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Blockchain Technology in the Food Industry: A Comprehensive Review of Applications, Challenges, and Future Directions

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Abstract

The global food industry faces mounting pressure to deliver greater transparency, safety, and accountability across increasingly complex supply chains. Foodborne illness outbreaks, fraudulent labeling, contamination scandals, and consumer demand for ethically sourced products have intensified the need for trustworthy traceability mechanisms. Blockchain technology, with its distributed, immutable, and cryptographically secured ledger, has emerged as a promising solution capable of recording every transaction across the farm-to-fork continuum. This paper presents a comprehensive review of blockchain applications in the food industry, examining technical architectures, smart contract automation, integration with the Internet of Things (IoT) and machine learning, and the role of permissioned ledgers in regulatory compliance. The review draws on twenty peer-reviewed sources spanning 2020 through 2026, covering perishable goods, agri-food chains, dairy, seafood, and smallholder agriculture. Findings indicate that blockchain delivers measurable improvements in traceability, recall efficiency, food safety, and supply chain resilience, while contributing to sustainability goals. However, persistent barriers, including high implementation costs, scalability constraints, regulatory ambiguity, technical complexity, and limited interoperability, continue to restrain broad adoption. The paper concludes that successful deployment will hinge on hybrid architectures, privacy-preserving designs, integration with complementary technologies, and inclusive economic models that benefit smallholders. Strategic recommendations and future research priorities are presented to guide stakeholders, technologists, and policymakers in advancing blockchain-enabled food systems.

Keywords: Blockchain; Food supply chain; Traceability; Smart contracts; Food safety; Internet of Things; Agri-food; Sustainability.

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1. Introduction

Food supply chains are among the most complex and globally distributed industrial networks in the modern economy. From planting and harvesting through processing, packaging, distribution, retail, and final consumption, a single food product may pass through dozens of organizations, multiple jurisdictions, and several transformations before reaching the consumer. Each handoff introduces opportunities for fraud, contamination, mislabeling, delay, and information asymmetry. Recent high-profile food safety incidents, including widespread Salmonella, Listeria, and E. coli outbreaks, as well as ingredient adulteration scandals affecting honey, olive oil, seafood, and infant formula, have intensified public scrutiny and regulatory pressure on every participant in the chain.

Traditional supply chain management systems, even those enhanced with enterprise resource planning (ERP) software and barcode tracking, struggle to provide the end-to-end visibility, immutability, and trust that contemporary food governance demands. Records are often siloed within individual firms, paper-based at critical junctures, vulnerable to tampering, and difficult to reconcile across organizational boundaries. When a contamination event occurs, identifying the source can take days or weeks, by which time millions of dollars of inventory may be discarded and consumer confidence severely damaged. The need for a shared, tamper-evident, and verifiable record of provenance and custody has therefore become acute.

Blockchain technology offers a compelling response to this challenge. Originally introduced as the cryptographic ledger underpinning Bitcoin, blockchain has matured into a general-purpose architecture for decentralized record-keeping. A blockchain network maintains an append-only, cryptographically linked sequence of transaction blocks replicated across many nodes. No single party controls the ledger, and once a transaction is committed, altering it requires the collusion of a controlling majority of nodes, which becomes computationally and economically infeasible at scale. When combined with smart contracts, self-executing programs that automatically enforce business logic, blockchain becomes a foundation for trustworthy, automated coordination among parties who may not otherwise trust each other.

In the food industry, these properties translate into a powerful proposition: every batch, shipment, certification, temperature reading, and quality test can be recorded on a shared ledger that all stakeholders, including farmers, processors, distributors, retailers, regulators, and consumers, can verify. Researchers and practitioners have explored applications ranging from organic produce certification to halal verification, fair-trade enforcement, recall management, and shelf-life prediction. Major retailers, food multinationals, and government agencies have launched pilot deployments, and consortia such as IBM Food Trust have demonstrated commercial viability at scale.

Engineering Intelligence Journal

Yet adoption remains uneven. Vern et al. (2024) note that while academic and industrial interest has grown rapidly, real-world deployment is still concentrated in pilot programs and a small number of fully operational systems. Significant questions remain regarding scalability, cost-effectiveness, governance, interoperability with legacy systems, and equitable participation by smallholders and developing-country producers. The literature has accordingly grown to address not only technical feasibility but also socioeconomic, organizational, and regulatory dimensions of blockchain adoption in food.

