchain-and-seed-traceability/
5	BCI SeedTrack	Providing unique UID (unique identity) of seeds	https://www.barcodeindia.com/
6	Blockchain and IoT	For food supply chain traceability based on Hazard Analysis and Critical Control Points (HACCP)	[34]
7	AgriBlockIoT	Tracking producefrom farm to fork	[9]
8	Agri-ICT	ICT system plus blockchain for agriculture	[10]
9	Consortium blockchain approach	In food supply chain, using improved practical byzantine fault tolerance (iPBFT) algorithm to trace trading portfolio	[11]
10	IoT	Greenhouse based traceability of seedlings and other agricultural products	[12]
11	Blockchain SDSS scheme	Secured Data Storage Scheme (SDSS) for Agricultural Products Tracking	[55]
12	Blockchain and IoT	Traceability for smart agriculture	[43]
13	Blockchain	SoybeanTraceability in Agricultural Supply Chain	[13]
14	SATHI (Seed Traceability, Authentication and Holistic Inventory) Portal	Centralized Online System for seed traceability, authentication and inventory	https://seedtrace.gov.in/ms014/english

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This entails being trustworthy in the seed market units tracing all classes of seed produce from the nucleus to the certified one (Figure 4). In Table 4, we presented a comparative analysis of various blockchain-based solutions for agricultural grain/seed supply chain management across different crops through a confined meta-analysis covering the available published manuscripts using the keywords 'Seed Traceability and Blockchain technology', and 'Seed Traceability' or 'Seed Quality assurance through seed traceability' from 'Google Scholar, Scopus, and PubMed libraries. However, we could find very few numbers of published manuscripts particularly on seed traceability. For instance, wheat (Triticum aestivum) is managed using a blockchain with IoT integration, ensuring efficient data handling [56]. Corn (Zea mays), on the other hand, leverages smart contracts on Ethereum to effectively verify seed origins [57]. Soybean (Glycine max) utilizes Hyperledger Fabric with RFID tracking, achieving good accuracy and efficiency for large-scale tracking [58]. Rice (Oryza sativa), equipped with blockchain technology integrating GPS and WSN, boasts a high accuracy of 96% and real-time environmental monitoring capabilities [59]. Cotton (Gossypium hirsutum), is managed by a blockchain network, and is efficient in low-resource settings. Barley, employing a private blockchain with QR codes, demonstrates moderate efficiency in seed traceability [60]. Oats (Avena sativa), utilizing a public blockchain with smart contracts, offer high transparency and efficiency. Sorghum (Sorghum bicolour) benefits from a blockchain system integrated with IoT and UAVs, enabling effective monitoring of conditions [61]. Finally, rye leverages a hybrid blockchain system incorporating RFID and GPS, ensuring efficient traceability and environmental data management (Table 4).

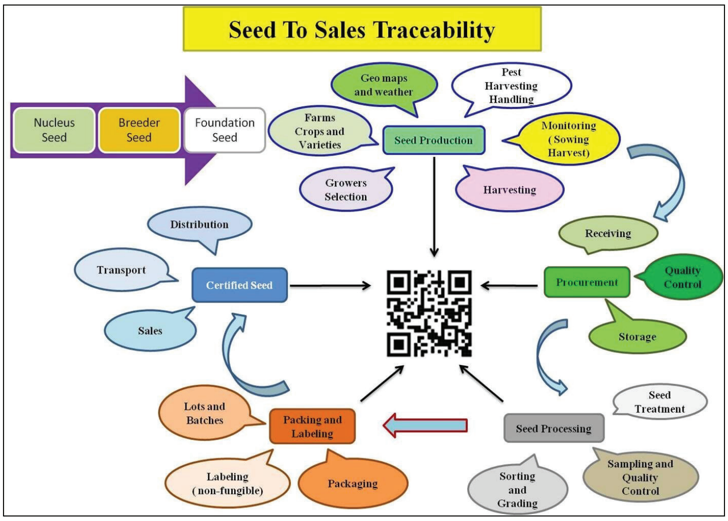

Figure 3. Schematic representation of seed traceability system. Source: (https://cicr.org.in/wp-content/uploads/CI-2024-2.pdf)

Table 3. Utilization of various blockchain platforms and traceability solutions.

