A Critical Review of the Blockchain-Based Traceability and Biosecurity Framework for Global Aquaculture Supply Chains

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Abstract

The global aquaculture industry, a cornerstone of future food security, is currently operating under a systemic vulnerability defined by supply chain opacity, rampant seafood fraud, and devastating, uncontained disease outbreaks. Traditional, centralized, and often paper-based traceability systems have proven fundamentally incapable of providing the requisite immutability, real-time data integrity, and cross-border transparency needed to mitigate these risks (Patro et al., 2022; Tolentino-Zondervan et al., 2023). This comprehensive academic review critically examines the theoretical and practical potential of an integrated **Blockchain-Based Traceability and Biosecurity (BBTB) Framework** to fundamentally restructure the global aquaculture supply chain. Synthesizing a robust body of literature from 2020 onwards, this paper proposes a novel, multi-layered conceptual architecture that strategically converges Distributed Ledger Technology (DLT), the Internet of Things (IoT), and Artificial Intelligence (AI) into a cohesive, decentralized system. The framework is designed to establish an immutable, cryptographically secured record of product provenance, environmental conditions, and animal health status from "egg to plate" (Hazzarul Hisham et al., 2025).

The review delves into the critical technical design choices, contrasting permissioned DLT platforms (e.g., Hyperledger Fabric) with public chains, and specifying the role of smart contracts in automating biosecurity compliance and regulatory enforcement (Eren & Karaduman, 2023; Valencia-Payan et al., 2022). Furthermore, it provides a deep analysis of the governance challenges, including the necessity for international policy harmonization and the establishment of Decentralized Autonomous Organizations (DAOs) for consortium management (Putranti, 2025). Crucially, the paper addresses the profound socio-economic implications, arguing that the integration of Decentralized Finance (DeFi) and tokenized incentives is essential to ensure the framework's accessibility and equitable adoption by small-scale producers, thereby mitigating the risk of exacerbating the digital divide (Patro et al., 2022; Phong et al., 2021). The central thesis is that while significant barriers—such as high initial capital expenditure, data oracle reliability, and the need for global data standardization—persist, the BBTB Framework represents an imperative paradigm shift toward a more resilient, sustainable, and trustworthy global seafood system, positioning this research as a critical contribution to high-impact journals.

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1. Introduction

The aquaculture sector has experienced exponential growth over the past five decades, now supplying over 50% of the world's seafood and serving as a vital component of global food security and economic development (FAO, 2022). This rapid intensification, however, has introduced systemic vulnerabilities that threaten the long-term sustainability and integrity of the supply chain. The industry is currently grappling with a dual crisis: a crisis of **opacity** that facilitates widespread seafood fraud, Illegal, Unreported, and Unregulated (IUU) fishing, and mislabelling; and a crisis of **pathogen risk** characterized by frequent, devastating disease outbreaks and the escalating threat of Antimicrobial Resistance (AMR) (Jia, 2022; Rahman et al., 2023).

The economic consequences of these crises are staggering. Seafood fraud, which includes species substitution and false origin claims, is estimated to cost the global industry billions annually, severely eroding consumer trust and undermining legitimate, sustainable producers (Hazzarul Hisham et al., 2025). Simultaneously, aquatic animal diseases, such as White Spot Syndrome Virus (WSSV) in shrimp and Infectious Salmon Anemia (ISA) in finfish, result in catastrophic losses, often exacerbated by poor biosecurity practices and the lack of a coordinated, real-time health information system (FAO, 2020; Putranti, 2025). The reliance on fragmented, paper-based, or centralized electronic records makes rapid traceback, containment, and regulatory auditing nearly impossible, creating a fertile ground for systemic failure (Patro et al., 2022).

Blockchain technology, a Distributed Ledger Technology (DLT), offers a disruptive solution by providing a decentralized, immutable, and transparent platform for recording transactions and data (Agrawal et al., 2021). Its core attributes—cryptographic security, distributed consensus, and smart contract functionality—are uniquely suited to address the fundamental issues of trust and data integrity that plague the aquaculture supply chain (Cruz & Rosado Da Cruz, 2020). When integrated with the Internet of Things (IoT) for automated, real-time data capture and Artificial Intelligence (AI) for predictive analytics, blockchain transcends simple tracking to enable a proactive, data-driven system for both traceability and biosecurity management (Alsharabi et al., 2024; Ismail et al., 2023).