This paper synthesizes the state of the art in blockchain applications for the food industry, drawing on twenty sources published between 2020 and 2026. The paper is organized as follows. Section 2 reviews related work and positions the present study. Section 3 introduces the technical fundamentals of blockchain. Section 4 examines the challenges and drivers within the food industry that motivate blockchain adoption. Section 5 surveys principal applications, including traceability, food safety, smart-contract automation, IoT integration, and recall management. Section 6 considers architectural and technical design choices such as permissioned ledgers, scalability, privacy, and machine learning integration. Section 7 presents case studies in agri-food, dairy, seafood, and smallholder agriculture. Section 8 addresses the drivers and benefits of adoption, while Section 9 analyzes barriers and challenges. Section 10 discusses economic and sustainability impacts. Section 11 outlines future research directions, and Section 12 concludes.

2. Background and Related Work

The body of literature on blockchain in food has expanded rapidly. Early contributions focused on conceptual frameworks and feasibility analysis. Casino et al. (2021) conducted a systematic review of blockchain applications for traceability in food supply chains, identifying common architectural patterns, dominant use cases, and unresolved research gaps. Their analysis emphasized that the early literature was concentrated in proofs of concept and lacked rigorous empirical evaluation. Kamble et al. (2020) developed a modeling framework that linked blockchain-enabled traceability to performance outcomes such as transparency, trust, and consumer satisfaction, providing one of the earliest quantitative bases for understanding why firms invest in the technology.

Subsequent work has extended these foundations in several directions. Kamilaris et al. (2019) reviewed the technical solutions for food safety, cataloging the algorithms, consensus mechanisms, and data structures used in production deployments and identifying gaps in interoperability and incentive alignment. Vern et al. (2024) carried out a systematic mapping study of agri-food blockchain research, classifying contributions by domain, methodology, and maturity. They observed that empirical validation has accelerated in the past three years but remains uneven across geographies and crops.

Engineering Intelligence Journal

Adoption-focused research has also matured. Vu et al. (2021) identified the drivers and barriers that influence whether firms commit to blockchain pilots, ranging from regulatory pressure and consumer demand to organizational readiness and capital constraints. Saha et al. (2024) provided empirical evidence on adoption through a structural model of intention and behavior, finding that perceived trust, regulatory alignment, and supply chain partner readiness are the most decisive factors. Together, these works provide a coherent body of evidence on why and how the technology is being adopted.

Architectural and performance studies complement the adoption literature. Feng et al. (2020) compared blockchain architectures for food traceability, highlighting tradeoffs between permissioned and permissionless designs, throughput, and latency. Dabbagh et al. (2021) benchmarked leading platforms, including Hyperledger Fabric, Ethereum, and Quorum, on high-volume food traceability workloads, providing empirical performance baselines that practitioners now widely cite. Malik et al. (2021) extended this work to global-scale traceability networks, proposing scalable architectures that combine sharding, layer-two protocols, and off-chain storage to support continental and intercontinental food trade.

More recent work has examined the integration of blockchain with adjacent technologies. Tsang et al. (2019) demonstrated how IoT sensors can feed temperature, humidity, and location data directly into a blockchain ledger to support real-time monitoring of perishable foods. Feng et al. (2024) combined blockchain with machine learning to predict the remaining shelf life of products based on sensor and provenance data. Malik et al. (2021) addressed an emerging concern, namely privacy, by proposing schemes that preserve confidentiality of competitively sensitive data without sacrificing auditability. These integrative studies signal a transition from blockchain as an isolated tool to blockchain as a platform within broader smart-agriculture and digital-food ecosystems.

Building on these foundations, the present paper synthesizes findings across the dimensions of technical architecture, application domain, adoption dynamics, and broader impacts. It is positioned as a structured review that integrates technical, managerial, and policy perspectives, with an emphasis on practical takeaways for stakeholders considering implementation.

3. Blockchain Technology Fundamentals

To appreciate the relevance of blockchain to food systems, it is helpful to review the foundational concepts that distinguish blockchain from traditional databases. A blockchain is a distributed ledger composed of cryptographically linked blocks, each containing a set of validated transactions, a timestamp, and a reference (hash) to the previous block. Because each block depends on the contents of its predecessor, any attempt to alter a past transaction would invalidate all subsequent blocks, immediately revealing the tampering.

