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Published in:
Seafood 4.0

DOI:
10.1016/B978-0-443-33750-5.00010-X

2025

Document Version:
Publisher's PDF, also known as Version of record

CHAPTER FIVE

Integrating blockchain technology into the seafood sector

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5.1 Introduction

Blockchain technology (BCT) is considered a revolutionizing tool for the challenges faced by the seafood sector, including fisheries, aquaculture, and the seafood industry. BCT has shown promising applications in terms of improving traceability, transparency, sustainability, and preventing frauds. As seafood is one of the most globally traded food products, it is prone to illegal, unreported and unregulated (IUU) fishing, mislabeling, supply chain inefficiencies and sustainability issues. Therefore, authenticity and ethical sourcing is a topmost priority for seafood stakeholders including government, businesses, and consumers (Petracci et al., 2023; Tokkozhina et al., 2023). Such technology allows for an immutable, transparent ledger that creates traceability all the way back to harvest time, thus helping preserve integrity within the seafood supply chain while building consumer confidence. BCT promises tremendous traceability, food safety, and sustainability improvement. This is very significant in features of blockchain to record every transaction within the supply chain, reducing the possibility of any fake product and thereby strengthening the food safety and quality measures. The use of blockchain with Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML) facilitates real-time data analysis. This integration allows the tracing of origin of food as well as every step involved in the production chain until it reaches the final consumer, thus ensuring operational efficiency (Tolentino-Zondervan et al., 2023). Such development is crucial because consumers increasingly demand transparency and clear

Seafood 4.0: Digital, Physical, and Biological Realms from Sea to Table
DOI: https://doi.org/10.1016/B978-0-443-33750-5.00010-X

information about product origins. The term "Seafood 4.0" refers to the digitalization and technology-based industrial shift, with blockchain being one of its foundational technologies. Seafood 4.0 integrates digital, physical, and biological innovations into the way seafood is produced and distributed in a more sustainable, productive, and consumer-friendly fashion. Several studies explored BCT's potential, adoption barriers and its integration with other emerging technologies such as IoT, AI, and ML to improve supply chain efficiency, regulatory compliance, and food safety. Although BCT offers numerous benefits, its adoption levels in seafood supply chain remains low due to technical, regulatory, and infrastructural challenges.

Blockchain technology has changed digital transactions with decentralized record-keeping on public or private ledgers and, thus, eliminates the need for an intermediary third party. The decentralization enhances security because transactions are validated using multiple nodes within the blockchain network. This validation ensures that each transaction recorded within the blockchain network is valid and unchangeable (Astill et al., 2019). Every transaction is written as a series of entries within a "block," and blocks are subsequently connected in an ordered pattern to form a "chain," hence the blockchain architecture (Panarello et al., 2018). The potential applications of blockchain in the food markets are high, and traceability is paramount, hence complemented by assurances of food safety that can help restore consumer confidence (Tsolakis et al., 2021). Data accessibility, accuracy, and accountability challenges are common problems in traditional centralized systems. Blockchain technology offers solutions to numerous problems that plague these systems, such as offering a transparent and immutable ledger for tracking events throughout the supply chain (Tsolakis et al., 2021).

In the seafood sector, blockchain technology has the potential to solve major issues such as IUU fishing and seafood fraud. One of the best examples of blockchain implementation in the food industry is the IBM Food Trust Network. This platform allows stakeholders, including seafood producers and retailers, to track products from the point of catch to the end consumer. It ensures transparency, cuts down fraud and only gives legally and sustainably sourced products to the market. The other one is provenance that employs blockchain technology to provide a full history of its products for consumers who can, therefore, verify if a seafood product is gained through proper sourcing. Mathisen (2018) identified the potential of blockchain technology in the Norwegian supply chain aquaculture, emphasizing its ability to enhance quality, sustainability, as well as efficiency. Due to the decentralized nature that's intrinsic to blockchain traceability is strong and margins held by profit are better as well; thus best suited for high-end fish farms with high control compliance standards regarding quality and safety as well (Mathisen, 2018). Furthermore, consumer advocacy for more transparency, sustainability, and better sourcing practice has created rising demand. The deployment of blockchain technology supports these requirements, enabling the seafood sector to respond appropriately to those concerns.

This chapter delves into the critical role blockchain technology plays in the Seafood 4.0 concept: its ability to transform a supply chain, promote sustainability, and respond to demands from regulatory stakeholders, retailers, and end consumers. First, it will describe essential concepts and features of blockchain and then move to the practice of blockchain across several domains, focusing on the application in the seafood sector. Other than that, technical issues with the implementation of blockchain, problems in adoption, and future trends driving innovation are discussed to give an all-rounded understanding of how blockchain may revolutionize the seafood sector.

5.2 Blockchain: Concepts and fundamentals

BCT is one of the types of the distributed ledger technologies (DLTs), which refers to a form of technology that uses cryptographical techniques to record, decentralize, and distribute information synchronized across the network of entities known as "nodes." While many other DLTs, such as IOTA and Hedera Hashgraph, use a directed acyclic graph (DAG) architecture to organize data, blockchain relies on a linear sequence of blocks for data storage. This difference reveals blockchain technology's distinct data validation and distribution process (Anderberg et al., 2019). All the blockchain technologies are DLTs, but all DLTs are not blockchain. Blockchain has proved to be the most accepted kind of DLTs, which has motivated huge research and applications in various fields. Despite the lack of a widely accepted definition of blockchain technology, many researchers and developers have tried to define the characteristics of blockchain.

5.2.1 Definition of blockchain technology

Table 5.1 summarizes the most cited definitions in the literature of BCT. Wang et al., (2022) have defined BCTs as follows: "Blockchains are decentralized and distributed systems based on cryptographic principles, namely an expanding chain of digital entries, which are mutually authenticated

Table 5.1 Examples of BCT definitions in the literature (Batwa & Norrman, 2021; Wang et al., 2022).

Reference	BCT definitions
Swan (2015)	The integrity of transaction data is preserved using a public ledger system.
Treiblmaier (2018)	A distributed, decentralized, and digital ledger where transactions are recorded and added chronologically to provide tamper-proof, permanent records.
Lacity (2018))	Every participating node receives a shared ledger, which is a peer-to-peer system for validating, time stamping, and permanently recording transactions and agreements.
Cole et al. (2019)	A consensus process and cryptography protect a distributed database system that stores transactional data or other information.
Du et al. (2019)	A series of data blocks, each one made to document a transaction.
Saberi et al. (2019)	A distributed database of records or shared public/private ledgers of all digital events carried out and shared among agents involved in the blockchain is what blockchain technology is.
Anderberg et al. (2019))	Peer-to-peer digital data exchange with few or no third parties or middlemen is made possible by BCT and other DLTs, which allow parties that do not trust one another.
Chod et al., (2020)	Distributed ledgers that are cryptographically safe and can allow for decentralized verification of transactions involving digital products.

through consensus mechanisms propagated across a peer-to-peer network." This definition highlights blockchain's core features: decentralization, cryptographic security, and consensus-driven data validation. BCT falls under DLT category. It utilizes cryptographic techniques to record, decentralize, and distribute data in a synchronized chain of blocks across a network of internet-connected devices called users, participants, or nodes. Unlike BCT, other DLTs, such as IOTA or Hedera Hashgraph, utilize protocols that do not rely on a chain of blocks but on a directed acyclic graph. The distinction between BCT and other DLTs lies in their data distribution, verification, and registration methods (Anderberg et al., 2019).

