Blockchain-enabled supply chain traceability in sustainable aquatic farming

Abdujalil Gapparov[1*]; Muhamed Fallahhusein[2]; Nizomjon Matkarimov[3]; Ruban Baltazar Fernandes[4]; Sanat Chuponov[5]; Dr. Rajesh Sehgal[6]; Dilnoza Tuychiyeva[7]

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Abstract

The paper investigates how blockchain technology might enhance the transparency of supply chains, the trust of consumers, and the sense of responsibility in sustainable aquaculture. There are challenges that traditional aquaculture supply chains face in terms of openness, data integrity, and regulatory compliance. The distributed and irreversible architecture of blockchain, together with the Internet of Things and smart contracts, may allow stakeholders to ensure accurate monitoring of health, environmental, and logistical data. The paper also discusses challenges associated with implementation, vulnerabilities in the legal system, and upcoming advances like incorporating artificial intelligence and compatibility with other chains. Based on the findings, it seems that implementing blockchain technology into global aquaculture systems can significantly enhance the sustainability and resilience of these systems, provided that technical and legal frameworks support them.

Keywords: Blockchain, Aquaculture, Traceability, Sustainability, Smart contracts

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1*- Senior Lecturer, "Interfaculty Foreign Languages", Gulistan State University, Uzbekistan.
Email: abdujalilgapparov@gmail.com, ORCID: https://orcid.org/0000-0003-4047-0587
2- Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University in Najaf, Najaf, Iraq; Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University in Najaf of Al Diwaniyah, Al Diwaniyah, Iraq.
Email: tech.iu.comp.mhussien074@gmail.com, ORCID: https://orcid.org/0009-0002-2213-4619
3- Associate Professor, Department of Ecology and Life Safety, Urgench State University, Uzbekistan.
Email: nizomjonmatkarimov@gmail.com, ORCID: https://orcid.org/0000-0003-0255-2565
4- Department of Marine Engineering, AMET University, Kanathur, Tamil Nadu, India.
Email: rubanfernandes@ametuniv.ac.in, ORCID: https://orcid.org/0009-0005-4122-8284
5- Senior Lecturer, Mamun University, Khiva, Uzbekistan.
Email: chuponov_sanat@mamunedu.uz, ORCID: https://orcid.org/0000-0001-7388-9224
6- Assistant Professor, Department of Management, Kalinga University, Raipur, India.
Email: ku.rajeshsehgal@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0002-0344-403X
7- PhD Student, Karshi State University, Uzbekistan. Email: dilnoza_tuychiyeva@list.ru,
ORCID: https://orcid.org/0009-0002-7712-8769
*Corresponding author
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Overview of Sustainable Aquatic Farming

Integrating marine species such as fish, shellfish, and seaweeds into existing agricultural systems is an example of sustainable aquaculture, also called aquatic farming. With seafood becoming more popular globally, it is no surprise that aquaculture is gaining attention because it uses less natural ocean resources while maintaining food security (Donkor and Zhao, 2023). Sustainable aquaculture aims to maintain the balance of ecosystems by minimizing the negative impact on the environment, animal health, and the overall well-being of living organisms. Despite the advances made using modern technology like morals and care for the environment, there is still a negative perception of aquaculture. Stricter regulations tend to increase as ingenuity steps in to address these issues. Important themes include moderation in the use of antibiotics and stringent control of water and feed (Ahmed & Rossi, 2024).

Significance of Supply Chain Transparency

Aquaculture's sustainability, traceability, and trust from consumers could be lost if accessibility to the supply chain is restricted (Marchesi, Mannaro, and Porcu, 2021). The aquatic food chain can include many participants in various locations, from hatcheries to processing, shipping, and sales. Without proper traceability, the sustainability pledges plus brand image could be sabotaged due to labeling errors, contamination, or void materials being used. Social and ecological practices are better controlled within open supply chains as consumers, businesses, and leaders make educated calls (Li and Huang, 2024).