Crop	Algorithm used/ Design/ Programme	Accuracy/ Efficiency	Reference
Wheat	Blockchain with IoT Integration	Efficient data handling	[56]
Corn	Smart Contracts on Ethereum	Efficient for verifying seed origins	[57]
Soybean	Hyperledger Fabric with RFID Tracking	Accuracy: good; Efficient for large-scale tracking	[58]
Rice	Blockchain with GPS and WSN Integration	Higher accuracy: 96%; Efficient for real-time environmental monitoring	[59]
Cotton	Blockchain Network	Efficient in low-resource settings	[60]
Barley	Private Blockchain with QR Codes	Moderate efficiency in seed traceability	[61]
Oats	Public Blockchain with Smart Contracts	High transparency and efficiency	[62]
Sorghum	Blockchain with IoT and UAVs	Effective for monitoring conditions	[63]
Rye	Hybrid Blockchain System with RFID and GPS	Efficient for traceability and environmental data	[64]

SATHI Portal: An Initiative on Seed Traceability, Authentication and Holistic Inventory (SATHI)

Agricultural infrastructure, including public irrigation, cold chains, rural marketplaces, warehouses, and agricultural machinery hubs, has to be upgraded, according to an inquiry by NITI Aayog in the year 2020. In this concern, the government of India planned to introduce an information technology system. Finally, on April 19, 2023, the Union Minister of Agriculture and Farmers Welfare, Govt. of India officially launched the SATHI Portal and Mobile App (Figure 5). This centralized online system for seed tracking, authentication, and inventory was created to address the issues associated with producing high-quality seeds, recognizing and certifying them. The NIC and the Union Ministry of Agriculture and Farmers Welfare created it with the concept "Uttam Beej - Samriddh Kisan" in view. From nucleus to breeder seed, breeder to foundation seed, foundation to certified seed, and finally distributing the seeds to farmers through authorized dealers, it will offer a comprehensive method covering the whole seed life cycle comprising several generations of seeds (Figure 6). SATHI intends to provide consistent seed quality and purity while enhancing the efficiency, accessibility, time and resource savings, and traceability of the seed supply chain. It simplifies the procedure for all parties involved in the seed manufacturing chain. Its objective is to improve, guarantee the seed's integrity and purity by providing a comprehensive digital platform. It covers the whole seed life cycle and enhance accountability

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through several modules to facilitate seed traceability and maximize SCI's on-field performance by minimizing error rates and incorporating technology into the system. Furthermore, it aims to compile MIS reports using GIS and the Bharat Map Interface to shorten the time it takes to register, and to get approved from lab tests, field inspections and certification. The SATHI portal verifies the seed production chain's source and determines the quality assurance system. Research Organization, Seed Certification, Seed Licensing, Seed Catalogue, Dealer to Farmer Sales, Farmer Registration, and Seed DBT are the seven interconnected verticals of the seed chain constitute the system. SATHI consists of various modules such as Nucleus to breeder seed management; Breeder to certified seed certification etc. These modules assist the user in easing the administration and management work. In the module of nucleus to breeder seed management, seeds are indented to agricultural organizations and registered production units, then after allocation of seed, labeling of tags is carried out, and allocated seeds are lifted from indenters. In the Breeder to certified seed certification module, seed growers and agencies are registered, samples and seed sources are verified and after inspection and proper testing, labeling of seed lots for distribution is done. Further, seed inventory manages the seed lots and supervises the stock management and the depository unit keeps all the records. Only duly certified seeds are permitted to be sold to centrally registered farmers by authorized dealers and these farmers would receive subsidies by direct bank transfer "DBT" into their pre-validated bank accounts.