Therefore, this chapter will primarily focus on BCT and only differentiate other DLTs when necessary. As BCT is a relatively new technology, there is currently no widely accepted definition for it. However, practitioners and researchers have proposed various definitions, reflecting the growing interest in BCT (refer to Table 5.1 for examples of popular BCT definitions in the literature).

Blockchain is also far from the classical client-server architecture in which the central servers act as an intermediary for data exchange. It is designed based on a peer-to-peer decentralized framework, wherein the participants or nodes collectively share and validate the ledger. Advanced cryptography, such as public-private key encryption, hash functions, and digital signatures, ensures the integrity and safety of data within the blockchain. These approaches make sure that the authentication process is strong, illegal access is prevented, and interference or fraud by the system is hard to occur. The type of information, which can be written on a blockchain, varies with the assets and documents that include but are not limited to financial transactions, insurance contracts, property title deeds, health care records, and official documents like birth and marriage certifications (Anderberg et al., 2019). This flexibility makes blockchain a sound and transparent foundation for varied industry applications. Unlike the traditional centralized databases, the blockchain's distributed ledger ensures data access, immutability, and trustworthiness for all nodes in the network, hence reducing the dependency on central intermediaries and the risks that accompany them.

5.2.2 Key features of blockchain networks

Four key characteristics define BCT as mentioned below (see Table 5.2).

1. Decentralization

Blockchain operates in a decentralized peer-to-peer network that removes the need for centralized institutions such as financial institutions or government agencies to regulate transactions. Digital signatures and cryptographic encryption technologies facilitate decentralization, which ensures safe and traceable exchange between the parties involved. The transfer of power in access to information and decision-making processes makes blockchain technology an agent of transparency and democratization in data governance (Narayanan & Clark, 2017; Wang et al., 2022).

1. Transparency and privacy

Blockchain is natively open because all validated transactions are maintained on a distributed and synchronized ledger accessible by all authorized parties. BCT is particularly rich for multi-organizational networks of businesses, such as SCM, where data sharing through stakeholders is crucial. A blockchain enables open access, thus fostering collaboration and trust across

Table 5.2 Features of BCT (Batwa, 2024).

BCT features	Explanation
Decentralized peer-to-peer networks	Communication occurs directly between nodes without intermediaries using distributed ledgers and cryptographic methods, including public-private key encryption, hash encryption, and digital signatures. This enhances security, reduces reliance on central points of failure, and increases resistance against cyber-attacks.
Transparency with privacy	Using cryptographic keys, BCT allows users to operate under pseudonyms. Hence, BCT can provide a secure environment where transactions are verifiable, maintaining a balance between privacy and transparency.
Immutability of transactions	Inability to alter, delete, or reverse recorded transactions once they are confirmed and added to the ledger. This ensures data integrity, security, and trust within the network.
Smart contracts	Self-executing contracts allow for the automatic execution of transactions based on predefined rules and conditions. They enable complex applications and agreements to operate autonomously without human interference.

Adopted from Pattison (2017), Yli-Huumo et al. (2016), Iansiti and Lakhani (2017)AU: For the citations "Yli-Huumo et al. (2016)" and "Iansiti and Lakhani (2017)", please provide publication details to be included in the references list., Cole et al., (2019, Hald and Kinara (2019)), and Wang et al., (2022).

industries through permission access to verified data (Hald & Kinra, 2019; Pattison, 2017).

1. Scope

The immutability inherent in blockchain technology ensures that any transaction is recorded and verified and cannot be altered or deleted. That nature of asset security of origin provides for the entire history of an asset-from creation to ownership-through the different changes that may have been applied to the assets in their lifespans. Proof of work (PoW) is a blockchain consensus mechanism where miners utilize computational power to solve complex puzzles, validate transactions, and secure the network. It is energy-intensive but highly secure. Proof of stake (PoS), on the other hand, selects validators to create new blocks based on the amount of cryptocurrency they stake as collateral. It is more energy-efficient and scalable than PoW and ensures transaction immutability through various network mechanisms. Each mechanism has different implications regarding scalability,

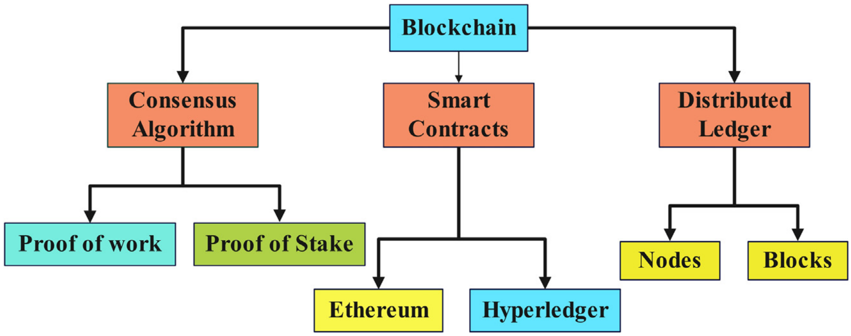


Figure 5.1 Blockchain technology architecture. *(Blockchain technology architecture (author contribution)).*

energy efficiency, and transaction speed, and it is possible to adapt blockchain solutions to various applications (Cole et al., 2019; Wang et al., 2022).

1. Smart contracts

Smart contracts are optional but integral to blockchain technology. They refer to self-executing contracts with predetermined rules and specific conditions that will automatically evoke certain actions, such as payments or approvals. Smart contracts can also certify non-financial transactions through proof of ownership or fulfillment of the regulatory requirements of a place, not only through financial transactions. Smart contracts provide process automation and build trust, making blockchain more effective and reliable (Pilkington, 2016). Fig. 5.1 provides a conceptual overview of blockchain technology by categorizing its key components into three main areas: consensus algorithm, smart contracts, and distributed ledger. Fig. 5.1 shows the features of blockchain technology with their explanations.

Fig. 5.1 represents the Blockchain technology architecture.

5.2.3 The blockchain process

In the process of funds transfer, agreement building, or simply data interchange between two nodes identified as Node A and Node B in a blockchain network, the transaction details are first communicated to a distributed network of computers called "nodes." The nodes, through this architecture, form a decentralized peer-to-peer system; hence it negates control by a single centralized authority. These nodes, therefore, depend on such known "consensus mechanisms" as PoW and PoS to ensure there is a group consensus of a transaction's validity and all nodes agree about the rules under which the network operates. Once a transaction is validated, it

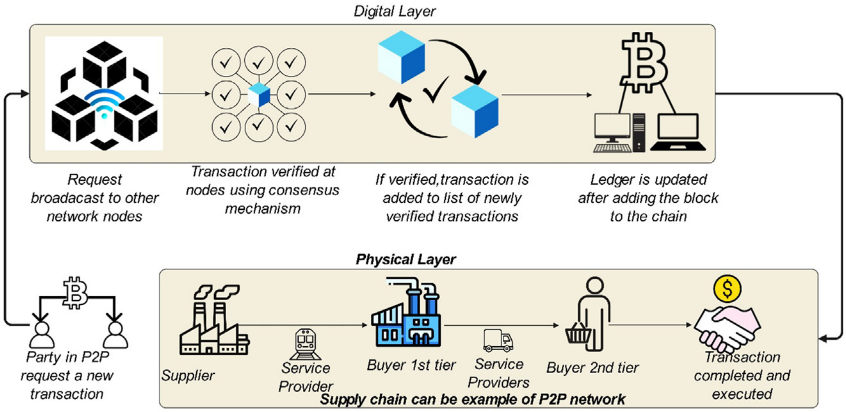


Figure 5.2 BCT process for a simple transaction. *(Author contribution).*

is bundled with other validated transactions to form a new "block." This block is cryptographically connected with its preceding block, and with this method, an inalterable chain of the records called the blockchain is attained. In every block, a block-specific hash of the block before is included, thus locking the integrity of data and being immutable. Any attempt to alter one block requires later blocks to be reverified, thereby making the blockchain extremely secure (Lumineau et al., 2020; Wang et al., 2022).

