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THE GOVERNANCE DEFICIT OF DIGITAL FOOD SAFETY: BLOCKCHAIN, AI, AND THE REGULATORY RECOGNITION GAP

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Abstract

In 2017, Walmart demonstrated that tracing sliced mangoes from retail shelf to source farm, a process taking 6 days, 18 hours, and 26 minutes conventionally, could be done in 2.2 seconds via Hyperledger Fabric blockchain distributed ledger. This 99.9% compression of traceback time is the most precisely documented efficiency gain in food supply chain history. It is not a regulatory standard. It is not a legal requirement. It is not an evidentiary benchmark. It is a commercially deployed capability operating in a complete governance vacuum. The blockchain food traceability market will grow from USD 3.04 billion in 2025 to USD 52.2 billion by 2035 at a CAGR of 32.9% (Future Market Insights, 2026). The AI food safety and quality control market will grow from USD 2.7 billion in 2025 to USD 13.7 billion by 2030 at a CAGR of 30.9% (BCC Research, 2025), with the broader AI food safety market projected to reach USD 53.5 billion by 2034. FSMA Rule 204 , the most significant traceability regulatory instrument in US history , was delayed from its January 2026 compliance deadline to July 2028, with Congress directing the FDA not to enforce it in the intervening period. The WTO SPS Committee has produced no binding standard governing digital certificate recognition or blockchain record evidentiary status. No court of any jurisdiction has issued a definitive ruling on the evidentiary weight of an immutable blockchain ledger entry in a food safety dispute. This paper introduces the Regulatory Recognition Gap (RRG) , the structural distance between the deployment velocity of digital food safety technologies and the legal, evidentiary, and institutional frameworks required to govern them , and quantifies it as a Technology-Regulation Speed Gap (TRSG) of approximately 8:1 to 11:1. It proposes the Digital Food Safety Governance Architecture (DFSGA) as the three-tier institutional framework for closing it: a Codex Digital Traceability Standard, a WTO SPS Digital Certificate Recognition Protocol, and National AI Food Safety Regulatory Frameworks addressing explainability, liability, and algorithmic consistency.

Аннотация

В 2017 году Walmart продемонстрировал, что отслеживание происхождения ломтиков манго от полки магазина до фермы-источника, занимавшее ранее 6 дней 18 часов 26 минут, стало возможным за 2,2 секунды благодаря блокчейн-технологии Hyperledger Fabric. Это сжатие времени прослеживания на 99,9% является наиболее точно задокументированным показателем эффективности в истории цепочек поставок продовольствия. Данная работа вводит концепцию Разрыва регуляторного признания (RRG) и предлагает Архитектуру цифрового управления безопасностью пищевых продуктов (DFSGA) в качестве трёхуровневого институционального механизма для его устранения.

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Keywords

Regulatory Recognition Gap (RRG), Technology-Regulation Speed Gap (TRSG), Digital Food Safety Governance Architecture (DFSGA), GIGO Problem blockchain food safety, FSMA Rule 204 compliance 2028, blockchain food traceability 32.9% CAGR, AI food safety USD 13.7 billion 2030, Walmart IBM Food Trust 2.2 seconds traceback, Hyperledger Fabric food supply chain, WTO SPS digital certificate recognition, Input Verification Protocol, Cross-Chain Interoperability Standard, Algorithmic Consistency Standard, AI explainability food safety, hyperspectral imaging mycotoxin 95% accuracy, food safety testing market, SGS IBM Watson partnership, EU Digital Product Passport, smart contract food compliance, GS1 standards FSMA 204, blockchain recall management FDA dataset.

Introduction

In November 2025, the United States Congress directed the FDA not to enforce FSMA Rule 204 prior to July 20, 2028.[1] The rule itself remains unchanged: its requirements for Key Data Elements (KDEs) at Critical Tracking Events (CTEs), and 24-hour response to FDA traceability requests for foods on the Food Traceability List, are legally in force. Only the enforcement date moved. The documented reason is precisely the governance architecture problem this paper analyzes: the implementation complexity of end-to-end digital traceability across multi-party food supply chains exceeded what the industry could accomplish within the original three-year compliance window. The most advanced food safety traceability law ever enacted in the United States was delayed not because the technology was unavailable, but because the governance architecture for deploying it at scale was incomplete.