Role of Blockchain Technology

Blockchain enables a decentralized, secure recording of data and transactions through the entire supply chain, suitable for aquaculture. Blockchain technology can enhance sustainability, prevent fraud, improve accountability and overall trust in data integrity within the framework of sustainable aquatic farming (Escobedo *et al.*, 2024). Using smart contracts and real-time data, aquaculture records each production stage, from water quality and feed ingredients to packing and harvesting (Iftekhar, Cui and Yang, 2020). This may transform supply chain management into something more resilient, dependable, aligned with global sustainability objectives, and enhance the overall traceability within the industry (Reddy and Thomas, 2024).

Literature Review

Traditional Supply Chain Models in Aquaculture

Traditional aquaculture supply chains create complexity in traceability and openness. Usually, depending on human record-keeping and scattered data systems, these methods might impede effective tracking of items from source to customer (Sudarssan, 2024).

Conventional aquaculture supply networks are examined in this paper, emphasizing problems like inadequate data collecting standards and poor stakeholder integration. The authors contend that these difficulties could cause inefficiency and worse product quality (Smith, Tan and Muller, 2021). Southeast Asian aquaculture, this study points out information flow and logistical obstacles (Iyengar and Bhattacharya, 2024). The research underlines the importance of technology solutions to improve supply chain coordination (Hossain *et al.,* 2024). This research contrasts conventional hand record-keeping with newly developed computerized approaches in aquaculture. Results show that data accuracy and traceability are much improved by digital systems (Nguyen and Lee, 2022).

Challenges in Current Traceability Systems

Efficient traceability ensures food safety, quality assurance, and consumer confidence in aquaculture. Nevertheless, several problems that impact their effectiveness occur in current systems (Rahman and Begum, 2024).

This research highlights attempt barriers in aquaculture including gaps in data standards, low participation of various stakeholders, and high implementation costs (Đurić and Djuric, 2024; Paul Thomas and Rajini, 2024). Traceability practices of global fish supply chains have been studied, and it was found that the varying international regulations and the level of technological advancement contribute to the challenges in tracing fish (Garcia and Thompson, 2023). This reveals that most stakeholders in the aquaculture industry perceive ignorance and the absence of adequate training as the primary reasons for the low adaptability of traceability systems (Rao and Chatterjee, 2024; Jaiswal and Pradhan, 2023).

Applications of Blockchain in Agri-Food and Aquaculture

By utilizing blockchain technology, the agri-food and aquaculture supply chains improve the operations of traceability, transparency, and efficiency.

This paper aims to propose a general-purpose blockchain-based agri-food supply chain management system. As explained in (Li, Chen and Wang, 2020), the proposed scheme allows effective traceability among numerous producers using smart contracts and customizable applications. The paper examines the use of IoT devices in blockchain technology to provide a tamper-proof system for tracking food products from the farm to the table. The response improves data security and accessibility without relying on a central authority (Rao and Krishnan, 2024). This article proposes a blockchain-based solution for food supply chains to provide transparency and trust. The framework, while promoting integrity and safety in the farming sectors, addresses problems like information manipulation and the need for a centralized system of control (Fernandez and Kim, 2021). This researcher shows how blockchain technology can address current challenges in the aquaculture supply system. Blockchain can help the industry adopt sustainable practices through increased transparency and openness (Ramachandran, 2023).

Conceptual Framework

Blockchain Architecture for Aquatic Supply Chains

As part of sustainable aquatic farming, a blockchain-based supply chain system is a decentralized ledger securely noting each transaction or occurrence throughout the product's lifecycle from hatchery to purchaser. Typically consisting of numerous basic building blocks peer-to-peer (P2P) nodes (farmers, processors, distributors, merchants), consensus mechanisms, data encryption, and smart contracts—the architecture also encompasses all members of the supply chain to maintain a synchronized copy of the ledger, permitting distributed data verification free of central authority reliance.

Generally, two varieties of blockchains will suit: permissioned (such as Hyperledger Fabric) and public (such as Ethereum). Public blockchains allow for complete openness; permissioned blockchains suit aquaculture supply chains where company secrecy and performance are key because they allow selective data view and more scalability. Hatchery records, feeding plans, water quality reports, harvest logs, processing data, and logistics information are among the items uploaded into the blockchain. Once confirmed, these entries become unchangeable so that customers and stakeholders may instantly check claims on sustainability, health compliance, and product origin.

