



Review

Enhancement of Hygiene and Safety in the Food Industry Through Digitalization With Blockchain Technology

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Abstract

The increasing demand for transparency, safety, and sustainability in the food industry necessitates the adoption of advanced digital technologies. Thus, this study aimed to examine the synergistic integration of the blockchain, artificial intelligence (AI), and the Internet of Things (IoT) as a transformative framework to enhance hygiene, safety, and operational efficiency throughout food supply chains. Hence, by ensuring end-to-end traceability, these technologies collectively mitigate food fraud, improve regulatory compliance, and foster environmentally responsible practices in fisheries and aquaculture. The paper highlights the capacity of the IoT for real-time data acquisition, the immutable record-keeping of the blockchain, and AI-driven predictive analytics in decision support. Furthermore, this study evaluates various mathematical and analytical models, including Mixed-Integer Linear Programming (MILP), Branch and Efficiency (B&E), Simultaneous Data Envelopment Analysis (SDEA), Karush–Kuhn–Tucker (KKT) optimization, and Fuzzy DEMATEL, as practical tools for designing IoT-integrated blockchain systems. By addressing adoption barriers and future opportunities, this study highlights the critical role of regulatory alignment, cross-sector collaboration, and standardization in fostering a safer, more transparent, and sustainable food industry.

Keywords: food industry digitalization; blockchain; IoT integration; traceability; sustainability; food safety

1. Introduction

The globalization and increasing complexity of food supply chains have introduced critical challenges in ensuring food hygiene, safety, traceability, and sustainability [1,2]. Conventional traceability systems, which are often fragmented, paper-based, or reliant on isolated digital tools, are inadequate for providing the real-time transparency and reliability necessary for effective risk prevention [3]. These limitations become especially evident during foodborne illness outbreaks, product recalls, or fraud investigations, compromising not only operational integrity but also consumer trust [3]. As the food industry, and particularly the seafood sector, operates in a highly dynamic and vulnerable environment, the need for secure, transparent, and real-time digital infrastructures has become more urgent than ever [4,5].

Blockchain technology has emerged as a powerful driver of digital transformation in food systems. With its decentralized and tamper-resistant ledger, blockchain enables immutable documentation of every transaction across the supply chain [6,7]. Unlike traditional centralized databases prone to manipulation or delays, blockchain ensures that producers, processors, regulators, and consumers share access to the same verified and synchronized data [8,9]. For seafood supply chains, this transparency is especially vi-

tal in verifying catch origin, monitoring handling practices, and combating illegal, unreported, and unregulated (IUU) fishing [10–12].

The integration of blockchain with the Internet of Things (IoT) significantly enhances traceability capabilities within supply chains. IoT devices—such as Radio-Frequency Identification (RFID) tags, Global Positioning System (GPS) trackers, and smart sensors—collect real-time data on critical parameters including temperature, humidity, location, and handling practices, while blockchain ensures that this information is securely recorded and accessible to authorized stakeholders [13,14]. In cold chain logistics, where even minor deviations can undermine hygiene and safety, IoT-enabled monitoring ensures strict environmental control, while blockchain validates and secures each recorded event [15,16]. This synergy creates a robust traceability infrastructure that not only improves responsiveness but also guarantees accountability and data integrity at every stage.

Beyond food safety and hygiene, blockchain and IoT hold far-reaching environmental and socio-economic implications. By optimizing logistics, reducing waste, and improving inventory accuracy, these technologies contribute to resource efficiency and carbon footprint reduction [17, 18]. Economically, blockchain promotes inclusivity and resilience by supporting access to credit, insurance, and



market information for small-scale producers, especially in fisheries and aquaculture [19]. Thus, the transition from static, post-hoc traceability to dynamic, real-time monitoring marks a broader paradigm shift toward transparent, data-driven, and sustainable food systems aligned with global development goals [18,19]. Nonetheless, significant challenges hinder the widespread adoption of these technologies. High implementation costs, lack of universal standards, limited digital literacy among stakeholders, and fragmented regulatory structures remain persistent obstacles [20–22]. Ensuring interoperability and protecting sensitive data are also central to building user confidence and maintaining legal compliance [23,24]. Addressing these challenges requires coordinated action among governments, industry actors, and academia to promote infrastructure investment, digital capacity building, and the development of open, interoperable standards [24].