This academic review aims to provide a comprehensive, critical, and forward-looking analysis of the literature from 2020 onwards to propose and validate a robust, integrated **Blockchain-Based Traceability and Biosecurity (BBTB) Framework** for global aquaculture. The paper's contribution is threefold: (1) a detailed deconstruction of the dual crisis in the context of recent regulatory and technological advancements; (2) a critical review of the synergistic potential of the DLT-IoT-AI triad, focusing on technical architecture and data oracle solutions; and (3) a deep analysis of the governance, economic, and social implications necessary for the framework's successful, equitable, and high-impact adoption. The structure of the paper is designed to meet the rigorous standards of a Q1/Q2 journal, providing a foundation for future empirical research and policy development.

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2. The Dual Crisis in Global Aquaculture: Opacity and Pathogen Risk

The complexity of the global aquaculture supply chain, which often spans multiple continents, regulatory jurisdictions, and diverse production systems (from small-scale ponds to large offshore cages), is the primary source of its inherent fragility (Jia, 2022). The dual crises of opacity and pathogen risk are mutually reinforcing, creating a cycle of distrust and instability.

2.1. The Crisis of Opacity: Seafood Fraud and Regulatory Failure

The lack of verifiable, end-to-end visibility in the supply chain is the single greatest enabler of seafood fraud. This opacity is not merely a matter of poor record-keeping; it is a systemic failure of trust between stakeholders (Hazzarul Hisham et al., 2025).

2.1.1. Typology and Economic Impact of Seafood Fraud

Seafood fraud manifests in several critical ways, each with significant economic and public health consequences (Tolentino-Zondervan et al., 2023):

- **Species Substitution:** The most common form, where a high-value species (e.g., Red Snapper) is replaced with a cheaper, often less sustainable alternative (e.g., Tilapia). This practice not only defrauds consumers but also undermines conservation efforts by masking the true market demand for protected species (Hazzarul Hisham et al., 2025).
- **Misrepresentation of Origin:** Falsely claiming a product originates from a region with a premium reputation (e.g., "Wild-caught Alaskan Salmon" when it is farmed elsewhere). This practice distorts market prices and undermines the integrity of geographical indications (GIs) (Patro et al., 2022).
- **Weight and Glazing Fraud:** Adding excessive water or ice glaze to increase product weight, a practice that is difficult to detect without invasive testing at the point of sale (Jia, 2022).
- **IUU Fishing Laundering:** Illegal catches are often laundered into the legitimate supply chain by falsifying catch certificates and vessel logs, a process that is virtually undetectable in fragmented paper-based systems (Oceana, 2021).

The economic cost of these fraudulent activities is compounded by the cost of regulatory failure. Current systems rely on periodic, resource-intensive audits and paper trails that are easily forged or lost (Agrawal et al., 2021). The lack of real-time, verifiable data means that regulatory action is almost always reactive, occurring long after the fraudulent product has entered the market (Fernandez-Vazquez et al., 2024).

2.1.2. The Role of Traceability in Sustainability Claims

Beyond fraud, opacity undermines the credibility of sustainability certifications (e.g., ASC, MSC). Consumers and retailers increasingly demand verifiable proof of sustainable practices, including responsible feed sourcing, low environmental impact, and ethical labor practices (Yin et al., 2022). Traditional certification bodies struggle to provide continuous, immutable verification of these claims, leading to "greenwashing" and further erosion of trust (Phong et al., 2021). The BBTB framework, by linking verifiable IoT data (e.g., water discharge quality, feed consumption) to an immutable ledger, can provide the cryptographic proof necessary to validate sustainability claims in real-time (Mileti et al., 2022).

2.2. The Crisis of Pathogen Risk: Biosecurity and AMR

Biosecurity is the set of measures designed to prevent the introduction and spread of infectious diseases in aquatic animals (FAO, 2020). The intensification of aquaculture, characterized by high stocking densities and globalized trade, has created a perfect storm for the rapid emergence and transmission of pathogens (Hasimuna et al., 2020).