This is the Regulatory Recognition Gap (RRG) in its most institutionally consequential form. The technology exists, is deployed, and is performing. Walmart has been tracing mangoes in 2.2 seconds using IBM Food Trust on Hyperledger Fabric since 2017. Blockchain food traceability is growing at 32.9% CAGR. The University of South Australia demonstrated 95% accuracy in hyperspectral imaging detection of mycotoxin contamination in nuts and grains using machine learning in August 2025.[2] By 2025, over 60% of AI adoption in food manufacturing was focused on real-time quality inspection and contamination detection.[3] In March 2025, SGS , the world's largest inspection, verification, testing, and certification company, operating 2,500+ laboratories in 115 countries , entered a strategic partnership with IBM to leverage Watson AI for food safety testing.[4] Yet the legal architecture that would make these technologies governable does not exist at any level of binding international law.

The RRG has three distinct dimensions. The Evidentiary Gap: digital food safety records have no formally defined evidentiary status in WTO SPS dispute resolution, EU food safety law, or US federal court. The Interoperability Gap: the absence of internationally standardized data formats means that a blockchain record produced in Vietnam cannot be legally relied upon by an EU regulatory system. The Deployment-Speed Gap: the Technology-Regulation Speed Gap (TRSG),

[1] FDA. (2025). FSMA Final Rule, Food Traceability Rule: compliance extended to July 20, 2028. Congressional directive November 2025. | Federal Register. (August 7, 2025). | Barley Snyder. (December 2025).
[2] Cervicorn Consulting. (2025). AI in Food Safety Market Size to Reach USD 53.51 Billion by 2034. University of South Australia, August 2025:
[3] BCC Research. (2025). AI Revolutionizes Food Safety and Quality Control Market. Over 60% of food manufacturing AI focused on real-time quality inspection and contamination detection.
[4] Technavio. (2025). Food Safety Testing Market Analysis 2024-2029. SGS-IBM Watson strategic partnership, March 2025.

digital food safety technology growing at 30-33% CAGR versus regulatory governance instruments growing at an estimated 3-4% annually, is approximately 8:1 to 11:1. For every binding regulatory instrument governing digital food safety technology, 8-11 units of deployed but ungoverned capability are added to the global food system annually.

This paper proceeds through four stages. Section 2 maps the RRG dimensions quantitatively. Section 3 analyzes the GIGO Problem as the foundational governance vulnerability of blockchain food safety systems. Section 4 examines the AI Regulatory Interface, the specific challenges of governing AI systems that generate regulatory-consequential food safety determinations. Section 5 proposes the DFSGA as the institutional architecture for closing the gap.

The Regulatory Recognition Gap: Mapping the Distance Between Deployment and Governance

The blockchain food traceability market, valued at USD 3.04 billion in 2025, is projected to reach USD 52.2 billion by 2035 at 32.9% CAGR.[5] The broader food traceability and blockchain solutions market reached USD 37.37 billion in 2023, rising to USD 41.56 billion in 2024, and is projected to reach USD 97.17 billion by 2032 at 11.2% CAGR.[6] The AI food safety and quality control market was valued at USD 2.7 billion in 2025 and is projected to reach USD 13.7 billion by 2030 at 30.9% CAGR, with the full AI food safety market reaching USD 53.5 billion by 2034.[7] The blockchain in agriculture and food supply chain market will grow from USD 0.83 billion in 2025 to USD 5.83 billion in 2030 at 47.5% CAGR.[8] These represent billions in operational deployed technology generating traceability records, inspection logs, and compliance data that food safety regulators are legally unprepared to evaluate.