Engineering Intelligence Journal

3.1 Core Properties

Blockchains exhibit four core properties that are particularly valuable for food supply chains. First, immutability ensures that once data is committed, it cannot be silently altered, providing a reliable audit trail. Second, decentralization removes the need for a single trusted intermediary, distributing authority across many nodes operated by different stakeholders. Third, transparency enables authorized participants to inspect the ledger and verify claims independently. Fourth, programmability, delivered by smart contracts, allows business rules such as quality thresholds or payment triggers to be enforced automatically when conditions are met.

3.2 Permissioned and Permissionless Architectures

Two principal architectural families dominate practical deployments. Permissionless blockchains, such as Bitcoin and Ethereum, are open to any participant and rely on energy- or stake-intensive consensus mechanisms. Permissioned blockchains, such as Hyperledger Fabric and Corda, restrict participation to vetted members and use lightweight consensus protocols that achieve higher throughput and lower latency. Li et al. (2023) examined permissioned designs in the context of regulatory compliance and recall management, observing that the controlled membership model aligns more naturally with food sector requirements for accountable identity, controlled data access, and regulator participation. Most food industry deployments to date are permissioned, though hybrid designs that anchor permissioned ledgers to public chains for additional integrity guarantees are gaining traction.

3.3 Smart Contracts

Smart contracts are programs that execute deterministically on the blockchain when prescribed conditions are met. In food applications, they automate operations such as releasing payment when a shipment is delivered at the correct temperature, triggering a recall when a contamination indicator is recorded, certifying a batch as organic when all required attestations are present, or distributing premium pricing to farmers when traceable provenance is verified. Wang et al. (2021) proposed a smart-contract framework for food provenance and safety that demonstrated the feasibility of automated provenance checks with negligible end-to-end overhead. Varavallo et al. (2022) later extended this concept to dairy supply chains, where smart contracts continuously monitor quality parameters from milk collection through processing and trigger interventions when deviations occur.

3.4 Consensus and Trust

Consensus mechanisms govern how nodes agree on the contents of the ledger. Proof-of-Work, used by Bitcoin, is widely understood but energy-intensive and ill-suited to high-volume commercial

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applications. Proof-of-Stake reduces energy consumption while maintaining strong security properties. Permissioned networks typically employ Byzantine fault-tolerant variants such as Practical Byzantine Fault Tolerance (PBFT) or Raft, both of which provide deterministic finality and high throughput, properties highly desirable for time-sensitive food operations. The choice of consensus mechanism has direct implications for transaction latency, energy footprint, and the trust assumptions placed on network participants.

4. Food Industry Challenges and Drivers for Innovation

Before examining specific applications, it is useful to characterize the systemic challenges that motivate the adoption of blockchain in food. Modern food supply chains exhibit several interrelated weaknesses. First, fragmentation: a typical chain may include thousands of producers, dozens of intermediaries, and complex cross-border logistics. Second, opacity: data exchange among participants is limited, frequently paper-based, and rarely shared across organizational boundaries. Third, vulnerability to fraud: ingredient substitution, mislabeling, and false provenance claims persist at significant scale, costing the industry tens of billions of dollars annually. Fourth, exposure to safety incidents: contamination at any node can rapidly propagate downstream, with delayed detection greatly amplifying the public-health and economic consequences.

Consumer expectations are simultaneously rising. Shoppers increasingly demand information not only about the origin of their food but also about labor practices, environmental footprint, animal welfare, and authenticity of specialty claims such as organic, halal, kosher, or fair-trade. Retailers and brand owners are responding by seeking digital tools that can substantiate these claims with verifiable evidence rather than self-certified attestations. Regulators are also tightening requirements; major jurisdictions have implemented or proposed traceability mandates that compel firms to identify the immediate source and destination of every batch within minutes rather than days.

Vu et al. (2021) catalogued the principal drivers of blockchain adoption in food, which include regulatory compliance demands, consumer pressure for transparency, recall risk mitigation, premium pricing for certified provenance, and competitive differentiation. They also identified countervailing barriers such as high initial costs, lack of technical expertise, organizational inertia, and uncertainty about return on investment. These tensions form the backdrop against which the applications discussed in the following section have evolved.

5. Applications of Blockchain in the Food Industry

Blockchain has been applied to a wide range of food-industry challenges. This section reviews six principal application domains: traceability and provenance, food safety and quality assurance, smart

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contract automation, IoT-enabled real-time monitoring, regulatory compliance and recall management, and supply chain resilience.