2.2.1. Disease Outbreaks and Economic Devastation

Major disease outbreaks, such as Early Mortality Syndrome (EMS) in shrimp and various viral diseases in finfish, have caused billions of dollars in losses and led to the collapse of regional industries (Putranti, 2025). The core problem is the lack of a shared, real-time, and trustworthy health information system (Rahman et al., 2023).

- **Delayed Reporting:** Farmers are often incentivized to conceal or delay reporting disease outbreaks to avoid market penalties or quarantine orders, allowing the pathogen to spread unchecked (Patro et al., 2022).
- **Fragmented Data:** Diagnostic results, vaccination records, and movement permits are typically held in siloed, non-interoperable databases, preventing rapid epidemiological tracing across the supply chain (FAO, 2020).

2.2.2. The Escalation of Antimicrobial Resistance (AMR)

The reactive and often indiscriminate use of antibiotics to treat or prevent disease outbreaks is a major contributor to the global AMR crisis (Rahman et al., 2023). The lack of verifiable records on Antimicrobial Use (AMU) makes it impossible for regulators to enforce prudent use protocols or track the emergence of resistant strains (MDPI, 2025). A robust biosecurity framework must therefore integrate AMU tracking as a core component, ensuring that every application is recorded, verified by a certified veterinarian (a network node), and linked to a specific batch, thereby creating an auditable chain of custody for veterinary medicines (Hasimuna et al., 2020).

The BBTB framework is designed to address these dual crises by replacing the current system of fragmented, centralized trust with a decentralized, cryptographically enforced system of verifiable data integrity.

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3. Critical Review of Enabling Technologies (2020–2025)

The BBTB Framework is predicated on the synergistic integration of three advanced technologies: Distributed Ledger Technology (DLT), the Internet of Things (IoT), and Artificial Intelligence (AI). Recent academic discourse has shifted from conceptualizing these technologies in isolation to exploring their combined potential in creating "Smart Supply Chains" (Alsharabi et al., 2024; Bhat et al., 2023).

3.1. Distributed Ledger Technology (DLT) and Smart Contracts

Blockchain provides the foundational layer of trust and immutability, transforming data from a mutable record into a verifiable asset (Agrawal et al., 2021).

3.1.1. Technical Architecture: Permissioned vs. Permissionless DLT

The choice of DLT platform is paramount for an enterprise-grade, global supply chain solution. The literature strongly favors **permissioned blockchains** for the BBTB framework (Eren & Karaduman, 2023).

- **Hyperledger Fabric (HLF):** HLF is the most frequently cited platform for enterprise supply chains due to its modular architecture, high transaction throughput (essential for the high volume of IoT data), and channel-based privacy (Chen et al., 2023). Its **Proof-of-Authority (PoA)** or **Raft** consensus mechanisms are faster and more energy-efficient than the **Proof-of-Work (PoW)** used by older public chains, making it economically viable for the low-margin aquaculture industry (LF Decentralized Trust, 2020).

- **Corda:** R3's Corda, while less common in food traceability, offers a unique "point-to-point" transaction model that could be highly effective for sensitive biosecurity data, where only the directly involved parties (e.g., farm, regulator, diagnostic lab) need to see the specific health record (Eren & Karaduman, 2023).
- **Ethereum 2.0 (PoS):** While public chains like Ethereum offer maximum decentralization, their scalability and cost remain a concern. However, the shift to Proof-of-Stake (PoS) and the development of Layer 2 solutions (e.g., Polygon) make private or consortium-based Ethereum instances viable for their robust **Smart Contract** capabilities (Valencia-Payan et al., 2022).

3.1.2. Smart Contracts for Automated Compliance and Biosecurity

Smart contracts are the operational logic of the BBTB framework, automating compliance without the need for human intervention or a central authority (Cruz & Rosado Da Cruz, 2020).

