

FROM “TRACEABILITY” TO “INTERVENTION”: A BLOCKCHAIN-ENABLED DYNAMIC RISK GOVERNANCE FRAMEWORK FOR PUBLIC HEALTH AND FOOD SAFETY

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ABSTRACT

The industrialization of Geographic Indication (GI) food products has introduced significant public health risks, particularly regarding heavy metal contamination (Cadmium and Methylmercury) in processed seafood. While blockchain-based traceability systems have been widely adopted, they suffer from the “Oracle Problem” immutably recording logistical data without verifying intrinsic chemical safety. This study proposes a “Digital Gatekeeper” framework integrating a permissioned consortium blockchain (Hyperledger Fabric v2.4) with a novel Supply Chain Risk Index (SCRI). The SCRI a composite metric incorporating bioaccumulation kinetics and processing factors was embedded into smart contracts (Trace_SC) as an automated validation mechanism. The system was evaluated using a synthetic dataset (N=5,000 transaction batches) simulating volatile pollution scenarios. The SCRI-embedded smart contract achieved 89.2% accuracy and 94.5% sensitivity in identifying high-risk batches. Time-to-Trace latency was reduced from 48–72 hours to <3 seconds. Cryptographic stress tests confirmed absolute tamper-resistance against retroactive data modifications.

Keywords: Public Health Informatics, Consortium Blockchain, Hyperledger Fabric, Supply Chain Risk Index, Oracle Problem, Food Safety Governance, Digital Intervention

CITATION INFORMATION: Li, Z., Soontornchai, S., & Fakkham, S. (2025). From “Traceability” to “Intervention”: A Blockchain-Enabled Dynamic Risk Governance Framework for Public Health and Food Safety. *Procedia of Multidisciplinary Research*, 4(3), 39.

INTRODUCTION

The globalization of traditional food supply chains has fundamentally altered global food safety landscapes. The Chaoshan Fish Ball, a prestigious National Geographic Indication product in China, exemplifies this trajectory. Historically manufactured in localized artisanal workshops using near-shore catches, the industry has expanded into a standardized, multi-billion RMB cluster. Raw material sourcing has consequently transitioned to intensive distant-water trawling operations targeting high-trophic-level predatory species such as *Saurida tumbil* (Lizardfish) and *Muraenesox cinereus* (Daggertooth pike conger). While these species possess ideal myofibrillar protein characteristics for premium surimi production, their ecological niches and longevity render them highly susceptible to bioaccumulating heavy metals, notably Cadmium (Cd) and Methylmercury (MeHg), from marine sediments. Unlike fresh produce, fish balls undergo extensive processing mechanical deboning, aqueous leaching, protein emulsification, and thermal dehydration creating a “Black Box” effect that obscures heavy metal migration pathways. Managing chronic dietary exposure to these neurotoxins via heavily processed seafood remains a paramount public health challenge.

To address consumer anxiety and combat deceptive “Green Washing,” the food industry has invested heavily in traceability systems. Initial paper-based ledgers proved sluggish, easily manipulated, and inadequate for rapid epidemiological response during food safety incidents. Blockchain technology characterized by decentralized consensus, cryptographic security, and immutable ledgers was heralded as revolutionary for supply chain transparency. However, current implementations suffer from the “Oracle Problem.” Blockchain consensus mechanisms verify data integrity once recorded but possess no mechanism to verify the truthfulness of external data at initial entry. If upstream actors input falsified data, the blockchain simply records this falsehood immutably. Consequently, existing systems function merely as passive location-based trackers, failing to provide risk-based quality assurance.

Effective public health protection requires transitioning from reactive “post-market recalls” to proactive “pre-market intervention” intercepting contaminated materials before manufacturing. This demands integrating Environmental Science, Toxicological Modeling, and Information Technology. By embedding dynamic risk assessment models directly into blockchain consensus layers transforming smart contracts into “Digital Gatekeepers” we can computationally validate raw material safety before ledger authorization.

Research Objectives

This study aims to:

- (1) design a permissioned consortium blockchain architecture utilizing Hyperledger Fabric v2.4, tailored for GI food supply chain privacy and throughput requirements;
- (2) operationalize a novel Supply Chain Risk Index (SCRI) embedded in smart contracts (Trace_SC), creating an automated mechanism for identifying and quarantining high-risk batches;
- (3) evaluate prototype efficacy using a synthetic dataset (N=5,000 batches); and
- (4) develop a consumer-facing “Smart Dietary Advisory” module converting ledger data into personalized Target Hazard Quotients for vulnerable demographics.

LITERATURE REVIEWS

Heavy metal accumulation in the marine environment constitutes a global ecological crisis with severe human health implications. Cadmium, a byproduct of industrial manufacturing and agricultural runoff, is widely distributed in coastal estuaries. Chronic Cd exposure leads to nephrotoxicity, renal tubular dysfunction, and bone demineralization; the International Agency for Research on Cancer classifies it as a Group 1 carcinogen (Järup & Åkesson, 2009).