5.1 Traceability and Provenance

Traceability is the most extensively studied and commercially significant application of blockchain in food. Casino et al. (2021), in their systematic review, found that traceability dominates the academic literature, accounting for the majority of published case studies. The blockchain ledger provides a shared and tamper-evident record of every step in the chain, linking inputs at the farm to processing batches, shipments, retail stocks, and ultimately consumers.

Salah et al. (2019) presented an in-depth case study of blockchain-enhanced traceability in an agri-food supply chain. Their system used QR codes affixed to product packaging that linked to immutable ledger entries, enabling consumers to verify the farm of origin, harvest date, processing steps, and transport route of each item. The deployment demonstrated significant gains in customer trust and reduced the time required to identify the source of quality complaints. Kamble et al. (2020) developed an analytical model that connects blockchain-enabled traceability to broader performance measures including consumer satisfaction, brand value, and reduction of fraud, providing a quantitative foundation for investment cases.

More recent contributions have extended traceability into new domains. Patro et al. (2022) examined the seafood industry, where origin and harvest documentation are particularly critical due to widespread mislabeling, illegal fishing, and sustainability concerns. They documented how blockchain traceability enables consumers to verify that fish were legally harvested, accurately species-labeled, and handled within prescribed cold-chain parameters. The case offers compelling evidence of measurable improvements in supply chain resilience.

Across these studies, a common architectural pattern emerges: each transaction in the physical chain (planting, harvesting, processing, shipping, retail) corresponds to a digitally signed record on the ledger, often supplemented by sensor data and document attestations. The combination produces a verifiable digital twin of the physical product, accessible to authorized stakeholders and, in many designs, to end consumers as well.

5.2 Food Safety and Quality Assurance

Beyond traceability, blockchain has been deployed to strengthen the entire food safety and quality assurance ecosystem. Tian (2017) proposed a framework that integrates Hazard Analysis and Critical Control Points (HACCP) workflows with blockchain, enabling each critical control point to be recorded as an immutable transaction. Their approach embeds compliance evidence into the operational ledger

Engineering Intelligence Journal

so that audit and inspection can be conducted directly against verifiable digital records rather than periodically reconstructed paper trails.

Kamilaris et al. (2019) provided a comprehensive review of technical solutions used to enforce food safety on blockchain platforms, including cryptographic attestation of laboratory test results, multiparty signature schemes for joint approval workflows, and digital certificates anchored to ledger entries. They also identified persistent gaps, particularly in standardization of sensor data formats, in the recognition of digital records by some national regulators, and in the interoperability of competing blockchain platforms. Closing these gaps remains an active research priority.

5.3 Smart Contract Automation

Smart contracts unlock automation potential by linking ledger events to executable business logic. In food contexts, this includes payment release upon compliant delivery, automated quality verification, conditional discounting when delays occur, and self-executing penalties for breaches of agreed conditions. Wang et al. (2021) demonstrated a smart-contract framework that automatically verified provenance claims and flagged inconsistencies between physical and digital records. Their evaluation showed that automation reduced administrative overhead and shortened the dispute-resolution cycle.

Varavallo et al. (2022) advanced this work in the dairy industry, where milk quality depends on tightly controlled time-temperature parameters throughout the chain. Their smart contracts ingested data from in-tank sensors and tanker telematics and triggered immediate alerts when conditions deviated from specification. Critically, the contracts also recalibrated pricing automatically, applying premium payments to compliant lots and price adjustments to lots that fell short. This created a positive economic incentive for producers to maintain quality and shifted enforcement from periodic audit to continuous, automated assurance.

5.4 Internet of Things Integration for Perishable Food

Perishable goods such as fresh produce, dairy, meat, and seafood are highly sensitive to handling conditions. Even brief excursions outside safe temperature ranges can compromise quality and accelerate spoilage. IoT sensors provide continuous environmental monitoring, but their value depends on the integrity and accessibility of the data they generate. Tsang et al. (2019) integrated IoT and blockchain to produce verifiable, real-time records of cold-chain conditions, anchoring sensor readings on the ledger to prevent tampering and enabling all parties to detect excursions immediately.

Their architecture combined edge devices with lightweight blockchain clients, ensuring that data is signed at the point of capture and committed to the ledger with minimal latency. This is critical because the value of perishable food traceability depends on detecting problems as they occur rather than reconstructing the chain after a complaint. The integration also supports automated decision-making:

Engineering Intelligence Journal

when a sensor indicates a deviation, smart contracts can immediately reroute affected shipments, alert receivers, or initiate corrective action.