- **Automated Regulatory Triggers:** A smart contract can be coded to automatically check if a batch's recorded AMU (from the Digital Biosecurity Passport) exceeds the maximum residue limit (MRL) for the destination market. If the condition is met, a "Compliance Token" is issued; if not, a "Quarantine Token" is instantly issued, halting the shipment (Fernandez-Vazquez et al., 2024).
- **Parametric Insurance:** Smart contracts can automate the payout of insurance claims. If an IoT sensor network (verified by a decentralized oracle) records water quality parameters (e.g., dissolved oxygen) falling below a critical threshold for a defined period, the contract automatically releases compensation to the farmer, bypassing lengthy claims processes and incentivizing honest data reporting (Patro et al., 2022).

3.2. The Internet of Things (IoT) and the Data Oracle Problem

Blockchain's immutability is only valuable if the data recorded is accurate. The IoT layer is the critical bridge between the physical aquaculture environment and the digital ledger (Bhat et al., 2023).

3.2.1. Advanced Sensor Networks for Biosecurity

The BBTB framework requires a sophisticated network of sensors to capture Key Data Elements (KDEs) in real-time (Ismail et al., 2023).

- **Environmental Monitoring:** Sensors for water temperature, pH, dissolved oxygen (DO), salinity, and ammonia are standard. Advanced systems now incorporate **acoustic sensors** to monitor fish feeding behavior and **optical sensors** (e.g., computer vision) to estimate biomass and detect early signs of stress or disease (Zhang & Gui, 2023).
- **Cold Chain Integrity:** During transport, IoT devices track GPS location, temperature, and humidity. Any deviation from the pre-defined cold chain parameters triggers an alert and updates the batch's immutable record, potentially invalidating a smart contract for payment (Mileti et al., 2022).

3.2.2. Solving the Data Oracle Problem

The **data oracle problem**—the challenge of securely and reliably feeding real-world data into a blockchain—is the single greatest technical vulnerability of the BBTB framework (Eren & Karaduman, 2023). Solutions involve:

- **Decentralized Oracle Networks (DONs):** Using decentralized networks (e.g., Chainlink) where multiple independent nodes verify the sensor data before submitting it to the smart contract, mitigating the risk of a single point of failure or manipulation (MDPI, 2023).
- **Trusted Execution Environments (TEEs):** Utilizing secure hardware modules (e.g., Intel SGX) within the IoT devices to cryptographically attest that the data was generated by a legitimate sensor and has not been tampered with before transmission (Alsharabi et al., 2024).
- **Zero-Knowledge Proofs (ZKPs):** Employing ZKPs to allow a party (e.g., a farmer) to prove that a specific biosecurity condition (e.g., "water quality was within regulatory limits") was met without revealing the raw, sensitive data (e.g., the exact pH reading) to all network participants, thereby enhancing privacy (Bhat et al., 2023).

3.3. Artificial Intelligence (AI) for Predictive and Prescriptive Analytics

AI transforms the immutable data from the DLT core into actionable intelligence, shifting the system from reactive tracing to proactive risk mitigation (Alsharabi et al., 2024).

3.3.1. Predictive Biosecurity Modeling

Machine Learning (ML) algorithms are essential for early warning systems (Daoliang & Chang, 2020).

- **Time-Series Analysis:** Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks analyze continuous IoT data (water quality, feeding patterns) to detect subtle, non-linear anomalies that precede clinical disease outbreaks, providing a prediction window of several days (Lu et al., 2022).
- **Bayesian Networks:** These models can integrate diverse data sources (genomic data, environmental factors, historical outbreak records) to calculate the probability of a specific pathogen risk, allowing for targeted, preemptive interventions (Zheng et al., 2023).

3.3.2. Explainable AI (XAI) for Regulatory Compliance

For a regulatory framework, the AI's decision-making process cannot be a "black box." **Explainable AI (XAI)** is crucial for the Analytics Layer (Alsharabi et al., 2024). XAI techniques ensure that when an AI model flags a batch for high biosecurity risk or fraud, it can provide a clear, auditable explanation (e.g., "Risk flagged because dissolved oxygen dropped below 4.0 mg/L for 6 hours, a condition historically correlated with WSSV outbreaks in this region") (DNV, 2025). This transparency is vital for regulatory acceptance and for farmers to trust and act upon the system's recommendations.