Stakeholders and Information Flows

Implementing a blockchain effectively depends on mapping the responsibilities of many aquaculture supply chain players. Usually, these people consist of:

- Record inputs, including feed type, medicine use, and water quality measures among producers, fish farms, and hatcheries.
- Processors: Enter information on fish handling, packaging, and safety testing.
- Track cold chain compliance and transportation benchmarks in distribution and logistics.
- Retailers: Use blockchain to guarantee consumers of quality and source assurance.
- Monitoring conformity to food safety and environmental norms helps certify bodies.
- Consumers: Use QR codes or smartphone applications to see the path of a product.

Data is entered at every level and transferred safely through encrypted entries on the blockchain as information moves in a linear but linked fashion. Linked and time-stamped, the data guarantees responsibility and continuity. Furthermore, using oracles middleware linking blockchain with outside data sources allows automated validation of real-world events as temperature variations or shipping delays.

This linked concept promotes openness across the supply chain. Using verified, real-time data, it reduces data silos and fosters teamwork, therefore empowering all participants. By making environmental performance auditable, such openness promotes food safety and sustainability.

Smart Contracts and IoT Integration

Smart contracts are self-executing agreements kept on a blockchain and activated by specific functions. In aquaculture farming, Smart contracts can greatly optimize processes such as:

Payments are made to farmers only when certain quality control conditions, such as chemical-free certification, are met. Alerting those in charge of logistics when the fish are ready for delivery. Notifications are instantly generated when the environmental data suggests the conditions are less than ideal. The automation of mundane tasks afforded by smart contracts increases the level of confidence, reduces the need for administrative expenses, and eliminates third parties because the fundamental principles of unbiased application of rules are always maintained.

Integration with Internet of Things (IoT) devices enhances the system's resilience even further. IoT sensors, for instance, are placed in fish tanks to monitor pH levels, dissolved oxygen, and temperature, sending the data directly to the blockchain. Similarly, RFID tags and GPS sensors on shipping containers can provide location, humidity, and temperature information, ensuring cold chain compliance.

The combination of smart contracts and IoT offers a precise aquaculture IoT smart cyber-physical system. Not only does this enhance the speed at which predictive analytics can be performed, allowing for faster corrective measures to be taken when necessary, but it also makes marine farming more sustainable, efficient, and responsible. Furthermore, these enhancements boost credibility while reducing fraud risk, fulfilling modern requirements wherein food procurement and quality control are scrutinized and necessitated by consumers.

Methodology

To explore the impact and significance of blockchain on the sustainability of aquatic farming and its supply chain traceability, a qualitative, exploratory research approach is employed, adopting a case study strategy. The focus looks at stakeholders invited to system demonstrations to showcase their models instead of relying on statistical generalizations. The experimental framework allows investigating unexplored waters such as integrating smart contracts and IoT into aquaculture. Emphasizing farms or aquaculture firms that have experimented with or implemented blockchain technologies, a single-case or a multiple-case approach might be utilized depending on the data availability.

Data Collection Methods

Industry reports, technical documentation from blockchain service providers, and regulatory frameworks in aquaculture traceability were reviewed. Academic journals and whitepapers from 2020–2025 focusing on blockchain in agri-food were used to support the analytical framework.

Figure 1 illustrates the sequential data flow among key stakeholders in the aquaculture supply chain—from fish farmers to end consumers. At each stage, relevant data (e.g., feeding logs, quality control reports, transport conditions) is uploaded to a shared blockchain ledger. This ledger acts as a secure, immutable repository of supply chain information. Consumers access this verified data through QR codes, enhancing trust and transparency.