Methylmercury (MeHg), biomethylated by anaerobic benthic bacteria, poses an insidious threat. Highly lipophilic, MeHg binds aggressively to sulfhydryl groups in myofibrillar proteins and biomagnifies up the trophic ladder. As a potent neurotoxin traversing blood-brain and placental barriers, MeHg induces neurological degeneration in adults and catastrophic neurodevelopmental delays in fetuses and children (Clarkson & Magos, 2006).

Food traceability has evolved significantly following high-profile scandals (BSE in Europe, melamine-tainted milk in China). First-generation systems relied on paper-based auditing and fragmented databases, suffering from data silos and vulnerability to tampering. Second-generation systems integrated RFID and centralized cloud computing, improving retrieval speeds but leaving fundamental trust issues unresolved. Third-generation traceability relies on blockchain decentralized distributed ledgers maintained by peer-to-peer networks. However, academic literature increasingly highlights the “Oracle Problem”: physical food products exist outside the ledger, and bridging physical and digital realms through IoT or human intervention introduces vulnerabilities that existing systems fail to address (Kamilaris et al., 2019; Caldarelli, 2020; Aung & Chang, 2014).

Within Public Health Informatics, risk assessment models such as the Hazard Index and Target Hazard Quotient (THQ) are validated tools for calculating chronic exposure risks. However, these models are applied retrospectively, used in academic publications months after population exposure. There is a notable absence of frameworks integrating predictive toxicological models into real-time industrial infrastructure (Yi et al., 2011; Marvin et al., 2017). Utilizing blockchain as a decentralized execution environment for public health algorithms represents this research’s primary contribution.

RESEARCH METHODOLOGY

The “Data-Model-Trust” Closed Loop

The architecture’s fundamental premise is the “Data-Model-Trust” closed loop: (1) Data break down silos by fusing governmental environmental monitoring data (G-side) with corporate production logs (B-side); (2) Model replace easily forged self-reported certificates with computationally reconstructed safety profiles using validated kinetic models and processing factor derivations; and (3) Trust utilize blockchain consensus to enforce mandatory risk model execution on every production batch.

Given commercial sensitivities in corporate supply chains, public permissionless blockchains are unsuitable due to absolute transparency and throughput limitations. A permissioned consortium blockchain utilizing Hyperledger Fabric v2.4 was engineered with the following topology: (i) Membership Service Provider a centralized Certificate Authority issuing X.509 digital certificates, authenticating participant identities and defining access control lists; (ii) Orderer Nodes exclusively hosted by governmental Market Supervision Administration, utilizing Raft consensus protocol to sequence validated transactions and cryptographically seal blocks; and (iii) Peer Nodes hosted by manufacturing enterprises and third-party laboratories, maintaining local ledger copies (LevelDB) and state databases (CouchDB) (Androulaki et al., 2018; Saberi et al., 2019; Dinh et al., 2017).

The Supply Chain Risk Index (SCRI)

To translate toxicological equations into machine-readable governance logic, the Supply Chain Risk Index was operationalized as a composite, dimensionless metric ranging from 0 (Absolute Safety) to 1 (Extreme Danger), developed via the Analytic Hierarchy Process (Saaty, 1990):

$$\text{SCRI} = \Sigma(w_i \times S_i)$$

Source Risk (S_1 , Weight = 0.45): Derived from First-order Bioaccumulation Kinetic Model using sediment heavy metal concentration at catch GPS coordinates. Process Risk (S_2 , Weight

= 0.25): Dynamically adjusted using the Processing Factor (PF) model; severe thermal dehydration without adequate leaching triggers “Concentration Effect” penalties. Logistics Risk (S_3 , Weight = 0.20): Integrated via IoT temperature sensors monitoring cold-chain integrity. Compliance History (S_4 , Weight = 0.10): Reputational metric derived from blockchain historical state data.

Smart Contract Logic: Trace_SC

The Trace_SC smart contract (Golang) enforces a deterministic Endorsement Policy: (1) Transaction Proposal Factory Admin submits batch metadata (catch coordinates, processing parameters). (2) Oracle Query the smart contract executes an API call to the trusted Oracle (Ministry of Ecology database) retrieving environmental sediment data. (3) Algorithmic Execution the contract executes Kinetic and PF models to compute the final SCRI score. (4) Decision Gate if $SCRI > 0.6$: transaction rejected, batch flagged “QUARANTINE,” regulatory alert dispatched; if $SCRI \leq 0.6$: transaction endorsed, cryptographic traceability token generated, verified state appended to ledger (Christidis & Devetsikiotis, 2016).

Experimental Setup

A localized Hyperledger Fabric testnet was deployed using Docker containers on Ubuntu 20.04 LTS. A Python-based synthetic data generator produced $N=5,000$ continuous transaction batches simulating five years of operations. Input parameters were calibrated against peer-reviewed literature regarding South China Sea biogeochemical cycles, including extreme edge cases: fraudulent coordinates, polluted monsoon seasons, and varying dehydration parameters. Back-testing compared automated SCRI predictions against theoretical “true” toxicity status.