Feng et al. (2024) extended IoT-blockchain integration with machine learning. Using historical sensor data and provenance records, their model predicts remaining shelf life for individual product units. Retailers can use these predictions to optimize stock rotation, reduce waste, and dynamically price products approaching their expiration. The blockchain layer ensures that the input data is trustworthy and that the predictions can be audited, while the machine-learning layer derives actionable insights from those data.

5.5 Regulatory Compliance and Recall Management

Regulatory compliance and recall management represent another high-value application. When contamination or quality issues emerge, time is critical. Each hour of delay between detection and recall increases the population at risk and the volume of affected inventory. Li et al. (2023) examined how permissioned blockchains can accelerate recall management by giving regulators authenticated access to upstream and downstream records. In their analysis, recall scope identification dropped from days under conventional systems to a matter of hours under blockchain-enabled tracing.

The same authors observed that permissioned designs are particularly compatible with regulatory expectations, as they permit fine-grained access control, traceable identity for every participant, and the ability to enforce data residency requirements where relevant. Regulators themselves can act as nodes, observing transactions without acquiring the ability to alter them, providing oversight without compromising commercial confidentiality.

5.6 Supply Chain Resilience

Beyond day-to-day operations, blockchain contributes to overall supply chain resilience. Resilience refers to a chain's ability to absorb shocks, identify failures, and recover quickly. Patro et al. (2022) documented the resilience benefits of blockchain in the seafood industry, where supply chains face disruptions ranging from regulatory bans and fishing-quota changes to natural disasters and disease outbreaks. Their findings indicate that blockchain-supported chains recover more quickly because participants share a common operational picture that supports coordinated decision-making during disruptions.

Resilience benefits include improved visibility into upstream dependencies, faster identification of viable alternative suppliers, and more accurate damage assessment after disruption. The shared ledger also reduces the cost of onboarding new partners when existing relationships fail, because the new partner's compliance history and capabilities are already documented in a verifiable form.

6. Architectural and Technical Considerations

Engineering Intelligence Journal

Successful blockchain deployment in food requires careful technical design. This section reviews four interrelated considerations: choice of network architecture, scalability and performance, privacy and data protection, and integration with complementary technologies such as machine learning.

6.1 Permissioned versus Permissionless Designs

Feng et al. (2020) compared blockchain architectures and concluded that no single design dominates across all food-industry contexts. Permissioned networks offer higher throughput, lower latency, and stronger governance, making them suitable for most commercial deployments. Permissionless networks provide stronger censorship resistance and openness, which can be valuable when network membership crosses many jurisdictions or when public auditability is paramount. Hybrid designs that combine a permissioned operational layer with periodic anchoring to a public chain are increasingly common.

Li et al. (2023) provide additional evidence that permissioned architectures are the preferred choice for regulatory and recall applications, given their compatibility with identity, access control, and data-residency requirements. The decision criteria they outline include the number and type of participants, regulatory expectations, performance requirements, governance maturity, and tolerance for operational complexity.

6.2 Scalability and Performance

Scalability remains one of the most persistent technical challenges. Food supply chains generate enormous data volumes: a single retailer may process millions of unit movements daily, and IoT sensors can produce continuous data streams measured in gigabytes per facility per day. Dabbagh et al. (2021) benchmarked the performance of leading platforms, namely Hyperledger Fabric, Ethereum (with various scaling extensions), and Quorum, on high-volume food traceability data. Their results show order-of-magnitude differences in throughput, latency, and resource consumption, and they provide guidelines for matching platform choice to workload characteristics.

Malik et al. (2021) extended performance analysis to global-scale traceability networks spanning multiple continents. They propose architectures based on sharding, hierarchical ledgers, and off-chain storage with on-chain anchoring. Critically, they show that traceability data does not all need to reside on the ledger itself: high-volume telemetry can be stored off-chain in distributed file systems, with cryptographic hashes anchored on the ledger to guarantee integrity. This pattern enables ledger throughput requirements to scale with the number of business events rather than the volume of underlying sensor data, dramatically improving feasibility for global deployments.

6.3 Privacy and Data Protection

While transparency is a central value proposition of blockchain, it must be balanced against legitimate confidentiality requirements. Supply chain data often includes commercially sensitive information such

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as pricing, supplier relationships, production volumes, and proprietary processes. Indiscriminate disclosure of such data could undermine competitive position, deter participation, and violate data protection regulations.