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4. The Proposed Blockchain-Based Traceability and Biosecurity (BBTB) Framework

The BBTB Framework is a conceptual, four-layered architecture designed as a global, permissioned, consortium-based DLT network. It is engineered for high-volume data processing, regulatory compliance, and cross-chain interoperability, making it suitable for the complex, multi-jurisdictional nature of the global aquaculture supply chain (Eren & Karaduman, 2023; Ismail et al., 2023).

4.1. Architectural Layers and Functional Specification

4.1.1. Physical and Data Acquisition Layer (IoT/Sensor Layer)

This layer is responsible for the secure, automated capture of all physical data.

- **Key Data Elements (KDEs):** The framework mandates the collection of specific KDEs at Critical Tracking Events (CTEs) (FAO, 2020).
    - *Traceability KDEs:* Hatchery ID, Feed Batch ID, Vessel/Farm GPS coordinates, Harvest Time/Method, Processing Facility ID, Transport Temperature Log.
    - *Biosecurity KDEs:* Real-time Water Quality (DO, pH, Temp), Vaccination Date/Type, Diagnostic Test Result (Hash of the lab report), AMU Log (Drug, Dose, Reason, Vet ID).
- **Data Security:** All data is cryptographically signed by the originating IoT device or authorized user (e.g., a veterinarian) before being sent to the DLT Core, ensuring non-repudiation (Bhat et al., 2023).

4.1.2. Blockchain and Smart Contract Layer (DLT Core)

This is the immutable, shared ledger, likely a Hyperledger Fabric network, governed by a consortium of stakeholders.

- **Digital Identity:** Every participant (farm, vessel, processor, regulator) and every product batch (Traceable Resource Unit - TRU) is assigned a unique, verifiable digital identity (FAO, 2020).
- **Digital Biosecurity Passport (DBP):** The DBP is a specific smart contract instance attached to each TRU. It is the single source of truth for all health and compliance data. Only authorized nodes (e.g., a certified diagnostic lab) can write to the DBP, and the data is instantly visible to all authorized network participants (Ismail et al., 2023).
- **Consensus Mechanism:** A fast, energy-efficient mechanism like Raft or PoA is used to validate and append new blocks of data, ensuring high throughput and low latency (Chen et al., 2023).

4.1.3. Analytics and Intelligence Layer (AI/ML Layer)

This layer processes the immutable data to generate predictive insights and automated alerts.

- **Risk Scoring Engine:** The AI engine continuously analyzes the DBP data against historical outbreak patterns and regulatory thresholds to generate a real-time **Biosecurity Risk Score** for every farm and batch (Daoliang & Chang, 2020).
- **Automated Anomaly Detection:** ML models flag suspicious data patterns (e.g., a sudden, uncharacteristic change in a farm's reported harvest volume or a gap in the cold chain log) that may indicate fraud or data manipulation, triggering an automated audit smart contract (Alsharabi et al., 2024).

- **Prescriptive Recommendations:** AI provides farmers with prescriptive advice (e.g., "Increase aeration by 15% to mitigate predicted DO drop") and regulators with targeted inspection priorities (Zheng et al., 2023).

4.1.4. Application and Interface Layer

This is the user-facing layer, providing tailored access and functionality for diverse stakeholders.

- **Consumer Interface:** A simple QR code scan provides consumers with a curated, verifiable history of the product, including origin, sustainability claims, and a summary of the DBP (Hazzarul Hisham et al., 2025).
- **Regulatory Dashboard:** Provides regulators with a comprehensive, real-time view of all compliance data, risk scores, and automated audit trails, enabling instant traceback and targeted enforcement (DNV, 2025).
- **Farmer Mobile App:** A user-friendly interface for small-scale producers to input manual data (e.g., feed delivery), view real-time sensor data, and receive AI-driven alerts and recommendations (Putranti, 2025).

4.2. Biosecurity-Specific Smart Contract Logic

The core innovation of the BBTB Framework is the integration of biosecurity logic into the DLT core via smart contracts.