Looking ahead, the combination of blockchain with other digital technologies such as artificial intelligence, big data analytics, and genomic identification plays a powerful role in strengthening food safety and hygiene management. Artificial intelligence (AI), in particular, enhances predictive capacity by predicting potential disruptions, optimizing logistics operations, and detecting anomalies in real time, while big data analytics and genomic tools further improve accuracy, traceability, and risk assessment across the supply chain [25–27]. Genomic tools complement these innovations by verifying species authenticity and origin, reinforcing protection against fraud and biodiversity loss [28,29]. Together, these technologies foster the development of a more intelligent, adaptive, and resilient traceability infrastructure [30–33]. This study aims to provide a comprehensive assessment of blockchain, particularly in synergy with IoT and AI, in enhancing hygiene, safety, traceability, and sustainability across food systems. It reviews existing implementations, evaluates technological frameworks, and examines analytical models such as Mixed Integer Linear Programming (MILP), Branch and Efficiency (B&E), Simultaneous Data Envelopment Analysis (SDEA), Karush-Kuhn-Tucker (KKT)-based single-level optimization, and the Fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) approach. In addition, it addresses socio-technical and regulatory barriers, while proposing strategies to foster effective digital integration across diverse value chains. By synthesizing current evidence and projecting future trajectories, this paper contributes to the discourse on digital food governance and outlines a framework for next-generation food safety and hygiene solutions.

2. The Synergistic Power of IoT and Blockchain in Modern Food Supply Chains

The convergence of the IoT and blockchain technologies presents a transformative opportunity for enhancing hygiene and safety across the food industry. Functioning

in complementary ways, IoT devices capture continuous real-world data, while blockchain secures, validates, and immutably records this information [14]. In food sectors such as seafood and aquaculture, where hygiene and environmental conditions are critical to safety and quality, IoT sensors monitor variables such as temperature, humidity, and handling practices throughout the product's journey. The resulting data are encrypted and stored on blockchain ledgers, ensuring protection against tampering and thereby safeguarding both data integrity and food safety [21].

Blockchain's decentralized architecture strengthens IoT networks by eliminating single points of failure and ensuring transparent, tamper-resistant traceability. Within this ecosystem, smart contracts automate interactions between devices and stakeholders, streamlining processes while enforcing compliance with hygiene and safety standards [22]. This is particularly critical in seafood cold chains, where even minor temperature fluctuations can lead to spoilage or contamination. Through real-time IoT monitoring supported by immutable blockchain records, deviations are quickly detected and corrective measures are activated without delay [21,22]. From a supply chain management (SCM) perspective, blockchain and IoT together enhance synchronization, accountability, and decision-making. Seafood value chains—which demand close coordination across harvesting, processing, transportation, and retail—are strengthened by continuous monitoring and secure automation [22]. Blockchain adds essential functions such as timestamping, authentication, process coordination, and secure transaction management, forming a foundation for hygienic handling and traceable documentation. These technologies also provide chain-of-custody verification and real-time feedback loops that prevent quality loss and fraudulent activities. By ensuring end-to-end transparency, blockchain not only protects food safety but also fosters greater trust among regulators, consumers, and industry stakeholders [30,34]. In combating food fraud, overfishing, and illegal trade, blockchain creates an immutable digital trail that safeguards both environmental sustainability and public health [12,34].

IoT technologies, including RFID tags, QR codes, and GPS trackers, are now widely deployed to collect detailed data at every node of the food chain—from fishing vessels and farms to processing units and distribution centers [13,14,35]. Auto-ID tools such as RFID and barcode systems assign unique identifiers to products and inputs (e.g., fish stocks, feed, packaging), enabling automated logging and traceability [36,37]. Blockchain integrates these records within decentralized, cloud-accessible ledgers, allowing seamless information sharing and real-time decisions [16,20,38]. These integrated systems support proactive hygiene management and rapid interventions during contamination risks. Built-in feedback mechanisms within blockchain platforms enable continuous improvement, waste reduction, and strengthened consumer protec-

tion [2,39]. Such features are crucial for maintaining cold chain integrity, isolating affected batches, and preventing widespread contamination.