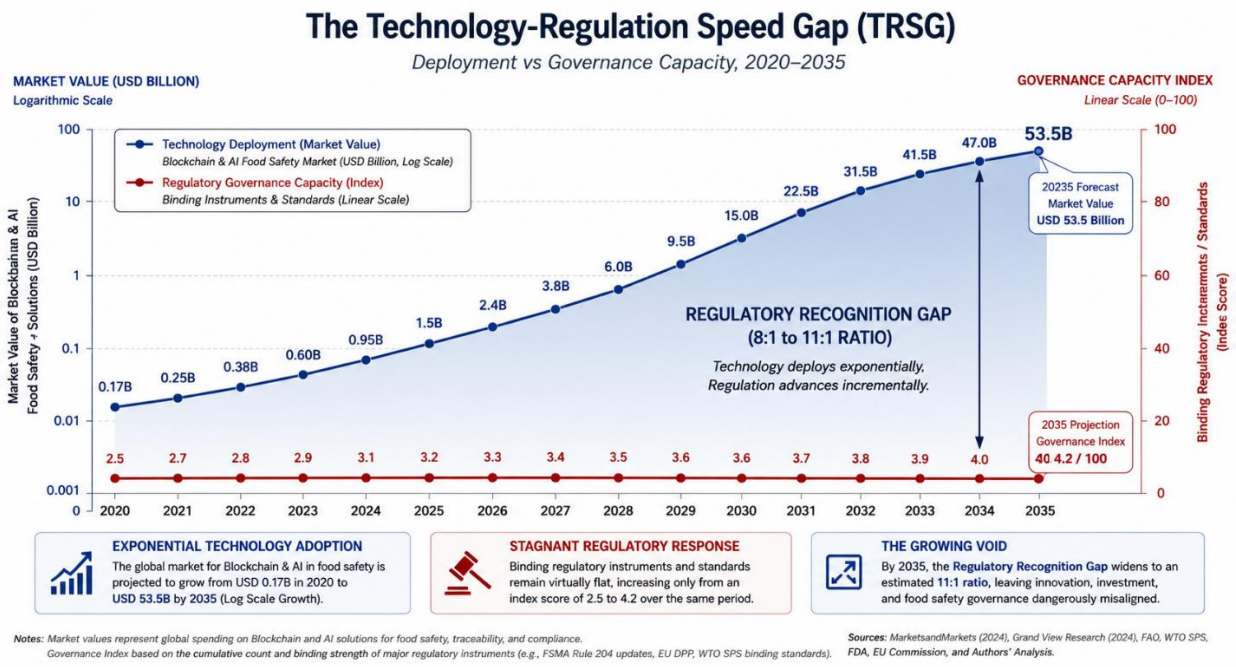
The regulatory response velocity is a fraction of the deployment rate. FSMA Rule 204 was finalized November 2022, effective January 2023, compliance extended to July 2028, and protected from enforcement by Congress in November 2025. The rule technically permits paper records, meaning a company with a USD 200,000 blockchain system is legally equivalent to a company with a paper logbook, both must respond to FDA data requests within 24 hours, but neither receives formal legal recognition or preference for their system's architecture.[9] The WTO SPS Committee's 2024 Final Report on SPS Agreement implementation , the most authoritative annual review available , contains no binding provision on digital certificate recognition, blockchain evidentiary standards, or AI inspection equivalence.[10] The EU Digital Product Passport initiative addresses digital traceability but its food-sector application is under development and its evidentiary status in food safety disputes is unestablished.

The Technology-Regulation Speed Gap (TRSG) is formally defined here as the ratio of annual percentage growth in deployed digital food safety technology value to annual percentage growth in binding regulatory governance capacity. At digital growth of 30-33% annually versus regulatory governance growth of 3-4% annually, the TRSG is 8:1 to 11:1.[11] The private sector is investing in digital food safety infrastructure at a pace that outstrips governance development by an order of magnitude, creating a widening structural gap that conventional regulatory development cannot

[5] Future Market Insights. (March 2026). Blockchain Food Traceability Market 2025-2035.
[6] Datamintelligence. (2025). Food Traceability and Blockchain Solutions Market
[7] BCC Research. (2025). AI food safety and quality control
[8] Business Research Company. (2026). Blockchain in Agriculture and Food Supply Chain Market.
[9] Federal Register. (August 7, 2025). Requirements for Additional Traceability Records, Compliance Date Extension. Rule allows paper records
[10] WTO. (2024). Members adopt key report on challenges and opportunities in SPS Agreement implementation.
[11] Mordor Intelligence. (2026). Food Traceability Market: blockchain segment.

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close at its present pace. Blockchain adoption currently involves 42% of large agribusinesses integrating blockchain-led traceability (Global Growth Insights, 2026), 38% of mid-scale US farms integrating blockchain solutions for compliance and production traceability, and a food traceability market in which blockchain-based platforms lead growth at 8.27% CAGR against an overall market of USD 20.70 billion in 2026.