Sensitivity Analysis under Low-Fidelity Data Conditions

To address the limitations of synthetic data, a sensitivity analysis was conducted simulating three degraded-data scenarios: (a) randomly missing IoT temperature readings at 10%, 20%, and 30% rates; (b) delayed environmental sensor updates of 12–48 hours; and (c) complete absence of sediment contamination data for a given batch. The results demonstrate that the SCRI algorithm defaults to a conservative elevated-risk classification when critical inputs are absent, thereby prioritizing public health protection over operational throughput. A temporal confidence weighting parameter (τ) was incorporated into the bioaccumulation kinetic model, discounting the kinetic estimate’s precision in proportion to the age of the most recent government sediment measurement, acknowledging that G-side monitoring data is typically collected on a quarterly basis.

RESEARCH RESULTS

Classification Performance

Back-testing demonstrated that the SCRI-embedded smart contract achieved 89.2% overall classification accuracy and 94.5% sensitivity successfully quarantining 94.5% of contaminated batches before ledger validation. Compared to traditional randomized spot checks (capturing fewer than 5% of supply chain defects), the SCRI-embedded blockchain increased hazard detection efficiency 18-fold.

Operational Efficiency

Simulating an acute food safety incident, Time-to-Trace (TTT) was measured: legacy systems required 48–72 hours using fragmented paper logs and isolated spreadsheets; the blockchain prototype achieved TTT of <3 seconds via cryptographic query against CouchDB, retrieving complete provenance from catch coordinates to processing temperatures.

Tamper-Resistance Verification

A malicious attack scenario simulated a corrupt administrator attempting to retroactively modify catch location data. The Hyperledger Fabric consensus mechanism instantly rejected the modification cryptographic hash mismatches between altered and subsequent blocks caused peer nodes to refuse validation, providing mathematical proof of post-commitment immutability.

DISCUSSION & CONCLUSION

Public Health Policy Implications

Current food labeling paradigms are binary and static (expiration dates, Pass/Fail marks), inadequate for addressing chronic cumulative bioaccumulation risks. The proposed consumer-facing interface deploys a “Smart Dietary Advisory” module that pulls batch-specific heavy metal concentrations and dynamically calculates Target Hazard Quotients, providing personalized interventions: Standard Adults “Safe for standard consumption”; Vulnerable Demographics “To prevent neurodevelopmental risks, limit consumption to 150g per week.” This shifts regulatory paradigms from corporate-centric (“Is it legally compliant?”) to patient-centric (“Is it biologically healthy for me?”).

Regarding behavioral barriers to QR code adoption: digital literacy constraints, particularly among elderly consumers and lower-income demographics in rural coastal areas, may limit engagement. Trust and privacy concerns regarding data tracking, as well as cognitive load from information-dense advisory outputs, present additional challenges. Future implementation should incorporate UX design principles and complementary SMS-based advisory channels to ensure equitable reach across demographic groups.

Economic Incentive Architecture

To incentivize corporate adoption, governmental institutions school districts, university cafeterias, and state hospital should mandate that only blockchain-verified products (SCRI < 0.4) are eligible for government catering tenders. This generates market demand for transparency, incentivizing enterprises to abandon polluted fishing grounds and adopt safer sourcing practices, aligning commercial profitability with public health goals.

The immutable “Compliance History” stored on the ledger serves as a verified enterprise risk profile. Financial institutions and insurers may be granted restricted read-only access, rewarding enterprises with consistently low SCRI scores through reduced Product Liability Insurance premiums and preferential supply chain financing rates, creating self-sustaining incentive cycles for public health compliance.

Cross-Regional Orderer Node Architecture

For producers sourcing from multiple provinces, the system employs a cross-channel anchoring protocol: each provincial governmental Orderer Node issues a cryptographically signed “Provenance Certificate” for its batches. These certificates are aggregated and verified by a designated National Coordination Node before a composite SCRI score is computed for the final product. This architecture ensures that no single regional node can unilaterally alter or suppress provenance data from another jurisdiction, preserving data integrity across provincial boundaries and enabling the framework to scale from a localized prototype to a national governance infrastructure (Androulaki et al., 2018; Dinh et al., 2017).

Future Outlook

This study addresses critical gaps in heavy metal contamination governance within globalized GI food supply chains by fusing environmental toxicokinetic modeling with cryptographic ledger technology. Three key conclusions are drawn: (1) Overcoming the Oracle Problem SCRI implementation as a mandatory consensus rule mathematically guarantees that only chemically safe materials enter the immutable ledger, achieving 89.2% hazard identification accuracy; (2) Automated Pre-Market Intervention the prototype computationally proves feasibility of shifting from reactive post-market punishment to instantaneous pre-market intervention, with trace latency <3 seconds; and (3) Personalized Health Communication THQ integration transforms traceability into a personalized public health intervention instrument protecting vulnerable populations.

Future iterations must incorporate emerging threats: microplastics acting as heavy metal vectors require expanded models with “Vector Factor” components simulating synergistic toxicity (Brennecke et al., 2016). Integration of AI specifically LSTM neural networks analyzing real-time satellite remote sensing data (Sea Surface Temperature, Chlorophyll-a) will enable autonomous environmental toxicity prediction, eliminating reliance on delayed laboratory reports.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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