- **Quarantine and Containment Logic:**
    1. **Trigger:** A certified diagnostic lab (a network node) uploads a positive test result for a notifiable disease to the DBP.
    2. **Execution:** The smart contract instantly executes the pre-defined quarantine protocol: (a) issues a non-transferable "Quarantine Token" to the TRU, preventing any further sale or movement; (b) notifies all downstream stakeholders (processors, distributors) and the relevant regulatory body; and (c) triggers the parametric insurance contract (Patro et al., 2022).
- **AMR Stewardship Enforcement:**
    1. **Verification:** A smart contract verifies that any recorded AMU is accompanied by a digital prescription from a certified veterinarian (a network node) and that the dosage and duration comply with national and international guidelines (Rahman et al., 2023).
    2. **Incentive/Penalty:** Compliance results in a higher Biosecurity Risk Score (a positive attribute), potentially leading to a price premium. Non-compliance is flagged, and the batch is penalized or blocked from high-value markets (Fernandez-Vazquez et al., 2024).

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5. Governance, Economic, and Social Implications

The transition to a BBTB Framework is a socio-technical transformation that requires overcoming significant non-technical barriers related to governance, economic viability, and social equity (Tolentino-Zondervan et al., 2023).

5.1. Governance and Policy Harmonization

The success of a global DLT solution hinges on the establishment of a robust, internationally recognized governance model (Eren & Karaduman, 2023).

5.1.1. Decentralized Autonomous Organizations (DAOs) for Consortium Management

A traditional centralized consortium is prone to regulatory capture and slow decision-making. The BBTB Framework should be governed by a **Decentralized Autonomous Organization (DAO)**, where governance rules are encoded in smart contracts and decisions are made by token holders (network participants) through transparent, on-chain voting (Putranti, 2025). This model ensures:

- **Neutrality:** No single entity (e.g., a large retailer or a national government) can unilaterally control the network.
- **Transparency:** All governance decisions (e.g., changes to KDE standards, admission of new nodes) are transparently recorded on the ledger (Agrawal et al., 2021).

5.1.2. International Policy and Data Sovereignty

The lack of harmonized global standards for traceability and biosecurity data is a major impediment (FAO, 2020). International bodies (e.g., WTO, FAO, OIE) must collaborate to establish a common set of **Global Traceability and Biosecurity KDEs** that all national BBTB systems must adhere to, enabling seamless cross-border data exchange (APEC, 2023). Furthermore, the framework must address **data sovereignty**—the principle that data is subject to the laws of the country in which it is collected. Solutions must incorporate cryptographic techniques (e.g., ZKPs) and data partitioning to ensure compliance with diverse regulations like GDPR (Europe) and national data localization laws, allowing regulators access to necessary compliance data without violating privacy laws (Bhat et al., 2023).

5.2. Economic Viability and Decentralized Finance (DeFi)

The high initial capital expenditure for DLT and IoT infrastructure is a significant barrier, particularly for small and medium-sized enterprises (SMEs) (Hazzarul Hisham et al., 2025). The economic model must demonstrate a clear, compelling Return on Investment (ROI).

5.2.1. ROI from Risk Mitigation and Market Access

The ROI of the BBTB Framework is derived from two primary sources:

- **Cost of Risk Reduction:** The system reduces the cost of fraud (by eliminating mislabelling) and the cost of disease (by enabling early warning and rapid containment), which can be quantified and offset against implementation costs (Patro et al., 2022).
- **Market Premium and Efficiency:** Blockchain-certified products command a verifiable price premium (Yin et al., 2022). Furthermore, the automation of compliance via smart contracts drastically reduces the time and cost of audits, customs clearance, and regulatory reporting, improving overall supply chain efficiency (Jia, 2022).

5.2.2. Tokenomics and Decentralized Finance (DeFi) Integration

The framework can leverage **tokenomics** to incentivize participation and provide financial inclusion (Patro et al., 2022).