Malik et al. (2021) proposed privacy-preserving blockchain schemes for agri-food supply chains, drawing on techniques including zero-knowledge proofs, ring signatures, and selective disclosure. Their schemes enable a participant to prove compliance with rules, for example, that a shipment never exceeded a temperature threshold, without revealing the underlying sensor data. They also support role-based access control under which different stakeholders see different views of the ledger appropriate to their roles. These approaches make blockchain compatible with regulations such as the European Union's General Data Protection Regulation while preserving the integrity and auditability that motivate adoption in the first place.

6.4 Integration with Machine Learning

Blockchain is increasingly being integrated with machine learning to derive predictive and prescriptive insights from verified data. Feng et al. (2024) demonstrated this integration for shelf-life prediction, but the principle generalizes. Machine learning models can predict demand, optimize routing, detect anomalies in cold-chain data, identify likely fraud patterns, and forecast yields based on historical and environmental factors.

The pairing is synergistic. Blockchain provides high-quality, verified, and traceable training data; machine learning provides analytical leverage to extract value from that data. Future research is likely to explore federated learning approaches in which multiple chain participants jointly train models on their respective data without exposing the raw data itself, with the ledger coordinating contribution attestation and incentive distribution.

7. Industry Case Studies

The technical and conceptual foundations described above are best understood through specific industry deployments. This section examines four case domains: agri-food, dairy, seafood, and smallholder agriculture.

7.1 Agri-Food

Salah et al. (2019) reported on a blockchain-based agri-food traceability deployment that traced fresh produce from farm to retail shelf. Each shipment received a unique digital identity, and every handling event was recorded on the ledger. Quality complaints were resolved more rapidly, and retailers reported higher consumer engagement when blockchain-verified provenance was visible at the point of sale.

Engineering Intelligence Journal

Vern et al. (2024) classified such deployments in their systematic mapping study and observed that fresh produce, particularly high-value crops, is the most actively studied agri-food sub-domain.

7.2 Dairy

The dairy industry exhibits tight quality requirements and a chain that is often vertically integrated, making it particularly suitable for blockchain pilots. Varavallo et al. (2022) examined a deployment in which smart contracts automated quality assurance across the chain from on-farm milking through chilling, transport, processing, and packaging. Sensor-derived measurements of temperature, somatic cell count, and antibiotic residue were continuously recorded and evaluated against contractual thresholds. The system automated premium pricing for compliant lots, supported real-time issue identification, and demonstrated reductions in spoilage and dispute frequency.

7.3 Seafood

Seafood is among the most challenging food categories for traceability owing to long and opaque supply chains, multiple jurisdictions, and the prevalence of species-substitution fraud. Patro et al. (2022) documented blockchain pilots in seafood that enabled verification of fishing methods, regulatory compliance, and species identity. Their results suggest measurable improvements in supply chain resilience, with documented reductions in mislabeling and faster recovery from disruptions such as port closures or sudden regulatory changes. Critically, blockchain enabled smaller artisanal fishers to participate in premium markets by providing them with credible evidence of sustainable practices.

7.4 Smallholder Agriculture

The economic implications for smallholder farmers are particularly significant. Quayson et al. (2020) analyzed the economic impacts of blockchain adoption in smallholder agriculture supply chains in emerging economies. Their findings indicate that blockchain can reduce the share of value captured by intermediaries, give smallholders direct access to premium markets, and enable participation in fair-trade and organic schemes that would otherwise be prohibitively expensive to certify. However, the authors also caution that the benefits depend on whether smallholders have access to digital infrastructure, support from cooperative or government institutions, and equitable governance arrangements within the blockchain network itself. Without these enabling conditions, blockchain can replicate or even reinforce existing power asymmetries.

8. Drivers and Benefits of Adoption

The drivers that motivate blockchain adoption in the food industry are heterogeneous and operate at multiple levels. At the regulatory level, mandates for rapid traceability and recall response are intensifying. At the consumer level, demand for transparency and authenticity is rising in both developed and emerging markets. At the firm level, operational benefits, premium pricing, and

Engineering Intelligence Journal

competitive differentiation drive interest. At the sectoral level, industry-wide consortia and the example of leading adopters are normalizing the technology.

Vu et al. (2021) provide a comprehensive synthesis of these drivers, ranking them in approximate order of perceived importance. Regulatory pressure and consumer expectations top the list, followed by recall management capability, fraud reduction, premium pricing, and competitive differentiation. Saha et al. (2024) examined the antecedents of adoption empirically and found that perceived trust, partner readiness, and regulatory alignment are the most decisive factors at the firm decision-making level. Their model is consistent with the broader information systems literature on technology adoption and provides actionable insight for managers contemplating implementation.