Each node in the network carries an up-to-date and synchronized copy of the blockchain ledger. This architecture type is prevented from having single points of failure as the chances of manipulating data or cyber-attacks are ruled out by the network's distributed architecture. In short, blockchain represents a decentralized and distributed ledger of all transactions performed through the network. Researchers have decomposed blockchain systems into distinctive layers, corresponding to different aspects of the process flow and data management of a specific transaction within the blockchain ecosystem Fig. 5.2.

5.3 BCT types

There are two types of blockchain technology, permissioned and permissionless, which differ from the access level of its control to the type of law regulating entering into that network. Each has peculiar characteristics, making it adaptable for several applications based on transaction type, privacy, and security necessities. discusses the classification of BCT.

5.3.1 Permissionless blockchain technology

Permissionless blockchain technology—that is, the network is open to any participant who wishes to participate in the network; by this, there are no restrictions on who might join the network to authenticate transactions or retrieve the information contained in the blockchain. In a permissionless framework, every participant is usually considered a node, and every participant can participate in the validation process through a consensus mechanism such as PoW or PoS. Since permissionless blockchains are inherently open and decentralized, they have no central authority controlling the network. Permissionless blockchain examples include Bitcoin and Ethereum, where the authentication mechanism is based on a decentralized network of nodes providing security and data integrity.

The basic features of permissionless blockchain technology are the following:

- Openness: Anybody can join the network and contribute.
- Decentralization: Power and authentication are distributed among all parties involved.
- Trust-minimized environment: The consensus protocol verifies the transactions, thus eradicating the need for mutual trust among participants.
- Public ledger: All records are publicly visible and available to everybody.

Permissionless blockchains are used in applications where openness, transparency, and decentralization are primary, such as cryptocurrency systems, decentralized applications, or global financial transactions, as they lack centralized control.

5.3.2 Permissioned blockchain technology

On the other hand, permissioned blockchain technology is also known as a private blockchain and runs on a more controlled membership system. It only allows pre-approved or identified people who must fulfill specific requirements before admission into the network. In the case of a permissioned blockchain, it has an authority or a consortium that handles membership and often restricts access to data or functionalities based on a participant's role in the network. Permissioned blockchains are, hence, more applicable in business and industry, where there is a need for transactional privacy, regulatory compliance, and security.

The basic features of permissioned blockchain technology are the following:

- Restricted access: Only authorized participants can join and validate transactions.
- Centralized governance: At least one entity controls the rules and sometimes even the rules or consensus mechanism.
- Higher scalability: Since the network participants are pre-verified, transaction speeds are generally faster and more scalable than permissionless blockchains.
- Privacy and confidentiality: Because permissioned blockchain-published data can have limited access, it ensures that confidential information is only accessible to relevant parties.

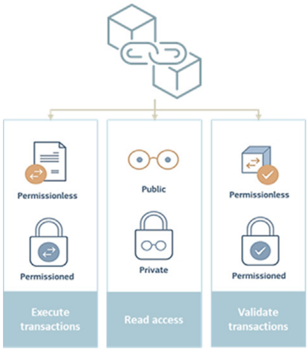
Permissioned blockchains are especially well-suited for enterprises or consortiums, which require a delicate balance between decentralization, control over who belongs, and confidentiality over the data. For instance, supply chain, finance, or healthcare industries can leverage these permissioned systems with added levels of privacy, security, and scalability. A good example is Hyperledger, which has gained popularity, especially in corporate environments (Hanif et al., 2024).

5.3.3 Suitable type of blockchain selection for various applications

The choice between permissioned and permissionless blockchain depends on the specific needs of the business or application.

- Permissionless blockchains are helpful in applications where openness to participation, transparency, and decentralization are crucial considerations, like public records, voting systems, and cryptocurrency.
- Permissioned blockchains are very useful in areas that require high privacy and compliance with regulations, governance at levels, and higher requirements like financial services and other fields such as supply chain and health.

Permissioned blockchains, in the context of the seafood industry, offer a robust and effective way to enhance transparency and traceability in supply chains without revealing confidential information on matters like pricing structures and proprietary business information. While BCTs share common basic properties, critical differences arise in design, data organization, and agreement among particular platforms. Such differences directly impact the degree to which BCTs can be applied and integrated into different environments (Werbach, 2018). An even more nuanced distinction than what is captured in Fig. 5.3 must arise considering such distinctions as



BCT Type	Explanation	Examples	Visualization
Public Permissionless BCT	Everyone can participate in the BCT's consensus mechanism. Everyone worldwide with an internet connection can transact and see the complete transaction log.	• Bitcoin • Litecoin • Ethereum	
Public Permissioned BCT	Everyone with an internet connection can transact and see the BCT's transaction log. Only a restricted number of nodes can participate in the consensus mechanism.	• Ripple • Private versions of Ethereum	
Private Permissioned BCT	Restrict both the ability to transact and view the transaction log to only the participating nodes in the system. The architect or owner of the BCT platform can determine who can participate in the BCT and which nodes can participate in the consensus mechanism.	• IBM's Hyperledger • R3's Corda	
Private Permissionless BCT	These BCTs are restricted in who can transact and see the transaction log, although the consensus mechanism is open to anyone	• Exonum (Partially)	

Figure 5.3 Types of BCT ((Batwa, 2024), adopted from (Anderberg et al., 2019)). *(Author Contribution).*

who is entitled to view or contribute to a transaction and the lines used to separate public and private BCTs. Other distinguishing differences between permissionless and permissioned BCTs would be based on the rights to execute and validate transactions. These are the important differences for understanding the specific use cases and benefits of each type of blockchain system.

5.3.4 Blockchain applications in the seafood sector

Catch-to-customer and farm-to-customer operations need to make the supply chain more efficient and sustainable with a boost in profitability in the seafood industry through aquaculture operations. The following are relevant fields for the application of blockchain technology in the seafood sector:

Increased traceability and transparency: Despite many challenges, BCT offers encouraging solutions for enhancing traceability and transparency in seafood supply chains. Ferreira et al. (2021) explored the potential of BCT technology in enhancing fish supply chain traceability and control. They stated that BCT offered a secure, end-to-end tracking system that enabled seamless data sharing among supply chain participants. It also highlighted how BCT can streamline processes, improve product safety assurance, and enhance value creation through transparency. Furthermore, it identified the need for further testing and evaluation to fully realize BCT's impact on supply chain management (Ferreira et al., 2022). Patro et al., (2022) proposed a private Ethereum BCT-based solution to enhance traceability, transparency, and security in the fishery supply chain, addressing issues such as food fraud, malpractice, and inefficiencies in existing systems. They introduced a solution architecture with five smart contracts to automate supply chain processes and presented ten algorithms for implementation, testing, and validation. Moreover, a security analysis confirmed the system's trustworthiness and reliability, while a comparative study highlighted its advantages over existing BCT and non-BCT solutions. Their smart contract code is publicly available on GitHub, promoting further research and development (Patro et al., 2022).