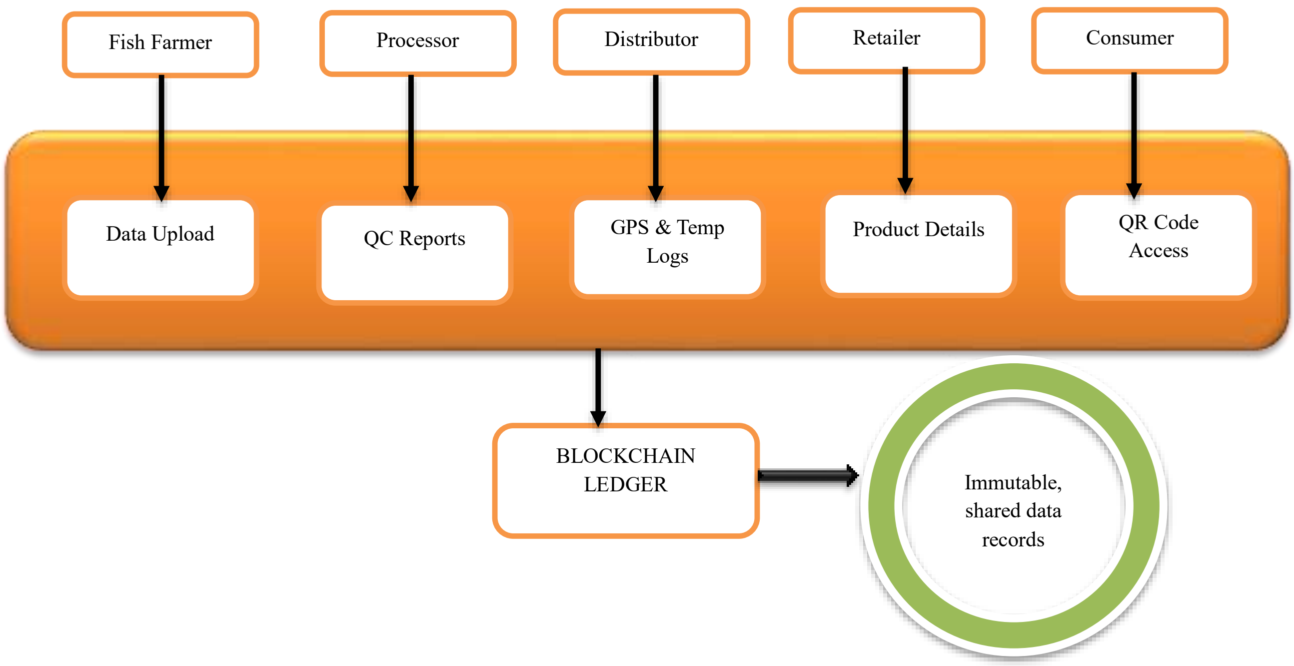

Figure 1: Stakeholder-based data flow in blockchain supply chain.

The diagram highlights how blockchain eliminates data silos by enabling each participant to contribute to and view real-time updates, ensuring accountability and traceability throughout the product's journey.