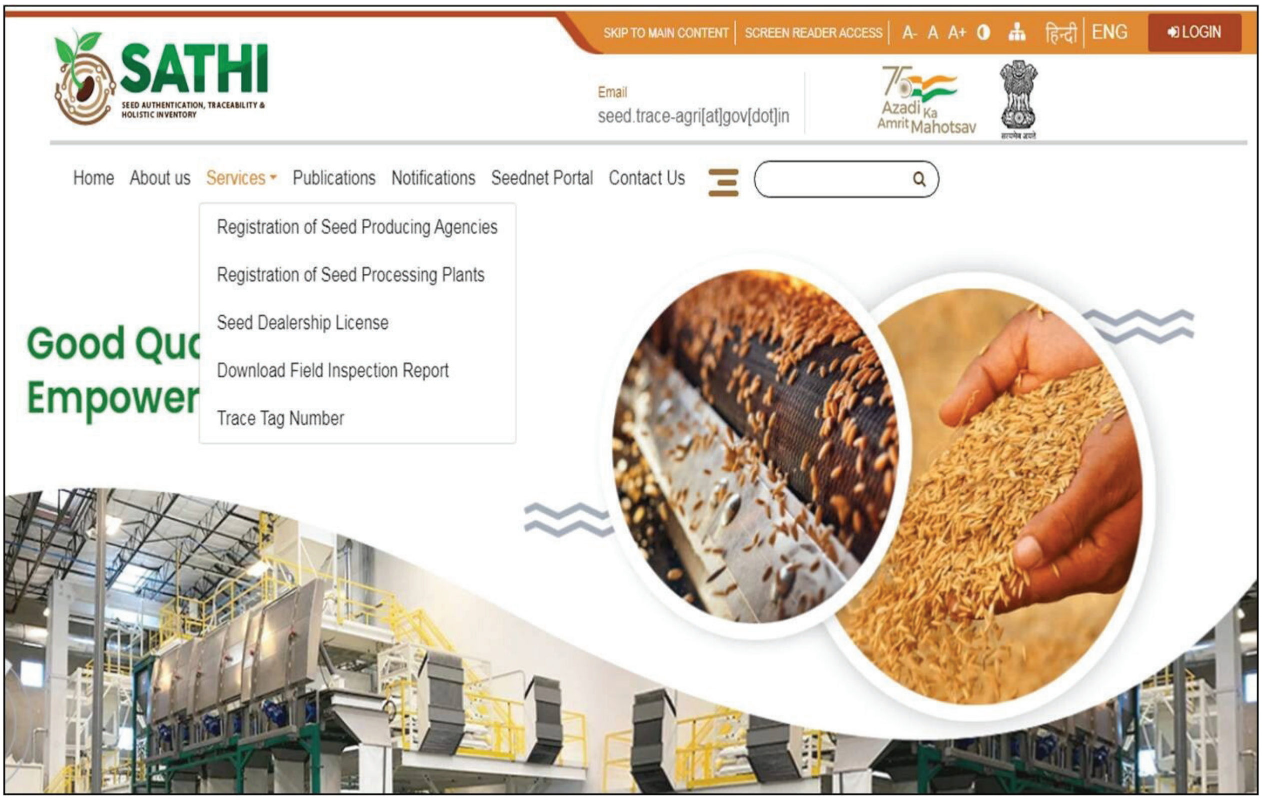

Figure 5. SATHI portal interface: A Government of India initiative on seed traceability. Source: (https://seedtrace.gov.in/ms014/english).

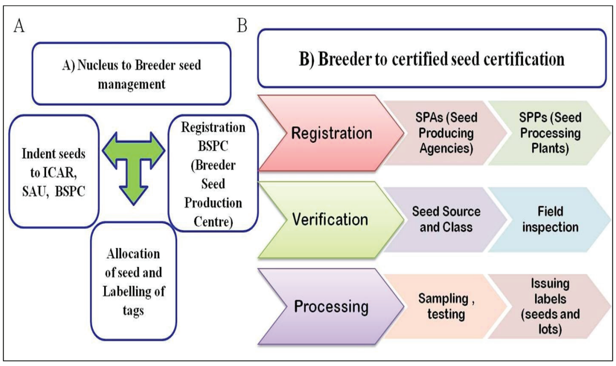

Figure 5. Various Modules of seed multiplication chain (A. Nucleus to Breeder seed, B. Breeder to certified seed) of SATHI; Source: https://seedtrace.gov.in/ms014/aboutUs

Challenges Associated and Future Opportunity

The problems of transparency, fraud in dealing with fake/spurious seeds, and illegal planting of GMOs have been resolved with the interventions of digital solutions in the seed value chain. Despite these solutions, there are still some limitations in the implementation of traceability solutions. The first issue is restrictions created by vindictive customers to create a monopoly and control system for personal benefits. High consumption of energy, time, and cost create more complications for the application of blockchain solutions [65]. A centralized system of traceability also leads to tampering, data integrity, and failure at single points. Asymmetrical information flow and negligence of transparency impede seed traceability by compromising quality assurance, supply chain integrity, market compliance, consumer trust, risk management, and innovation in the agricultural sector [66]. The major issue is that the

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platform provides access to all information in a single web space which can lead to a leak of confidential information [67]. Untruthfulness of data recorded and entered into the system undermines the reliability and accuracy of information, compromising decision-making and operational effectiveness. In addition, standard data format is not available in the protocol and can vary with the provided solution [68]. These limitations can be minimized with limited accessibility of records at the ministry level and checking the flow of information between the supply chain units and public consumers.

In context with future prospects of seed traceability for quality assurance, the implementation of traceability solutions such as blockchain-based, IoT-based, BCI seed track, TraceX, SATHI and upcoming designs in the seed value chain is considerable and gaining interest. These solutions are promising means to minimize fraud, and errors in the supply chain and to enhance quality assurance and safety. In addition, artificial intelligence and the sensor-based traceability system can be remarkable changes in the management of the seed value chain by detecting the agro-climatic changes and minor alterations at different stages of seed production, processing, and distribution that assist in the complete understanding of the system from source to end-user.

Conclusions

In conclusion, the fusion of blockchain and IoT technologies offers a transformative approach to enhancing traceability in the agricultural supply chain. By providing an immutable record of a product's journey from seed to consumer, these technologies ensure transparency and trust among stakeholders. The capacity to access comprehensive information about agricultural products not only improves food safety and quality assurance but also empowers consumers and farmers alike. As the agricultural sector increasingly adopts these innovations, the implications for efficiency, accountability, and sustainability are profound, paving the way for a more resilient food system. Future research and development in this area will be crucial in maximizing the potential benefits of blockchain technology in agriculture.

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