The graph titled "The Technology-Regulation Speed Gap: Deployment vs Governance Capacity 2020-2030" illustrates the diverging trajectories of the global digital food safety technology market (blockchain + AI combined, USD billions) against the cumulative count of binding international and national regulatory instruments specifically addressing digital food safety technology governance. The exponential deployment curve versus the near-flat governance curve is the visual representation of the RRG as a structural, accelerating institutional failure.

Source: Author construction based on Future Market Insights (2026); BCC Research (2025); Cervicorn Consulting (2025); Datamintelligence (2025); Business Research Company (2026); Mordor Intelligence (2026); WTO SPS Committee records 1995-2025; Federal Register digital traceability rule timeline.

The GIGO Problem: Why Technical Excellence Does Not Substitute for Governance Architecture

The Walmart-IBM mango case is the canonical evidence of blockchain traceability's transformative potential: traceback from 6 days, 18 hours, and 26 minutes to 2.2 seconds across 16 farms, 2 packing houses, 3 brokers, 2 import warehouses, and 1 processing facility, capturing 23 different lot codes and tens of thousands of sliced mangoes in a 30-day pilot.[12] By 2020, Walmart had mandated blockchain compliance for all leafy greens suppliers. A 2025 ScienceDirect case study confirmed that the blockchain implementation delivered a 50% reduction in food waste from more targeted recalls and a 15-20% improvement in consumer trust scores in post-implementation surveys.[13] A peer-reviewed study in ScienceDirect (May 2025) analyzing FDA recall dataset data

[12] Yiannas, F. (2017). Walmart mango traceback benchmark
[13] ScienceDirect. (2025). Tracking transparency: Blockchain in the global supply chain

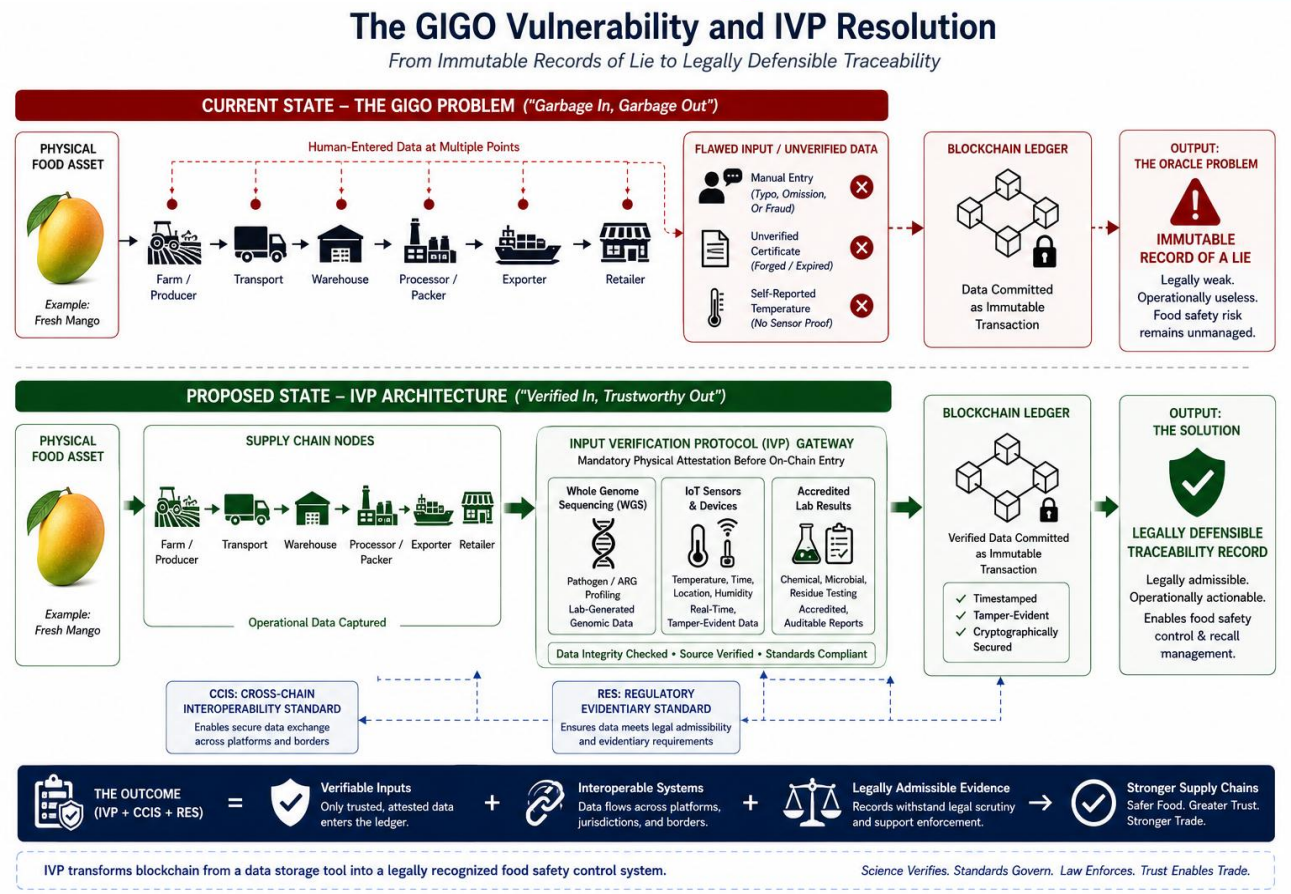
found that companies adopting blockchain technology have statistically significantly shorter recall durations than non-adopters.[14] These are precisely documented, peer-reviewed impacts. They are also entirely non-regulatory: blockchain deployment reduces recall time not because the law requires it or recognizes it, but because physics reduces traceback time.