Blockchain-enabled digital transparency empowers consumers by granting direct access to verified product histories through smart devices. Buyers can examine when and how seafood was harvested, processed, stored, and transported, including hygiene-related data such as temperature logs and handling protocols [2]. This fosters informed purchasing decisions and strengthens consumer trust. Beyond this, blockchain can display extended details such as fishing methods, cleaning and packaging processes, and shelf-life information, highlighting its full potential for promoting food hygiene [2,21]. To facilitate the adoption of these technologies, new methodological frameworks have been proposed, integrating supply chain modeling, traceability systems, and blockchain infrastructures specifically for food and aquaculture industries [40,41]. By addressing procurement, production, logistics, and post-market traceability, these models provide comprehensive solutions that ensure food safety from source to consumption [41]. In summary, the convergence of IoT and blockchain establishes the backbone of a new generation of digital food safety and hygiene management systems. These technologies not only enhance traceability and anti-fraud mechanisms but also contribute directly to protecting public health, building consumer trust, and advancing sustainability in global food networks.

3. Mathematical and Analytical Models for Blockchain-IoT Integration

Several innovative approaches and analytical models have been developed to leverage the potential of IoT-integrated blockchain systems.

3.1 Hybrid Blockchain Models for Enhanced Food Supply Chain Transparency

As noted by [7,42], a major advancement is the design of hybrid blockchain models specifically adapted to food supply chains. These models link all stakeholders seamlessly—from raw material suppliers and processors to distributors, retailers, and ultimately end consumers. At their core lies an advanced Access Control (AC) mechanism that combines role-based access control (RBAC) with attribute-based encryption (ABE). Within this framework, two types of nodes are defined: physical nodes (NoE), responsible for on-chain transactions and block creation, and consumer nodes (NoC), dedicated to querying and verifying food safety information. The AC system encrypts portions of transaction data, ensuring that sensitive details remain visible only to the relevant participants. Meanwhile, both NoCs and NoEs retain access to essential product data, thereby strengthening consumer confidence and reinforcing food safety.

3.2 Optimizing Green Supply Chain Management (GSCM) With Blockchain

A significant study [9] classified approaches for integrating blockchain into Green Supply Chain Management (GSCM) and developed related mathematical optimization models. In particular, four distinct MILP models were proposed to minimize the combined costs of physical supply chain operations and blockchain deployment. These models were efficiently solved using the B&E algorithm and the SDEA approach, which incorporates both conventional performance criteria—such as cost and service—and new dimensions introduced by blockchain adoption. The study offers valuable guidance for decision-makers, showing how blockchain can be strategically deployed depending on network design, transparency demands, service levels, and cost considerations.

3.3 Bi-Level Modeling for Sustainable Market Competition

The research presented by [43] introduced a bi-level model to analyze competitive dynamics between traditional and organic producers. This model examined the role of governments, the expansion of international exports, the type of information technology applied in decision-making, and the pursuit of broader sustainability goals. It further compared public versus private blockchain architectures in the organic sector, assessing their effects on transparency, costs, and environmental impacts. The bi-level model was transformed into a single-level model through the KKT approach, and findings demonstrated that balanced environmental, social, and economic outcomes can be achieved through such integrated modeling strategies.

3.4 Sustainable Development Challenges in Developing Countries

The study [29] identified critical barriers faced by developing countries in adopting emerging technologies—particularly blockchain—including weak infrastructure, concerns over data security, interoperability difficulties, and limited awareness and education. The maritime sector was highlighted as facing especially severe challenges in implementing blockchain, IoT, and AI. To address these issues, the researchers applied the Fuzzy DEMATEL method to systematically prioritize the obstacles and propose a roadmap for effective technology adoption in such contexts.

Advanced analytical models are essential for solving socio-technical challenges and unlocking the full transformative potential of integrated IoT-blockchain systems, especially within the food industry.

4. Understanding the Mathematical Core of IoT-Blockchain Integration

This section explores various mathematical models and concepts crucial for integrating the Internet of Things (IoT) with blockchain technologies, focusing on enhancing security, efficiency, and traceability, particularly within the context of food supply chains.