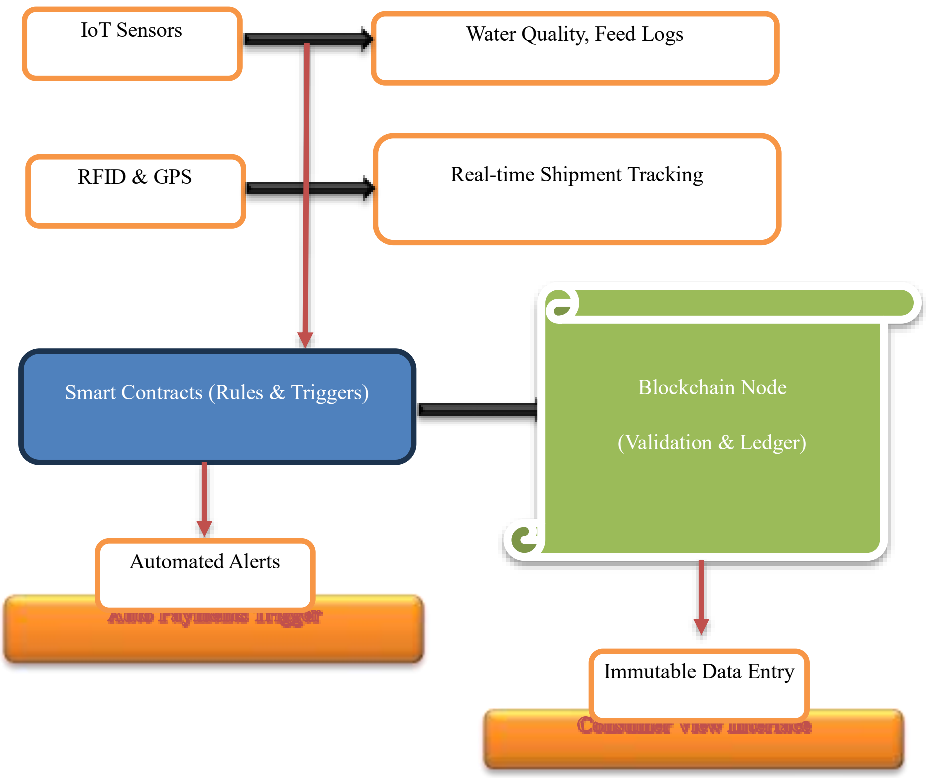

Figure 2: Technology integration with smart contracts and IoT.

Figure 2 shows how smart contracts and IoT sensors combine with blockchain to increase traceability in aquatic farming automatically. IoT devices' real-time environmental and logistical data is stored in smart contracts with predefined rules that perform activities such as payment triggering or alert creation. Blockchain nodes interact with these smart contracts verifying and immutally storing data. Therefore, important processes like compliance verification, cold chain monitoring, and quality control are visible and automated. This approach reduces human mistakes, assures only certified, high-integrity data arrives to consumers and authorities and increases efficiency.

Benefits and Value Creation

Blockchain technology revolutionizes sustainable aquaculture with flawless records, real-time information transfer, and traceability. Better monitoring of supply chains enhances responsibility and reduces fraud and mislabeling, while every element of the supply chain can be meticulously tracked. This traceability makes the accurate assessment of sustainability criteria such as feed efficiency and water quality, carbon footprint, environmental compliance, and reporting possible. Verified transactions and smart contract execution build trust among stakeholders, and blockchain enhances trust among stakeholders. The adoption of IoT and Blockchain increases trust by consumers as they gain confidence in food safety, authenticity, and the sourcing of products. For manufacturers, trust being a brand value, especially those who claim to follow standards set environmentally becomes beneficial.

Challenges and Limitations

While blockchain has great prospective benefits, it comes along with new challenges. Many farms, especially small-scale ones, struggle with implementing digital frameworks due to lacking skills. Legal and regulatory policies still face changes, and there is no clear governance on digital traceability, data ownership, and international interaction between countries. All these factors make the technology costly, leading to the claim that it is detrimental to resources. All these barriers can be overcome with public and policy support, stakeholder cooperation, and investment. This allows blockchain technology to be inclusive and align to global aquatic sustainability policies, enabling the development of scalable solutions.

Future Directions

Going forward, sustainable aquaculture will be defined with blockchain by converged technologies and policy initiatives. The advanced developments include more user-friendly designs for interface for farmers in rural areas and lightweight blockchains tailor-made for low-resource environments. The integration of continentally scoped systems and global traceability will pivotally rely on cross-chain interoperability—where multiple platforms of blockchains interface or communicate with each other. Using blockchain with artificial intelligence would also improve risk mitigation, feed optimization, and predictive analytics about disease outbreaks. Policies must set rules governing the digital tracing of the products along the value chain and promote data governance to protect stakeholder interests while ensuring transparency through tax or subsidy incentives.

Conclusion

This paper aimed to assess the impact of blockchain technology on the traceability of supply chains concerning the sustainability of aquaculture. Greater measures towards sustainability, heightened transparency, and improved trust among stakeholders are some primary advantages. However, the blockchain's lack of crypto-centric business models remains a barrier to general acceptance: the complex technology, high costs, and legal ambiguity. For managers, the implications are clear: blockchain requires strategic ecosystem and partnership investment, perhaps more than other technologies, but delivers a powerful customer engagement and quality assurance advantage. Ultimately, equitably accessible scalable solutions and supportive government frameworks will determine blockchains' boundless adoption toward sustainable aims. Sufficiently managed, blockchain has the potential to support a more open and resilient global aquaculture industry.

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