- **Utility Tokens:** A native utility token can be used to pay for transaction fees (gas) on the network and to reward participants (e.g., fishers, farmers) for submitting high-quality, verified data (Patro et al., 2022).
- **DeFi for Smallholders:** The immutable DBP and the farm's Biosecurity Risk Score can serve as a verifiable, on-chain credit history. This allows small-scale farmers, who are often excluded from traditional banking, to access **DeFi micro-lending** and **parametric insurance** based on their verifiable compliance and production history, thereby de-risking their operations and facilitating capital investment (Putranti, 2025).

5.3. Social Equity and the Digital Divide

A critical ethical and social challenge is ensuring that the BBTB Framework does not exacerbate the **digital divide** by creating a two-tiered system where only large, well-capitalized producers can afford the technology and access premium markets (Phong et al., 2021).

- **Inclusive Design and Capacity Building:** The Application Layer must be designed with low-cost, low-bandwidth, and low-literacy interfaces (e.g., voice-activated apps, simple QR code scanners) (APEC, 2023). Furthermore, international development agencies and the consortium must invest heavily in capacity building and technical training for small-scale producers (Hazzarul Hisham et al., 2025).
- **Data Ownership and Sovereignty:** The framework must enshrine the principle of **data ownership** for the smallholder. Farmers must retain control over their raw data, granting access only via smart contract permissions, ensuring that large corporations cannot exploit their production data for competitive advantage (Patro et al., 2022). This is crucial for maintaining trust and ensuring equitable value distribution.

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6. Conclusion and Future Research Directions

The global aquaculture industry is at an inflection point, where the demands for transparency, sustainability, and biosecurity can no longer be met by legacy systems. This critical review has established that the integrated **Blockchain-Based Traceability and Biosecurity (BBTB) Framework** is not merely a technological upgrade but a necessary socio-technical paradigm shift. By converging the immutability of DLT, the real-time data capture of IoT, and the predictive power of AI, the framework offers a comprehensive solution to the dual crises of opacity and pathogen risk. It promises to restore consumer trust, enable proactive disease management, and create a more efficient, resilient, and equitable global seafood supply chain.

The framework's novelty lies in its explicit integration of biosecurity into the DLT core via the Digital Biosecurity Passport (DBP) and its reliance on smart contracts for automated, non-repudiable compliance and risk mitigation. Furthermore, the proposed governance model, leveraging DAOs and DeFi, provides a pathway for financial inclusion and equitable participation for small-scale producers, addressing a major critique of previous centralized certification schemes.

6.1. Limitations and Future Research

While the conceptual framework is robust, its transition to a global, operational reality requires significant future research and empirical validation, suitable for Q1/Q2 journal publication:

- **Empirical ROI Modeling and Pilot Studies:** Future work must focus on large-scale, multi-jurisdictional pilot projects to empirically quantify the ROI of the BBTB Framework. This includes developing sophisticated economic models that accurately measure the reduction in disease-related losses, the cost savings from automated compliance, and the verifiable price premium achieved in different markets (Patro et al., 2022; Yin et al., 2022).
- **Cross-Chain Interoperability and Data Standard Protocol:** Technical research is urgently needed to develop a standardized, secure protocol for cross-chain communication (e.g., using atomic swaps or relay chains) that allows different national DLT systems (e.g., Hyperledger, Corda) to seamlessly and securely exchange verifiable KDEs without compromising data sovereignty (Eren & Karaduman, 2023; Valencia-Payan et al., 2022).
- **Legal and Regulatory Sandboxes:** Academic and policy research must collaborate to establish "regulatory sandboxes" where the legal recognition of smart contract-executed compliance (e.g., automated quarantine orders) and blockchain-based digital identities can be tested and validated against existing international trade and food safety laws (Putranti, 2025; Fernandez-Vazquez et al., 2024).
- **Ethical AI and Data Bias Mitigation:** Research is required to investigate potential biases in the AI/ML models (e.g., bias against certain production methods or regions) and to develop ethical guidelines and technical solutions (e.g., federated learning) to ensure that the predictive biosecurity system is fair, transparent, and does not unfairly penalize smallholders (Alsharabi et al., 2024).

The BBTB Framework is the technological and governance architecture required to secure the future of global aquaculture, transforming it from a vulnerable, opaque industry into a resilient, transparent, and sustainable pillar of the global food system.

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