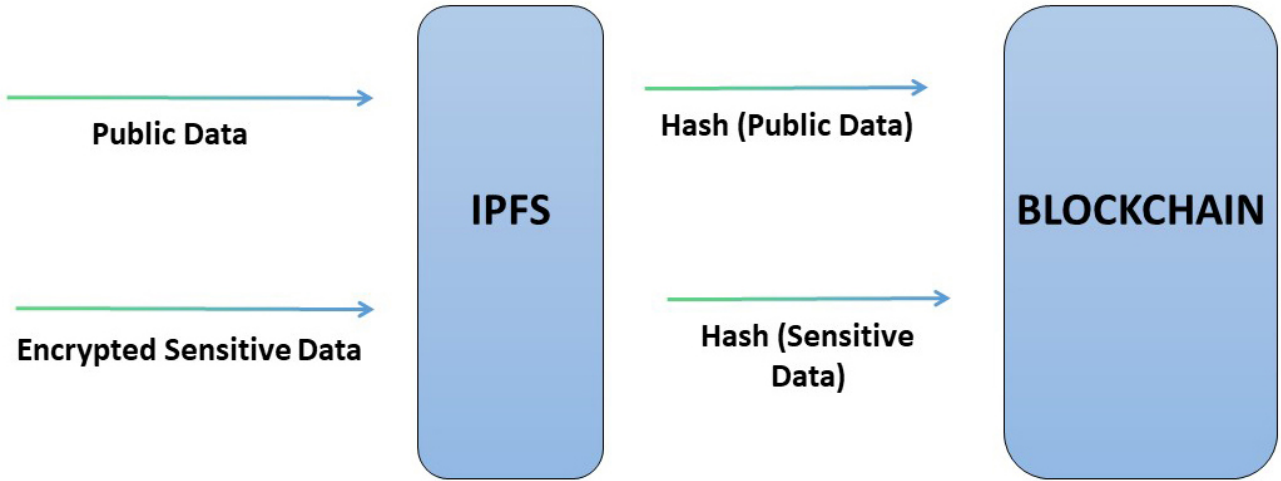


Fig. 1. A hybrid system of blockchain and InterPlanetary File System (IPFS) system for information in agricultural food supply network from [49].

4.1 Hybrid Blockchain Model

The hybrid blockchain model combines characteristics of both private and public blockchains, offering a partially private and partially public structure. This allows for selective transparency: some transactions are restricted to authorized users, while certain data remains publicly accessible. This model provides enhanced control, enabling better achievement of organizational goals. It integrates aspects of centralized and decentralized systems, maintaining core blockchain traits such as transparency, integrity, and security [44,45]. Its flexibility allows for easy participation in private blockchain networks, further bolstering security and transparency [46,47]. This approach is particularly advantageous in enterprise applications, supply chain management, and financial services. Structurally, it operates similarly to standard blockchain systems, with each block comprising relevant data, data from the previous block, and block metadata. Block data typically includes the block hash and account number, while metadata contains the block creation time and signature [45].

A personalized recommendation system based on deep learning under a hybrid blockchain model is given in the following equation.

$$R_{wi} = \sum_{k=1}^K w_k \cdot f_k(u, i)$$

Here, R_{wi} represents the recommendation score of item i for user u , w_k represents the weight coefficients, and $f_k(u, i)$ represents the factors based on user and item characteristics.

The loss function is given as below:

$$L = \sum_{(u,i) \in D} (R_{wi} - \hat{R}_{wi})^2 + \lambda \cdot \|\Theta\|^2$$

Here, D represents the training dataset, \hat{R}_{wi} the predicted score, Θ is the model parameters, and λ is the regularization coefficient. This model can be used to develop a secure and efficient recommendation system in the hybrid blockchain structure [48].

Additionally, [49] developed a tracking system that stores encrypted data on both blockchain and InterPlanetary File System—IPFS (Fig. 1, Ref. [49]) to facilitate information flow and reduce blockchain overhead. Recording agricultural data on IPFS provides the foundation for reliable food supply chains.