Traceability-focused frameworks: Numerous studies proposed specialized frameworks focused on traceability and fraud prevention. Petracci et al., (2023) introduced CERTFish, a BCT-based traceability system designed to certify fish origin and prevent seafood fraud. They mentioned that widespread mislabeling—especially in restaurants, where farmed fish is falsely sold as wild, BCT can offer a decentralized and tamper-proof solution for ensuring transparency in the seafood supply chain. Furthermore, CERTFish integrates secure digital tags, IoT tamper-proof devices, and location/time data to track fish from catch to consumer, and the system has been validated in real-case scenarios, demonstrating its potential to enhance trust, authenticity (Petracci et al., 2023), and traceability in the seafood industry. Nguyen et al., (2023) examined the adoption of BCT in Vietnam's fishery supply chain, focusing on its role in enhancing traceability, transparency, and security. Through a review of contemporary literature, their research achieved four key objectives: analyzing BCT's benefits for Vietnamese fisheries, proposing a four-stage application framework integrating IoT, outlining five transformational phases for small- and medium-sized enterprises (SMEs), and identifying policy implications related to infrastructure, regulation, and human capital (Nguyen et al., 2023). Their findings suggest that BCT has strong potential to drive growth in Vietnam's fishery export industry, provided that key challenges are addressed. Rani et al., (2024) introduced "Sea to Table," a BCT-enabled framework designed to enhance transparency, traceability, and sustainability in seafood supply chains. Built on the Ethereum BCT, the system digitally records and securely stores all key processes—from harvesting to distribution—ensuring immutable and verifiable data. This allows stakeholders and consumers to track seafood origin, handling, and environmental impact in real-time, promoting food safety and sustainability. By providing accurate, trustworthy information, the framework aims to boost consumer confidence, prevent fraud, and support responsible seafood consumption (Rani et al., 2024). Similarly, Hopkins et al., (2024) explored traceability in UK seafood supply chains, highlighting how monitoring technologies and regulatory changes have improved traceability and reduced illegal fishing risks. By mapping three seafood supply chains, the study found that shorter supply chains enhance traceability, but vulnerable nodes in processing and distribution can lead to traceability gaps. It further stated that the UK seafood supply chains meet regulatory requirements; however, many stakeholders aim for best practices to build consumer trust and industry confidence (Hopkins et al., 2024).

Food safety and quality guarantee: Blockchain ensures data integrity, allowing stakeholders to verify the different handling, storage, and processing conditions, thus ensuring safe and quality products. Blockchain technology creates a protected monitoring system which ensures information transparency across seafood supply chain processes while maintaining unalterable records. BCT delivers optimum storage conditions by using real-time tracking together with IoT sensors to check for temperature and humidity while observing handling practices thus diminishing contamination possibilities. The authentication process provided by BCT technology continually fights unresolved seafood fraud and incorrect labelling to deliver legitimate seafood products to customers. BCT improves recall speed because it permits instant tracking of tainted batches which enables authorities to find contamination origins in under a minute. Food safety improvements through smart contracts occur because these systems automatically maintain quality standards which result in authorized seafood reaching markets. Through its role in fraud prevention and improved regulatory adherence blockchain establishes higher consumer trust levels which leads to greater seafood supply chain safety (Alsharabi et al., 2024).

Sustainable fishing practice: Blockchain technology enhances sustainable fishing practices by improving traceability, ensuring regulatory compliance, and promoting transparency across the supply chain. Luna et al., (2024) proposed a BCT-based framework, incorporating smart contracts, to help the EU aquaculture sector meet stringent environmental policy compliance requirements. By enhancing traceability, transparency, and fraud prevention, the approach aimed to support the industry's long-term sustainability while ensuring trust and security across the supply chain (Luna et al., 2024). John and Mishra (2024) presented a sustainable tuna fish supply chain model integrating green technology, BCT traceability, and waste reduction strategies. By implementing integrated multi-trophic aquaculture (IMTA) at the farming stage and using fish waste utilization and seaweed bioplastic packaging at the processing stage, the model significantly reduced emissions, plastic pollution, and waste. BCT enhanced transparency to prevent illegal and unsustainable tuna from entering the market. Optimization results showed an 80% reduction in emissions and over 95% waste reduction, offering a scalable solution for sustainable seafood supply chains (John & Mishra, 2024). Bharathi et al., (2024) explored the potential of BCT in transforming seafood supply chain management by integrating technology-organisation-environment theory with situation-actor-process and learning-action-performance models. It presented a BCT-based framework aimed at enhancing data efficiency, sustainability, and seamless integration across the seafood supply chain. Key factors for successful adoption included accurate data management, stakeholder involvement, regulatory compliance, cybersecurity, cost-effectiveness, and transparency. By ensuring real-time traceability and informed decision-making, BCT enables optimized resource allocation, reduced inefficiencies, and a more sustainable seafood industry (Bharathi et al., 2024). Alwi et al., (2024) introduced a novel design that preserved BCT's anonymity and immutability while addressing storage constraints. By incorporating carbon footprint tracking alongside traceability, the model aims to ensure sustainability and quality assessment. Though not yet tested in real-world scenarios, simulations and evaluations indicate its potential for future implementation (Alwi et al., 2024).

Yang et al., (2024) examined the latest advancements and challenges in seafood traceability and authentication, highlighting their ecological importance and role in combating mislabeling and illegal fishing. It explored technologies such as isotope and chemical fingerprinting, DNA identification, smart sensors, digital systems, and BCT, assessing their effectiveness in verifying seafood provenance. The study also analyzed global regulatory frameworks, policy implementation challenges, and the role of eco-labels in promoting sustainability. Emphasizing the need for integrated and advanced traceability solutions, it identified key areas for further research to enhance marine resource sustainability and secure the future of the seafood industry (Alsharabi et al., 2024; Yang et al., 2024). Alsharabi et al., (2024) explored the integration of BCT and AI technologies to create sustainable, biodiverse, and transparent fisheries of the future. BCT ensured secure traceability of fishery products from harvest to market, while AI monitored fish populations, predicted stock levels, and enhanced decision-making to prevent overfishing and biodiversity loss. Preliminary results suggested that combining these technologies can improve sustainability and transparency, fostering healthier marine ecosystems. However, further observational studies are needed to validate AI-driven fisheries management. The study highlighted the transformative potential of BCT and AI in shaping the future of responsible and sustainable fisheries (Alsharabi et al., 2024). Similarly, Platonava et al., (2024) discussed current and potential BCT applications in aquaculture, focusing on enhancing transparency, traceability, and sustainability within seafood supply chains. The paper reviewed BCT adoption in tracking, quality control, transportation, and payments. It provided a theoretical foundation for future research and offered practical insights for stakeholders, policymakers, and researchers. The findings suggested that integrating BCT with advanced technologies like IoT could further enhance its efficiency and impact in aquaculture, paving the way for a more sustainable and transparent seafood industry (Platonava et al., 2024).