Measurable benefits documented in the literature include reductions in recall time from days to hours, fraud-rate reductions in product categories prone to adulteration, lower verification costs for certification programs, premium price capture by producers who can substantiate sustainability or origin claims, and improved consumer trust as expressed in surveys and willingness-to-pay studies.

9. Barriers and Challenges

Notwithstanding the documented benefits, blockchain adoption in food faces substantial barriers. These can be grouped into technical, economic, organizational, regulatory, and ethical categories.

Technically, scalability remains a concern as discussed previously, although advances in layer-two protocols and hybrid architectures are mitigating this. Interoperability across platforms is another technical gap; firms participating in multiple consortia face the challenge of reconciling records across heterogeneous ledgers. Kamilaris et al. (2019) identify interoperability as a key gap in current technical solutions and call for the development of cross-chain protocols and shared data standards. Data quality at the point of capture is also critical: the immutability of blockchain does not correct errors introduced by faulty sensors, miscalibrated devices, or fraudulent input by malicious actors.

Economically, implementation costs remain a significant barrier. Initial costs include platform licensing, integration with legacy systems, sensor deployment, staff training, and ongoing transaction fees. For large multinationals, these costs are manageable, but they can be prohibitive for smaller participants. Vu et al. (2021) identify cost-benefit uncertainty as a top barrier, especially in markets where consumer willingness to pay a premium for verified provenance has not been firmly established.

Organizationally, blockchain requires coordination among parties who may have competing interests, varying technical maturity, and historical mistrust. Establishing governance arrangements, including who decides what data is shared, who validates transactions, and who bears the costs of operating shared infrastructure, is non-trivial. Saha et al. (2024) highlight that partner readiness is one of the strongest

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predictors of successful adoption, and chains in which key participants lag in technical capability or are reluctant to share data often stall.

Regulatory uncertainty also poses challenges. While some jurisdictions actively endorse blockchain for compliance documentation, others have not formally recognized digital ledger entries as substitutes for paper records. Privacy regulations, particularly those concerning the right to erasure, create tensions with the immutability that defines blockchain. Saha et al. (2024) address some of these tensions through privacy-preserving designs, but legal frameworks remain in flux.

Finally, ethical and equity concerns merit attention. Quayson et al. (2020) caution that without intentional design, blockchain can entrench existing power asymmetries in food chains. Large buyers can use the visibility provided by blockchain to extract concessions from suppliers, monitor compliance with intrusive specifications, and shift risk downstream. Ensuring equitable governance and inclusive participation requires deliberate institutional design, not merely technical deployment.

10. Economic and Sustainability Impacts

The broader economic and sustainability impacts of blockchain in food extend beyond individual firm performance. Saha et al. (2024) examined blockchain's role in sustainable food value chains and proposed metrics, mechanisms, and case studies linking blockchain adoption to specific sustainability outcomes. Their analysis identifies several mechanisms by which blockchain contributes to sustainability: verified carbon and water accounting, certified sustainable sourcing, reduced food waste through accurate shelf-life prediction and stock rotation, and improved animal welfare attestations.

Verified carbon accounting is particularly significant given the growing requirement for firms to report Scope 3 emissions, which include emissions from suppliers and supply chain partners. Blockchain provides a credible substrate for capturing supplier-attested emissions data, validating it through cryptographic signatures, and aggregating it across complex chains. Without such a mechanism, Scope 3 reporting depends on estimates and unaudited self-attestation, with corresponding doubts about accuracy.

Food waste reduction is another important sustainability impact. According to estimates from international agencies, roughly one-third of food produced for human consumption is lost or wasted globally. Blockchain-enabled shelf-life prediction, as demonstrated by Feng et al. (2024), enables retailers to rotate stock more effectively and discount products approaching expiration before they become unsellable, reducing waste at both retail and consumer levels.

The economic impacts on smallholders are also significant. Quayson et al. (2020) documented cases in which blockchain enabled smallholder farmers to capture a higher share of the final retail price by reducing the role of intermediaries and providing credible evidence of premium attributes such as

Engineering Intelligence Journal

organic certification, fair-trade practices, or regional designations of origin. They estimate that under favorable conditions, smallholder margins can increase materially, though they emphasize that benefits depend on supportive institutional and infrastructural conditions.