4.2 The Access Control (AC) Mechanism

Blockchain-based access control (AC) mechanisms address the vulnerabilities of traditional central authority-managed systems, which are prone to single points of failure. By leveraging decentralized structures, these mechanisms eliminate such weaknesses. They utilize key blockchain components like smart contracts, consensus algorithms, and cryptographic protocols to regulate user and device access to resources. For instance, [50] introduced a scheme based on attribute-based and threshold homomorphic encryption for heterogeneous multi-chain data access control, facilitating fine-grained and secure cross-domain access control in cross-chain networks [51]. This approach is especially vital for securing large and dynamic networks, such as the IoT. Examples include hierarchical blockchain-based multi-chain coded access control models designed to enhance IoT device security. Another study [13] proposed an access control model that effectively controls member

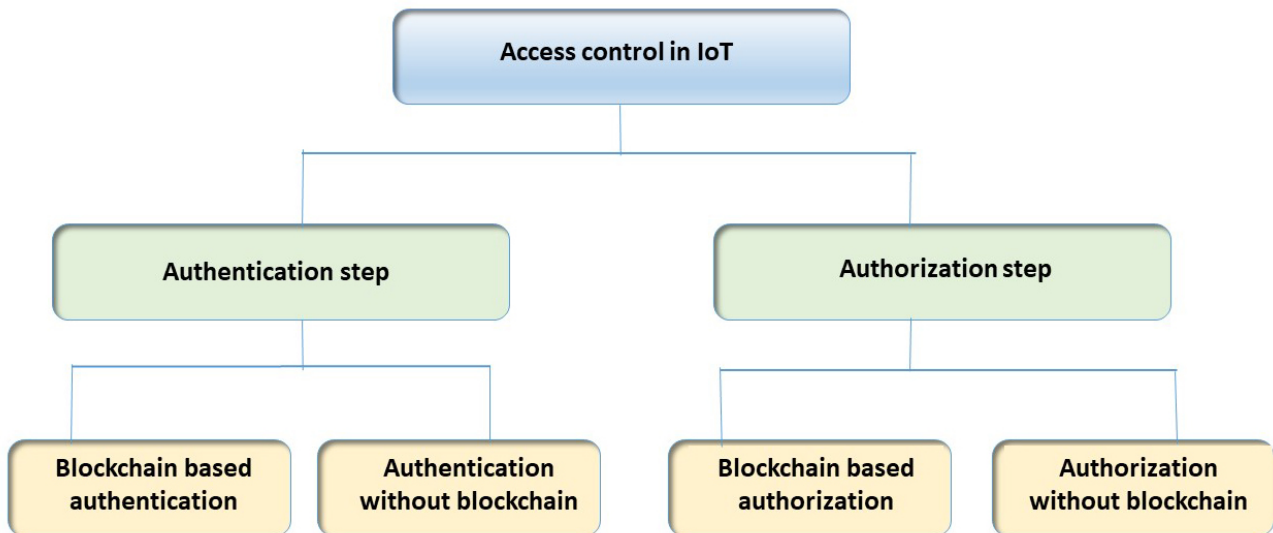


Fig. 2. Access control steps from [53]. IoT, Internet of Things.

access and preserves results continuously by replacing traditional blockchains with a more efficient deployment. Despite their advantages, blockchain-based access control systems face challenges related to scalability, compatibility, and energy efficiency, areas that require further research for broader adoption [52].

Additionally, one study [53] showed in their study that access control techniques go through two different steps, one is authentication and the other is authorization, and that there are solutions using blockchain technology for both cases (Fig. 2, Ref. [53]).

4.3 Role-Based Access Control (RBAC)

The role-based access control (RBAC) model is employed to provide secure and flexible access management within blockchain environments. Blockchain technology, with its decentralized structure and immutable record features, offers effective alternatives to conventional access control mechanisms. In the RBAC model, security policy permissions are assigned to users based on their defined roles within the system [54]. This model is extensively used in the management and operation of information processing resources [55]. Each user, assigned one or more roles, gains specific permissions through these roles, allowing them to perform operations such as page viewing, data reading, writing, or deleting [56].