Blockchain applications in small-scale and rural fisheries: While BCT solutions have been widely explored in large-scale fisheries, their application in small-scale and rural fishing communities is gaining attention. Khan et al., (2022) introduced ShrimpChain, a BCT-based framework designed to enhance traceability, transparency, and certification in Bangladesh's shrimp export industry. Traditional paper-based record-keeping hampers efficient tracking, leading to malpractices and limiting export growth. ShrimpChain leverages a hybrid BCT model where data from production to packaging is entered via mobile/web apps and IoT devices, authenticated through community consensus and timestamping. It proposes a distributed, score-based certification system to improve food safety, quality, and compliance with best practices. By empowering shrimp farmers with greater market control, the framework aims to boost the industry's export potential and access to high-value markets (Khan et al., 2022). Similarly, Enayati et al., (2024) explored the potential of a BCT-enabled framework to enhance livelihood sustainability for rural fishermen in Alappad, Kerala, India, addressing issues such as low profitability, lack of transparency, trust deficits, and dependence on intermediaries. Through thematic analysis of 43 interviews, five key challenges were identified: business costs, government regulations, digital illiteracy, socio-cultural barriers, and reliance on middlemen. The study proposes a BCT-based e-commerce solution to improve market access, reduce exploitation, and enhance trust and transparency in the local fish trade. Aligned with five UN sustainable development goals (SDGs), this approach presents an innovative alternative to conventional solutions, fostering economic resilience and rural development (Enayati et al., 2024). Tian and Jiang (2024) presented a BCT-based traceability system for Yangcheng Lake hairy crabs, integrating IoT technology to enhance brand value, market competitiveness, and consumer trust. By covering the entire supply chain—from breeding to sales—the model ensured end-to-end transparency, authenticity, and data security. At the technical level, the research introduced the Enhanced Cuckoo Merkle Index model, demonstrating how cuckoo filters outperform Bloom filters in reducing false positives and improving query efficiency. The findings offered a practical BCT solution for smart agriculture and contributed to China's rural revitalization strategy (Tian & Jiang, 2024). Hachicha et al., (2024) introduced PreSA, an intelligent BCT-based platform designed to monitor and predict water quality for smart aquaculture. By integrating ML and BCT, the system enhanced control, management, and security in fish farming. The platform used the Trophic Index to assess aquatic ecosystem health, employing ARIMA, Random Forest (RF), and K-Nearest Neighbor models to predict water pollution levels. Evaluation results showed RF provided the highest accuracy. BCT ensured secure data storage and traceable alerts, enabling real-time interventions to prevent water contamination. This solution enhanced aquaculture sustainability and fish welfare by enabling early pollution detection and proactive management (Hachicha et al., 2024). Hisham et al., (2025) examined BCT's role in securing the global aquaculture supply chain, addressing challenges such as fraud, mislabeling, and food safety concerns. With 20% of seafood mislabeled, consumer trust is at risk, and regulatory actions—such as the EU's temporary suspension of Thai fish imports—highlights the need for better traceability. BCT provided an immutable, transparent ledger, enhanced by IoT devices and QR codes, to track product origin, quality, and handling in real time. This integrated solution improved compliance, reduced fraud, and fostered sustainability. The study emphasized the need for further BCT adoption in small-scale and developing aquaculture sectors, ensuring a safer, more responsible seafood industry (Hazzarul Hisham et al., 2025).

5.4 Successful deployments of blockchain in seafood

This section gives real-world applications of blockchain in the seafood sector. Many projects are underway worldwide to demonstrate the disruptive power of blockchain in seafood supply chains. Some examples include:

- Indonesia: Source, Bumble Bee Fair Trade Yellowfin Tuna, This Fish, Jumbo Tilapia Blockchain (Tolentino-Zondervan et al., 2023)

- Pacific Island Nations: Pacifical-Atato, TraSeable .
- Philippines Tracey
- Ecuador: Sustainable Shrimp Partnership
- Thailand: eMin
- Australia: South-Central Patagonian Toothfish and Spencer Gulf King Prawn Fishery Opening
- Norway: IBM Blockchain Transparent Supply and Seafood Chain (Chod et al., 2020).
- United States: New England Fishery Blockchain Seafood, Fishcoin in Alaska (Fishcoin, 2024).

The next few sections will introduce two concrete instances: one with private blockchain and two with public blockchain to illustrate how these systems overcome some issues and bring value.

5.4.1 Private blockchain: IBM food trust

The Sustainable Shrimp Partnership (SSP) in Ecuador epitomizes private blockchain utilization to transform shrimp production and supply chains. As the world's second-largest shrimp producer, exporting millions of tons annually, Ecuador aimed to align its shrimp production with strict socio-environmental standards, including antibiotic-free practices, minimal environmental impact, and full traceability. Through collaboration with IBM Food Trust, SSP uses a private blockchain network to track shrimp at every stage of the supply chain, enabling end consumers to verify critical information, such as farming practices, environmental impacts, and the general health of the shrimp. Unlike traditional shrimp farming, which often sacrifices sustainability for lower costs, SSP uses blockchain technology to promote transparency and accountability. This program makes Ecuador's quality shrimp unique in international markets and allows consumers to make informed decisions, creating more trust and loyalty. With blockchain, SSP has inspired other industries, such as coffee and cocoa, to develop similar frameworks in tracing and sustainability (IBM, 2024).

5.4.2 Public blockchain: FishCoin

Fishcoin is a public blockchain application that solves the fragmentation of seafood supply chains. This decentralized peer-to-peer network motivates all players, fishermen, processors, distributors, or retailers to share data in the harvest chain through consumption. Fishcoin's concept works through digital vouchers, tokens exchanged between buyers and sellers as seen in through mobile application. These tokens incentivize the participants while sharing data, thus ensuring the traceability and security of that information in the blockchain network. The decentralized nature of Fishcoin eliminates intermediaries, thereby reducing administrative costs while enhancing trust. The traceability burden is shifted to the downstream actors, such as hotels, restaurants, or retailers, who benefit more from the transparent supply chain, making the system fiscally sustainable and generating value for all parties involved. This Fishcoin system is open, where companies and developers can develop and exploit it according to their needs. It thus creates a very flexible and scalable whole system (Fishcoin, 2024).

5.4.3 Public blockchain: SeafoodChain

SeafoodChain is an advanced public blockchain solution developed based on the UNISOT Asset Traceability Platform, combining blockchain and AI technologies to improve traceability, verification, and labelling procedures within seafood and aquaculture supply chains. With simplified labelling procedures, SeafoodChain ensures that the correct, accurate information reaches all the stakeholders, from fishers, aquaculturists, processors, and retailers. This system enhances transparency and compliance with regulatory requirements and strengthens relationships among producers and consumers, all of which help to advance sustainability and authenticity in seafood activities (Probst, 2020). The seafood supply chain is a complex system of activities that starts with catching fish or genetically sourcing fish eggs at hatcheries and moves forward through critical phases such as breeding, feeding, environmental oversight, harvesting, processing, distribution, retailing, transportation, preparation, and even recycling. SeafoodChain can collect vast amounts of data and monitor each one of these stages (Fishcoin, 2024).

5.4.3.1 Key features of SeafoodChain

It applies the usage of some sophisticated tools and technologies, including:
- For fishermen: Mobile applications allow the data to be entered directly, hence traceability at the source.
- Hatchery data: Collect genetic and environmental data on fish eggs to make the breeding process more transparent.
- IoT sensors and environmental monitoring: It tracks water quality, temperature, and other vital conditions in the fish's lifecycle.
- Automated sizing, weighing, and inspection for quality by computer vision technology for different stages of fish processing.