The GIGO Problem, Garbage In, Garbage Out , is the structural vulnerability that the 2.2-second benchmark does not address. When IBM's Brigid McDermott was explicitly asked about data quality at the time of the Walmart pilot, she stated: 'Initially, the data will not be any cleaner than it is today.[15] Blockchain's foundational property is immutability: once data is written to the ledger, it cannot be altered. But immutability is a guarantee of record permanence, not a guarantee of record accuracy. A blockchain system that records a false temperature reading, a forged organic certification, or a fabricated batch origin creates an immutable, cryptographically verified, permanently preserved record of a lie. The system cannot detect the lie; it guarantees its permanence. The Springer systematic review on blockchain in food supply chain management (June 2025) identifies this explicitly: “The quality of data kept in a database is contingent upon the accuracy and reliability of the input, frequently referred to as the GIGO problem.” The review further notes that 40% of blockchain adoption challenges are cost-related, 30% are interoperability gaps, and 15% reflect data sharing reluctance, but the GIGO problem intersects all three, because it is not a technology problem addressable through better blockchain design. It is a governance problem requiring external verification architecture.[16]

The governance response to GIGO requires three institutional mechanisms absent from all current regulatory frameworks. First, the Input Verification Protocol (IVP): a mandatory standard requiring that every data entry at a Critical Tracking Event be paired with an independently verifiable physical attestation, an IoT sensor reading, RFID scan, accredited laboratory result, or certified inspector attestation, before being written to the ledger. Without IVP, blockchain immutability amplifies rather than mitigates the consequences of fraudulent input, because it makes the fraudulent record impossible to correct. Second, the Cross-Chain Interoperability Standard (CCIS): a binding international data standard defining minimum data elements, authentication protocols, and transfer formats for a blockchain food safety record to be legally read and relied upon across jurisdictions. Without CCIS, the IBM Food Trust records of Walmart's mango chain cannot be integrated with EFSA's One Health WGS system, the EU RASFF alert network, or any other jurisdiction's food safety digital infrastructure, a gap that limits blockchain's food safety value to within-network operations and prevents the global traceback capability that the technology theoretically enables. Third, the Regulatory Evidentiary Standard (RES): a formal determination by Codex Alimentarius or the WTO SPS Committee of the evidentiary weight a blockchain record carries in an inspection, dispute, or liability proceeding. Without an RES, blockchain records and paper records are legally equivalent, an equivalence that incentivizes minimum compliance rather than maximum traceability investment.