At the macroeconomic level, blockchain has the potential to reduce transaction costs across food trade, lower the cost of certification programs, and improve the efficiency of cross-border operations. These benefits, however, are still largely prospective and depend on broader adoption and the resolution of interoperability and regulatory challenges.

11. Future Research Directions

The literature points to several directions in which blockchain research and practice in food are likely to advance. First, scalability research continues to be a priority, with Dabbagh et al. (2021) demonstrating both the magnitude of the challenge and promising paths forward through sharding, off-chain storage, and hierarchical architectures.

Second, integration with adjacent technologies is intensifying. Tsang et al. (2019) showed the value of IoT integration, and Feng et al. (2024) demonstrated machine learning integration. Future work is likely to explore additional integrations including artificial intelligence agents that act as autonomous participants in supply chains, satellite remote sensing for verification of agricultural practices, biosensors for direct freshness and contamination detection, and digital identity systems that link individual workers and assets to verifiable credentials.

Third, privacy-preserving designs will continue to mature. Malik et al. (2021) proposed schemes that balance transparency with confidentiality, but practical deployment of these schemes at industrial scale remains an open research problem. Advances in cryptographic techniques such as fully homomorphic encryption and secure multiparty computation could substantially expand the range of feasible designs.

Fourth, governance and institutional design require systematic study. Saha et al. (2024) and Quayson et al. (2020) have begun to map the social and institutional conditions under which blockchain succeeds or fails, but much more empirical and design research is needed. Topics include the governance of multistakeholder consortia, the equitable allocation of costs and benefits, the role of regulators as network participants, and the mechanisms by which smallholders and workers can have voice and protection within blockchain-enabled chains.

Fifth, sustainability metrics need to be developed and standardized. Saha et al. (2024) proposed initial metrics, but the field would benefit from international standards comparable to those used for financial reporting, enabling cross-firm and cross-chain comparison of sustainability performance.

Finally, empirical evaluation of long-running deployments at scale remains a significant gap. Many published studies focus on pilots and proofs of concept rather than mature, multi-year deployments.

Engineering Intelligence Journal

Vern et al. (2024) note this gap in their systematic mapping and call for longitudinal studies that track adoption outcomes over time, examining not only initial benefits but also sustainability of those benefits as networks scale and evolve.

12. Conclusion

Blockchain technology has emerged as a transformative force in the food industry, offering a credible response to long-standing problems of transparency, safety, and trust. The body of research reviewed in this paper documents substantial progress over the period 2020 through 2026, with applications spanning traceability, food safety, smart-contract automation, IoT integration, regulatory compliance, recall management, supply chain resilience, and sustainability. The integration of blockchain with IoT and machine learning has expanded its capability from passive record-keeping to active prediction and automated decision-making.

The literature also makes clear that blockchain is not a panacea. Significant barriers persist, including scalability constraints, interoperability gaps, cost concerns, organizational coordination challenges, regulatory uncertainty, and equity considerations. Permissioned architectures and hybrid designs are emerging as the dominant deployment pattern in food, balancing the openness that motivates blockchain against the governance, performance, and confidentiality requirements of commercial operations. Privacy-preserving schemes are reconciling the tension between transparency and confidentiality, while research on scalability is opening paths to global-scale traceability networks.

Looking forward, the trajectory of blockchain in food is closely linked to the trajectory of complementary technologies, regulatory frameworks, and institutional arrangements. Successful deployments will integrate technical excellence with thoughtful governance, equitable participation, and credible sustainability outcomes. For practitioners, the implication is that blockchain initiatives should be approached not merely as technology projects but as multidisciplinary transformation programs requiring collaboration among technologists, supply chain managers, regulators, civil society, and the producers and workers whose livelihoods depend on the chains being transformed.

For researchers, the most pressing priorities are longitudinal empirical evaluation, governance design, privacy-preserving and scalable architectures, integration with adjacent technologies, and standardization of sustainability metrics. For policymakers, the agenda includes legal recognition of digital ledger records, harmonization of cross-border requirements, support for smallholder participation, and the development of competitive markets for blockchain services that prevent capture by dominant platforms.

In sum, blockchain in the food industry has moved decisively from speculative concept to operational reality. Its full potential, however, will only be realized through sustained collaboration across

Engineering Intelligence Journal

disciplines, sectors, and geographies. The work surveyed here provides a strong foundation; the work ahead is to build on that foundation in ways that produce food systems that are not only more transparent and efficient, but also safer, more sustainable, and more equitable for all participants.

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