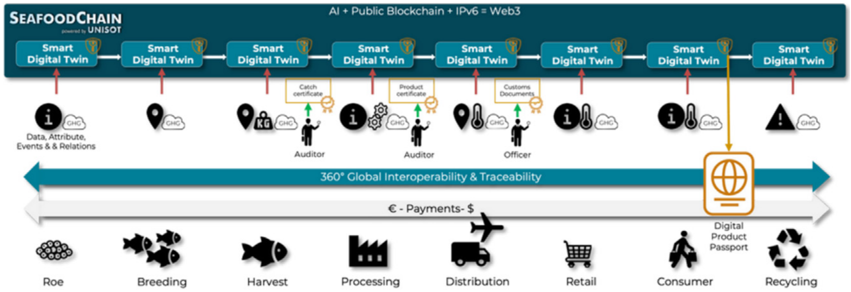


Figure 5.4 Application of the SeafoodChain technology across a fish supply chain (SeafoodChain, 2024).

- ERP plugins: Smoothing and integrating blockchain functionalities within enterprise resource planning frameworks to enhance supply chain management.
- Big data analytics and ML: Supply chain optimization, environmental factors, and markets demand anticipatory insights.

5.4.3.2 Impact of SeafoodChain

- Improved traceability: The system has ensured that every stage of the supply chain is recorded in an immutable blockchain ledger. Thus, traceability can be achieved from the hatchery or fishing vessel to the consumer.
- Improved labelling accuracy: SeafoodChain makes labelling simple and standard; it reduces error possibilities and ensures adherence to regional and international laws.
- Sustainability support: By enhancing environmental and ethical standards at each step of the process, SeafoodChain promotes responsible fishing and aquaculture toward contribution to global sustainability efforts.
- Consumer trust and participation are enhanced because end-users are provided with accurate, detailed information about the products they use, thus leading to confidence and enabling an informed purchasing decision.

5.5 Technological integration across the supply chain: SeafoodChain

This all-around approach of SeafoodChain (Fig. 5.4) shows how blockchain technology can help transform supply chain management by integrating AI and IoT technologies. It takes data capture and validation straight from the fishing boat using mobile apps and brings big data analytics for market insight to the table so that the entire supply chain remains well-connected and transparent. Interconnectivity between such systems helps the manufacturers to follow best practices while serving the consumers with an excellent confidence level about the authenticity and sustainability of their seafood. Incorporation of such technologies in the Seafood Chain is a new benchmark of public blockchain applications in seafood, enabling digital transformation as a process to align economic interests with ecological and moral obligations (SeafoodChain, 2024).

SeafoodChain introduces the concept of a Digital Product Passport (DPP), an elastic tool that will offer full and personal information about seafood products throughout their life cycle. The content of a DPP is product-dependent; it contains information about origin, manufacturing, or processing data, distribution and delivery data, usage instructions, and disposal guidelines. For example, DPP provides basic information on the fishing ground or aquaculture facility where the fish was caught, giving detailed information on feed, harvesting, processing, packaging, and quality control measures. In addition, it contains logistic information such as route of transportation and storage condition, as well as consumer advisory concerning handling, preparation, and storage of the product to ensure the safety and quality of the commodity. Furthermore, it suggests environmentally conscious disposal or recycling methods, supporting sustainability goals. The DPP (Fig. 5.5) serves a dual purpose: it benefits consumers and companies alike. The DPP fosters trust and engagement for consumers by offering insights into the seafood's track record, allowing them to confirm sustainable practices, trace products back to their origin, and verify quality certifications. This level of transparency enhances customer relations and aligns with growing consumer demand for responsibly sourced products. This makes the DPP a depository database for organizations; hence, practical insights may be easily derived from this data. An enterprise may use this information to rate the effectiveness of supply chains, optimize logistics and inventory management, identify potential inefficiencies, and ensure conformity to food safety and sustainability standards (SeafoodChain, 2024).

The DPP is an industry-wide influence that pushes business change while fostering sustainability. Driving digitalization and allowing for timely access to information on supply chains makes it more efficient and with less waste on the part of the enterprise. The transparencies established within the DPP allow for building trust between stakeholders, such as fishers,

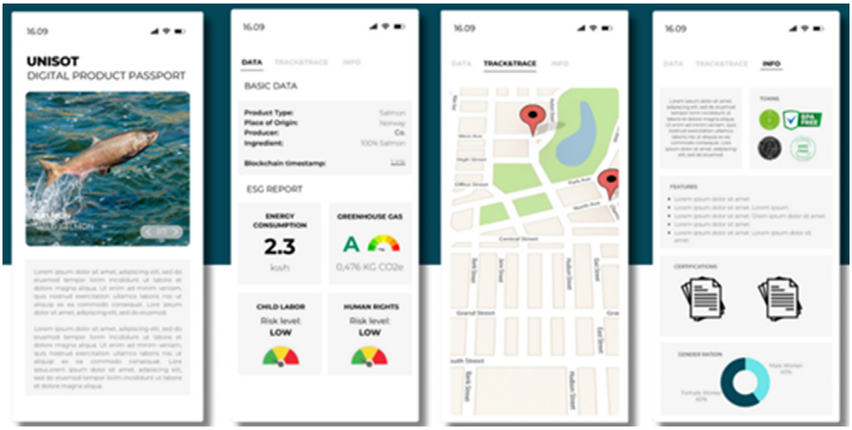


Figure 5.5 Example of the UNISOT Digital Product Passport utilizing SeafoodChain, a blockchain-enabled technology (SeafoodChain, 2024).

processors, retailers, and consumers, in sound and effective relationships. Apart from the record-keeping in DPP, food safety regulations, labelling, and environmental conservation are assured by keeping up-to-date records. In international terms of sustainability, DPP works for responsible practices with each supply chain step that highly contributes to overfishing, habitat destruction, and carbon emissions. This way, the DPP of SeafoodChain improves performance in the seafood industry concerning standards and is a huge step towards higher-level social and environmental sustainability goals (SeafoodChain, 2024).

5.6 Challenges and solutions to blockchain implementation

The seafood sector is characterized by challenges that could be overcome using blockchain. However, applying blockchain within complex supply chains, such as seafood products comes with its own challenges. This section explores some of the BCT challenges, solutions, and highlights future directions for its implementation in the seafood sector. In a research investigation, six major CBFs were identified that inhibited the implementation of blockchain technology in China's fish supply chain (Nisar et al., 2024).