[14] ScienceDirect. (May 2025). Blockchain's effects on responsiveness to recalls in the food and beverage industry.
[15] McDermott, B. (2017). IBM Vice President of Food Safety
[16] Springer / Business and Information Systems Engineering. (June 2025). Digital Transformation of Food Supply Chain Management

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The Walmart case also surfaces the physical-digital integrity problem: what prevents someone from swapping physical goods after the blockchain record has been created? In the mango pilot, the blockchain recorded the journey of documented mangoes through documented supply chain nodes. It did not verify that the physical mangoes in the scanned container were the same mangoes whose data was entered at the source farm. This physical-digital interface problem, sometimes called the Oracle Problem in blockchain literature, is the second-order GIGO vulnerability: even with perfect data accuracy at input, the blockchain record cannot guarantee correspondence between the digital record and the physical product at every subsequent supply chain node. Addressing the Oracle Problem requires IoT integration at every node, continuous sensor monitoring that links the physical state of the product to its digital record in real time, a technical solution that is commercially available but is not legally required by any current food safety traceability standard.

The AI Regulatory Interface: Governing Systems That Decide Before They Explain

The AI food safety market's 30.9% CAGR deployment trajectory introduces a governance challenge qualitatively different from blockchain recognition. Blockchain is a data storage and verification technology, its governance challenge is evidentiary. AI is a decision-making technology its governance challenge is procedural. When an AI food safety inspection system flags a production batch as high-risk based on sensor data, temperature patterns, and contamination probabilities, the regulatory consequence: quarantine, testing, or clearance, is a determination that may be subject to due process requirements, appeal rights, and liability standards. When that determination is made by a machine learning model whose decision pathway is not fully

explainable, the procedural architecture of food safety regulation faces a structural challenge no current framework has addressed.

The deployment scale of this challenge is established by market data. As of 2025, 60% of AI adoption in food manufacturing targets real-time quality inspection and contamination detection. Biological hazards represent the largest AI food safety application at 42.1% of the market by risk type. The University of South Australia's August 2025 demonstration of 95% mycotoxin detection accuracy in nuts and grains via hyperspectral imaging and machine learning, non-destructive, real-time, without sample destruction, establishes a detection standard human inspection cannot match. An integrated AI-IoT system pilot study demonstrated 25% increased spoilage detection accuracy and 30% improved response time. The SGS-IBM Watson strategic partnership (March 2025) has deployed AI-powered food safety decision support into the inspection services used by food safety regulators across 115 countries.[17] These are not experimental deployments. They are operational AI systems generating regulatory-consequential determinations globally, without explainability, liability, or algorithmic consistency standards.