One of the major hurdles to BCT adoption in the seafood sector is industry's resistance to digitization, trade dynamics, and regulatory issues. Thompson and Rust (2023) analyses the resistance to BCT adoption in the Australian seafood supply chain. They found that despite its potential to enhance traceability and transparency, the key barriers include the industry's limited digitization, the dominance of powerful wholesalers who control trade dynamics, and the reluctance of smaller players to jeopardize their business relationships. While BCT could reduce information asymmetry, it threatens existing power structures, making widespread adoption unlikely unless influential stakeholders perceive its value (Thompson & Rust, 2023). Similarly, Meera et al., (2023) highlights the barriers to BCT adoption in seafood exports, despite its potential to enhance transparency and traceability. Based on feedback from seven companies, their study identified regulatory uncertainty as the biggest obstacle, highlighting the need for compliance reforms. Additionally, they found that high implementation costs also pose a significant challenge and suggested that cost reduction strategies are crucial for wider adoption of BCT in seafood supply chains (Meera et al., 2023). Finally, in Norway, Konstantopoulou and Mikalef (2024) examined BCT adoption in the fish supply chain, focusing on its potential to combat illegal fishing and improve traceability (Konstantopoulou & Mikalef, 2024). They analyzed the Norwegian Directorate of Fisheries' CatchID Program, where they explored stakeholder perceptions using affordance theory. While BCT is recognized for enhancing transparency, data integrity, and security, barriers such as integration challenges and regulatory complexities hinder its adoption. Their study highlighted the need for strategic alignment between technology and socio-cultural factors to ensure successful BCT implementation in the seafood industry. Other than regulatory and structural barriers, technical and infrastructural challenges further make it difficult for BCT adoption. Alwi et al., (2024) proposed an integrated BCT and big data solution to enhance traceability and carbon footprint management in the fishery supply chain (Alwi et al., 2024). Although BCT has been used to tackle illegal fishing and emissions control, its storage limitations hinder managing large-scale data, such as images and videos. Tokkozhina et al. (2022) conducted a systematic literature review, and found that existing BCT implementations when evaluated, highlighted their potential to combat illegal fishing, ensure ethical sourcing, and improve end-to-end visibility. Although, the authors found that BCT offered significant benefits for fish distribution and stakeholder value creation, they identified key challenges such as interoperability issues and data management inefficiencies that must be addressed for wider industry adoption (Tokkozhina et al., 2023). Ouled Abdallah et al., (2023) explored BCT-based seafood supply chain management, addressing challenges such as malpractices, unsustainable resource management, inefficiencies, and mistrust among stakeholders

(Ouled Abdallah et al., 2023). They mentioned that with the increasing demand for transparency and accurate product information, BCT is seen as a promising solution to improve traceability and operational efficiency.

In another research, Tsolakis et al., (2021) studied the design of blockchain-centric food supply chains that promote UN SDGs within the Thai fish industry context. They identified the concerns relating to the fish supply chain operations in Thailand as follows:

- Lack of connectivity between different departmental databases.
- There is no logbook requirement for local fishing vessels.
- Lack of requirement for vessel monitoring system (VMS) installation on local fishing vessels.
- Inability to share logbook information in real-time.
- A 20% tolerance allowance on the accuracy of the number of fish caught.
- Unregistered vessels.

In this aspect, blockchain became a technological intervention that made fisheries businesses more feasible and sustainable in Thailand. However, it was underlined that this success depends on the correct supply chain design and crucial technology implementation decisions. As given the root issues of the Thai fish industry, Table 5.3 is a summary synthesis of relevant recommendations for designing a supply chain based on blockchain technology.

Data asymmetry in seafood supply chains leads to challenging issues associating activities with the UN SDGs. Four elementary principles have been suggested to ensure the effective use of blockchain, which focuses on solid data frameworks. The first principle is Data Archetypes, which postulates the creation of interlinked data stores at all tiers of a supply chain so that information is consistent and coheres. The interlinking allows for the communication of verifiable information throughout the chain. The second principle is Data Capture, which uses advanced mechanisms and systems to capture data correctly. Proper control of these systems determines the accuracy and reliability of data entered by blockchain systems with reduced chances of error and fraudulent activities (Probst, 2020). The third principle is Data Consistency, which takes data requirements beyond regulatory compliance into real-world operational complexities. Most of the fleet consists of local fishermen not equipped with vessel monitoring systems. The risk of data adulteration, commercial fraud, and misrepresentation of fishing activities is high. These gaps have to be addressed to ensure holistic data integrity (Alwi et al., 2024).

Data interoperability includes all the activities of the supply chain and, no matter whether major or minor, function. Minor functions normally

Table 5.3 Blockchain-centric supply chain design recommendations and solutions (Tsolakis et al., 2021).

Key challenge	Potential blockchain-centric solution
Data fragmentation across multiple databases	Create a decentralized blockchain-based database for unified, real-time data access.
Inaccurate data on fish catch	Implement smart systems (e.g., on-board weighing) that automatically record and transmit accurate data to the blockchain.
Untraceable vessels and illegal fishing	Use blockchain-linked monitoring systems (e.g., radar, GPS) to trace and verify vessel activities.
Delays and inefficiencies in data reporting	Replace paper-based systems with blockchain-integrated electronic reporting for real-time traceability.
Lack of consistent monitoring and enforcement	Deploy IoT devices and blockchain to monitor and verify compliance with regulations continuously.
Food safety concerns due to improper storage	Blockchain can link IoT sensors for continuous monitoring and verification of storage conditions.
Traceability gaps	Implement blockchain-enabled tracking systems (e.g., RFID) for full supply chain traceability.
Limited transparency and auditability	Blockchain can provide real-time, full-chain transparency, and enable continuous audits.
Data interoperability issues	Implement a hybrid or permissioned blockchain to allow selective data sharing across stakeholders.

receive impacts that heavily influence a supply chain's transparency and efficiency level. In addition to these basic tenets, further guidance has been provided in more detail to make blockchain technology implementation in seafood supply chains successful. Vigorously pursued due diligence in all legal, commercial, and operational areas should be carried out before the commitment to implementing blockchain solutions. These include comprehensively grasping every conceivable supply chain event and situation to allow for constant traceability. For the standardization of blockchain integration, CTEs and KDEs have to be defined at a very high degree of accuracy. Besides that, administrative, logistical, and legal considerations are relevant, too, concerning the various jurisdictions within the supply chain for the custody of seafood. The same comprises flag states, coastal states, port states, processing entities, and end-market participants, which play key roles in regulation. The final stage involves traceability system weaknesses in use. Deep knowledge of the system's operational and logistical weaknesses helps develop bespoke blockchain solutions, thus ensuring such systems meet the specific requirements of the seafood industry, be it robust traceability and strict adherence to standard regulatory compliance (Fishcoin, 2024; Ferreira et al., 2022).