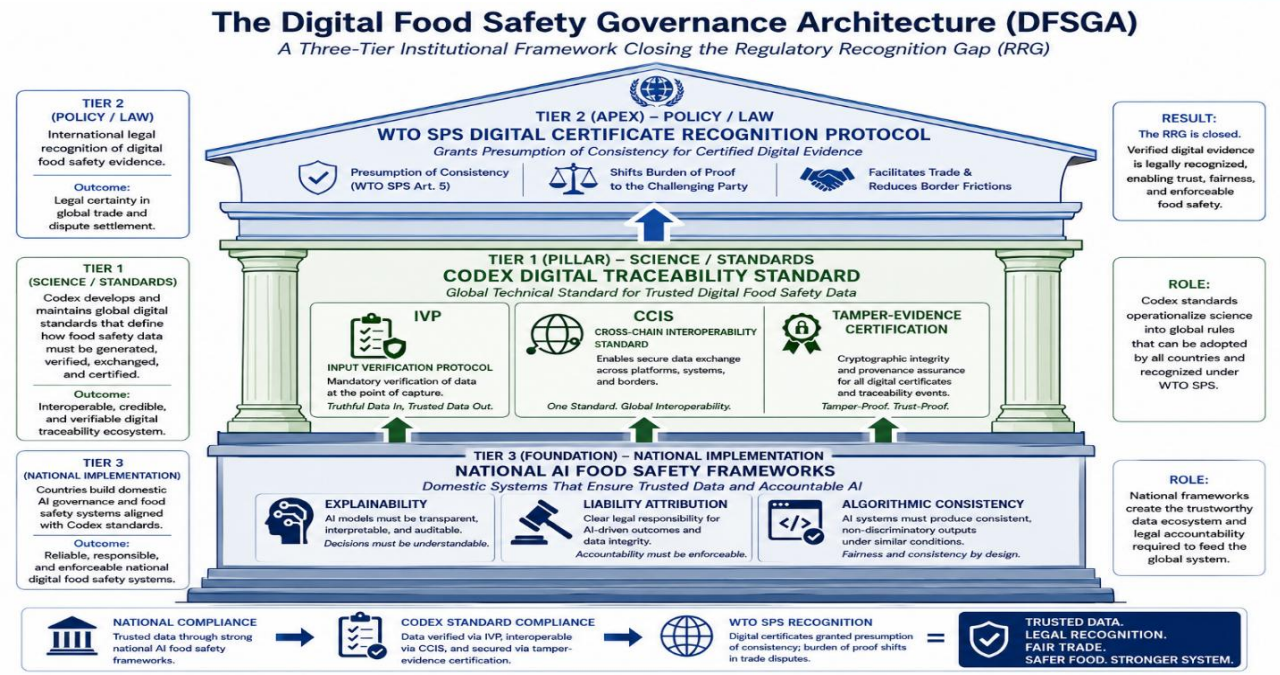
The AI Regulatory Interface has three unresolved governance dimensions. The Explainability Requirement: the legal principle that a regulatory determination adversely affecting a party's interests must be capable of explanation that the affected party can understand and challenge. Deep learning models and ensemble classifiers, the architectures most commonly used for food safety pathogen detection and risk scoring, cannot provide full decision-pathway explanations for individual determinations. When an AI system triggers a quarantine order, the affected producer has no standard legal mechanism for reviewing the model's reasoning in any food safety regulatory jurisdiction. No version of FSMA, EU Regulation 178/2002, or the Codex General Principles of Food Hygiene contains an AI explainability requirement. The Liability Attribution Problem: when an AI food inspection system produces a false positive, flagging safe food as contaminated, causing avoidable economic loss, or a false negative, clearing contaminated food for market, resulting in consumer illness, who bears legal liability? Current food safety liability law assigns responsibility to the food business operator, not to the technology they deploy. As AI systems make an increasing proportion of quality and safety determinations, operator-based liability creates a growing disconnect between who makes the decision and who bears its legal consequences. The Algorithmic Consistency Standard: the absence of any binding standard defining the minimum accuracy, false-positive rate, false-negative rate, and validation methodology required for an AI system to claim legal equivalence to human inspection. The 95% mycotoxin detection accuracy is a significant achievement, but a 5% false-negative rate applied at scale could result in thousands of contaminated batches cleared annually. Without a minimum performance floor, there is no accountability for AI systems whose accuracy degrades as deployment environments diverge from training data.

The Digital Food Safety Governance Architecture: Three Tiers for Closing the Regulatory Recognition Gap

The Digital Food Safety Governance Architecture (DFSGA) closes the RRG through three interdependent institutional tiers, each addressing a specific dimension of the gap through existing institutional channels without requiring new international bodies.

[17] ScienceDirect. (2025). Harnessing Artificial Intelligence to Safeguard Food Quality and Safety.

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Tier 1: Codex Digital Traceability Standard, Making the Blockchain Record a Legal Instrument

The first tier tasks the Codex Alimentarius Commission with developing a Digital Traceability Standard (DTS) establishing minimum technical requirements for a digital food safety record to be recognized as legally equivalent to a paper Codex-compliant food safety certificate under WTO SPS Article 3. The DTS requires three elements. First, the Input Verification Protocol (IVP): every data entry at a Critical Tracking Event must be paired with a machine-readable physical verification signal before being written to the ledger, closing the GIGO vulnerability by requiring physical-digital data linkage as a condition of legal recognition. Second, a Cross-Chain Interoperability Standard (CCIS) aligned with GS1's existing FSMA 204 implementation guidelines and the EPCIS Electronic Product Code Information Services standard, defining universal data formats for CTEs and KDEs across all recognized blockchain platforms. Third, a Tamper-Evidence Certification (TEC) requiring all legally recognized food safety blockchain systems to be certified by an accredited body against a defined cryptographic security standard. Countries implementing DTS-compliant systems would receive the WTO SPS Article 3 presumption of consistency for their traceability-based measures, creating a direct regulatory incentive whose commercial value to food exporters would dwarf the certification cost.

Tier 2: WTO SPS Digital Certificate Recognition Protocol, Creating Legal Hierarchy for Digital Evidence

The second tier establishes a Digital Certificate Recognition Protocol (DCRP) through a formal WTO SPS Committee Decision creating a legal evidence hierarchy: Codex DTS-compliant digital records receive a higher presumption of accuracy than paper records in any SPS dispute where food origin, chain of custody, or safety status is at issue. This reverses the current legal equivalence between paper and digital records and creates a regulatory incentive for digital adoption by attaching trade law advantage to DTS compliance. The DCRP further establishes that any WTO Member imposing a food safety import restriction cannot sustain that restriction against a supplier whose DTS-compliant blockchain record provides molecular-level provenance data, IoT

monitoring records, and AI risk scores showing no hazard signal, unless the imposing Member provides equally detailed counter-evidence. This is the Forensic Diplomacy principle applied to digital traceability: the burden of proof in food trade disputes shifts toward the party relying on less precise evidentiary methods. Combined with the EU Regulation 2025/179 WGS mandate and PulseNet International forensic attribution infrastructure, the DCRP would create the first fully integrated digital evidence standard in international food trade law.

Tier 3: National AI Food Safety Regulatory Frameworks, Explainability, Liability, and Algorithmic Consistency

The third tier establishes the national-level governance template for AI food safety systems, drawing on the EU AI Act's high-risk application classification and applying it specifically to food safety inspection contexts. Three requirements. First, Explainability: AI systems generating regulatory-consequential food safety determinations must maintain and provide upon request a plain-language summary of primary input variables and their directional contribution to the model's output, not full model transparency, but human-reviewable decision factor documentation. Second, standardized Liability Attribution: AI developers are liable for accuracy degradation below certified performance benchmarks; operators are liable for deployment in environments substantially different from validation parameters; certification bodies are liable for approvals not meeting minimum validation standards. Third, Algorithmic Consistency Standards: minimum 98.5% overall accuracy, maximum 2% false-negative rate for biological hazard detection, mandatory annual re-validation against current pathogen profiles, below which an AI food safety system may not claim compliance equivalence to human inspection. These three requirements do not prohibit AI deployment in food safety. They define the governance floor below which deployment creates unacceptable regulatory risk, and above which deployment creates recognized, legally defensible food safety superiority.

Conclusion

The transformation of global food safety from paper-based, periodic, human-led inspection to digital, continuous, algorithmically-mediated control is not a future scenario. It is a present operational reality with a precisely documented commercial scale. Blockchain food traceability at USD 3.04 billion in 2025, growing to USD 52.2 billion by 2035. AI food safety at USD 2.7 billion in 2025, growing to USD 13.7 billion by 2030. 2.2-second mango traceback operational at Walmart since 2017. 95% mycotoxin detection accuracy demonstrated in August 2025. 60% of food manufacturing AI deployment focused on real-time inspection. The governance architecture governing this transformation: one delayed US traceability rule, no binding international digital certificate standard, no WTO recognition of blockchain records, no explainability requirement for AI food safety determinations, no liability standard for AI false negatives.

The Technology-Regulation Speed Gap of 8:1 to 11:1 is the quantified expression of the governance failure. The GIGO Problem demonstrates why immutability without input verification governance amplifies rather than resolves the fundamental food safety traceability challenge. The AI Regulatory Interface demonstrates why the most capable detection technology in food safety history, 95% accuracy, real-time, non-destructive, operates without the explainability, liability, and consistency standards that would make its outputs legally defensible and its failures legally accountable.

The Digital Food Safety Governance Architecture does not ask the food industry to wait for governance before deploying. It provides the governance that makes deployment permanent, legally recognized, and trade-advantaged. The Codex Digital Traceability Standard converts blockchain records from operational tools into legal instruments. The WTO SPS Digital Certificate

Recognition Protocol converts digital traceability investment into trade law advantage. The National AI Food Safety Frameworks convert AI detection superiority into regulatory recognition. Together, they close the RRG, not by slowing deployment, but by constructing the institutional architecture that makes the deployed technology governable, legally defensible, and commercially self-reinforcing. The technology is not waiting for governance. The governance is waiting for institutional will. The DFSGA provides the roadmap for that will to become architecture.

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