5.7 Prospects and research directions

As BCT adoption continues to evolve, its integration with emerging technologies presents new opportunities. Zhang et al., (2024) presented an enhanced BCT-based cold chain traceability system for marine fishery vessels, addressing challenges such as limited communication, computing resources, and unstable environments. It introduced an Internet of Vessels (IoV) system using Iridium Satellites (IoV-IMS) for real-time marine cold chain monitoring. To improve throughput, transaction latency, and communication efficiency, it proposed a Node-grouped and Reputation-evaluated PBFT (NR-PBFT) consensus algorithm, which optimized node selection and reduced processing overhead. Experimental results showed significant improvements over traditional PBFT, including an 81.92% reduction in transaction latency, an 84.21% increase in throughput, and an 89.4% decrease in communication overhead, demonstrating the system's effectiveness and scalability in real-world marine applications (Zhang et al., 2024). Ismail, Reza, Salameh, Kashani Zadeh, & Vasefi, 2023 proposed a BCT-based fish supply chain framework designed to enhance fish quality, authenticity, and traceability. By integrating BCT, big data, AI, and IoT, the framework ensured end-to-end tracking from harvest to consumer while improving visibility and security. It followed a layered architecture, incorporating a Supply Chain layer, an IoT layer, and a BCT layer. A key innovation is the AI-powered Quality, Adulteration & Traceability device, which can identify fish species and assess quality. Built on the Ethereum BCT with smart contracts, the framework undergoes extensive validation, demonstrating its practical feasibility for improving fish supply chain transparency and reliability (Ismail, Reza, Salameh, Kashani Zadeh, & Vasefi, 2023). Bhusan et al., (2025) explored the integration of information technology (IT) in fisheries and aquaculture, highlighting its role in enhancing sustainability, productivity, and traceability. BCT enhanced supply chain transparency to combat illegal fishing. This study underscores the need for continuous technological adaptation to drive a smarter and more sustainable future in fisheries (Bhusan et al., 2025). Saha et al., (2024) explored the role of BCT in combating food fraud within the increasingly complex and globalized agri-food supply chain (AFSC). Using Interpretive Structural Modelling, it identified key enablers for successful BCT adoption, including immutable ledgers, data security, and transparency. They stated that by ensuring traceability, accountability, and trust, BCT can significantly reduce fraudulent practices in the AFSC. This research provided valuable insights for policymakers and industry stakeholders, highlighting BCT's potential to reshape the agri-food industry by fostering trust, security, and transparency across the supply chain (Saha et al., 2024). These findings could be relevant to the seafood sector, where traceability, accountability, and trust play a crucial role in addressing fraud and improving supply chain transparency. Similarly, Ismail et al. (2023) explored the integration of BCT and IoT in the fish supply chain to combat IUU fishing and enhance traceability, transparency, and security. By leveraging DLT, the proposed Intelligent BCT IoT-enabled supply chain framework enables real-time tracking of fish products across harvesting, processing, packaging, shipping, and distribution. The study also examined traditional vs. smart supply chain systems, outlining key design considerations for effective BCT-based traceability models. Additionally, it highlighted the role of ML in improving fish quality assessment, freshness monitoring, and fraud detection, demonstrating the transformative potential of BCT-IoT-ML integration in enhancing efficiency and sustainability in the fish supply chain (Ismail, Reza, Salameh, Kashani Zadeh, & Vasefi, 2023).

5.8 The future of blockchain technology in the seafood sector

The prospects for blockchain in the seafood sector are promising, as its implementation can address industry hurdles while increasing the efficiency and sustainability of fisheries and aquaculture operations. Further research is needed to align BCT implementation with industry policies and regulations. Shamsuzzoha et al., (2024) proposed a BCT-enabled traceability system to enhance transparency and achieve a sustainable seafood industry, introducing Tracy, a blockchain-based system designed to assist Filipino fishermen in overcoming challenges related to regulatory compliance, export standards, and catch certification (Shamsuzzoha et al., 2024). A key feature of Tracy is its smartphone application, which enables fishermen to track fish capture details, transaction histories, and sales records, thereby improving supply chain visibility. Similarly, Pratiwi et al., (2024) conducted a systematic review on BCT's role in fisheries, highlighting its ability to enhance traceability, sustainability, and economic efficiency by providing real-time data sharing and reducing transaction costs through the elimination of intermediaries. However, the study also noted challenges such as integration with existing systems and the need for stronger stakeholder collaboration (Pratiwi et al., 2024). Mileti et al. (2022) explored BCT applications in IMTA through a case study in Italy, demonstrating its potential to improve supply chain transparency and sustainability while fostering credibility among producers, retailers, and consumers. However, the study emphasized that successful implementation requires active industry-wide participation to unlock blockchain's full potential in seafood trading and aquaculture management (Mileti, Arduini, Watson, & Giangrande, 2022).

To fully realize blockchain's potential, various methods can encourage adoption and further development. One promising application is the integration of decentralized finance solutions, which could revolutionize seafood industry financing, capital access, and insurance management. Blockchain-based platforms would enhance transparency and efficiency in financial services, significantly reducing intermediaries, and transaction costs. This would particularly benefit SMEs by making financial resources more accessible, thereby enabling them to compete globally. Another critical strategy is the implementation of incentive-based mechanisms to reward truthful reporting, sustainability practices, and transparent transactions. For example, fishermen could be incentivized to report real-time catch data accurately, while processors and distributors could receive rewards for following higher safety and handling standards. Such mechanisms would align supply chain actors' interests, fostering collaboration and ethical business practices.

The introduction of automation technologies, such as robotics and IoT, provides another avenue for optimization. Temperature and humidity sensors can collect real-time data throughout seafood production and distribution, ensuring traceability and minimizing human interference. DPPs could further enhance transparency by documenting each step of a product's journey—from catch to consumer—strengthening trust and giving ethically sourced products a competitive edge. Additionally, AI and ML can analyze blockchain-generated data, detect fraud, optimize resource management, and enhance supply chain efficiency. AI-driven insights could predict market trends, reduce waste, and ensure compliance with evolving food safety regulations.

Global cooperation and regulatory standardization are also essential for blockchain's success in the seafood sector. Standardizing blockchain protocols and regulations across jurisdictions would facilitate seamless international trade, improved traceability, and regulatory compliance, ultimately ensuring a more sustainable and transparent seafood market. Moreover, education and training for industry stakeholders—especially for SMEs in developing nations—are crucial for widespread adoption. Targeted training programs, workshops, and resources can increase blockchain literacy and participation, fostering an inclusive and innovation-driven seafood industry.

These collective approaches can transform the seafood sector, improving traceability, regulatory compliance, and sustainability. Blockchain's success will depend on technological integration, tangible industry benefits, and international collaboration. By addressing existing challenges and leveraging its transformative potential, blockchain can pave the way for a more efficient, transparent, and equitable seafood industry.

5.9 Summary of the chapter

This chapter addressed the application of blockchain technology in the seafood sector: its power to revolutionize many issues in the chain of management, traceability, and sustainability. It explained the initial concepts of blockchain, clarifying its nature as decentralized, transparent, and immutable approaches toward strengthening security and data integrity and promoting more efficient operational processes. Furthermore, it details different blockchain system types, including permissioned and permissionless blockchains, and their appropriate applications within distinct industry-related contexts. It discusses some of the basic applications of blockchain technology within the fishery sector and focuses on the three major domains, that is, improved traceability and transparency, assurance of seafood safety and quality, and augmented sustainability in fishing. The chapter discusses practical blockchain initiatives such as IBM's Food Trust, FishCoin, and SeafoodChain, which can effectively improve transparency and product quality monitoring and enhance sustainability from capture to end consumer. Furthermore, the chapter covered the hindrances the seafood industry might face in embracing blockchain technology. These are complex supply chains, issues about data accuracy, a too large cost to implement, regulatory compliance issues, and data security and privacy issues. Case studies from countries such as China and Thailand have portrayed such challenges and presented possible solutions like reducing data asymmetry, enhancing connectivity between supply chains, and easy, instantaneous data sharing. To address these challenges, the chapter presented various recommendations to be implemented in the future. Among these are the adoption of decentralized finance solutions to have better access to capital, incentives for sharing data, IoT in automation of data, DPP to make the process more transparent, AI in the supply chain for optimization, international blockchain standards, and an investment in education and training of all stakeholders involved. Blockchain promises enormous transformation for the seafood sector, as supply chains are expected to become more transparent, sustainable, and efficient. Still, to be implemented successfully, all the technological, operational, and regulatory challenges must be overcome. With appropriate adoption strategies, blockchain will support greater resilience and accountability for seafood supply chains while strengthening producers and consumers toward achieving global sustainability goals.

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