Risk-based access control models make access decisions dynamically based on risk assessments. In these models, the risk value is usually calculated as follows:

$$Risk(u, o, a) = f(Sensitivity(o), Trust(u), Context(a))$$

Here,

u : User

o : Source

a : Action (e.g., reading, writing)

$Sensitivity(o)$: Sensitivity level of the object

$Trust(u)$: User's confidence level

$Context(a)$: Contextual information of the action by [57].

RBAC consists of three basic modules: risk factor, risk estimation, and access policies. The estimated risk value is then compared with the access policies to decide whether to allow access or not [58].

4.4 Attribute-Based Encryption (ABE) Techniques

Attribute-Based Encryption (ABE) is a robust cryptographic method that ensures fine-grained access control and data security. It enables the enforcement of detailed access policies on encrypted data, particularly beneficial in environments like cloud storage. For example, the integration of ABE and blockchain is utilized in Electronic Health Records (EHR) management to provide secure and authorized access to patient data [59]. However, challenges exist in ABE's blockchain applications, including efficiency and the absence of a direct attribute revocation mechanism. To address these, various solutions like blockchain-based, auditable record ABE systems have been proposed [60]. The integration of ABE techniques into blockchain systems significantly enhances data security and integrity by offering secure and flexible access control mechanisms, which are crucial for protecting sensitive data in cloud and distributed systems.

Below, the basic components and mathematical models of ABE are presented:

1. Setup:

A trusted authority (TA) creates the system parameters:

Public key: PK

Master secret key: MK

This process is expressed as:

$(PK, MK) \leftarrow Setup(\lambda)$

λ is security parameter.

2. *Key Generation (KeyGen):*

The private key is generated according to the user's attributes:

$SK_x \leftarrow KeyGen(MK, A_x)$

Here is the user attribute set.

3. *Encrypt:*

A message is encrypted with a specific access policy or attribute set:

$CT \leftarrow Encrypt(PK, M, \Gamma)$

Here, Γ is the access policy or attribute set.

4. *Decrypt:*

User decrypts encrypted data with his/her private key:

$DT \leftarrow Decrypt(CT, SK_x)$

If the user's attributes meet the policy set during encryption, decryption is successful [61].

4.5 The Physical Node (NoE) and the Consumer Node (NoC)

The rapid advancements in technology and communication networks have led to the widespread adoption of IoT-based applications [62]. IoT enables physical devices to function as components, delivering services to end-users [63]. Within the Access Control Mechanism, which combines ABE techniques and RBAC, two primary node types are defined: the Physical Node (NoE) and the Consumer Node (NoC). Physical Nodes (NoE) are typically IoT devices integrated as endpoints in blockchain networks, responsible for creating on-chain transactions and blocks [64]. These nodes are foundational to IoT systems, performing critical functions such as effective data collection, processing, and transmission across various application areas. They are located at the interface with the physical world, where data is generated and consumed [65]. Conversely, Consumer Nodes (NoC) generally refer to client applications or user devices that interact with blockchain networks to perform transactions. These nodes are primarily used for querying and verifying information, such as food safety data [64].

The following equations can be used to model the flow of data or material between NoE and NoC:

1. *Flow Balance Equation:*

The balance of incoming and outgoing flows for each step:

$$\sum_{j \in N} f_{ji} - \sum_{k \in N} f_{ik} = s_i$$

Here:

f_{ji} : Flow from node j to node i

f_{ik} : Flow from node i to node k

s_i : Resource or consumption amount of node i

This equation states that the net flow at each node is equal to the production or consumption amount of that node.

2. *Capacity Constraint:*

Maximum capacity constraint for each link

$$0 \leq f_{ij} \leq c_{ij}$$

Here:

c_{ij} : The capacity of the link from node i to node j

This constraint ensures that the flow through each link does not exceed the capacity of that link [66].

4.6 Four Mixed Integer Linear Programming (MILP) Models

MILP models are highly relevant in optimizing processes within various industries, including seafood production. For instance, [67] developed a decision model for planning and scheduling in an Indonesian seafood manufacturing company. Due to the perishable nature of seafood, the company needed to coordinate production and distribution with traceability to ensure quality and customer satisfaction. The authors successfully modeled this integrated production-distribution problem as an MILP problem, demonstrating its practical utility in ensuring efficiency and product traceability in the seafood supply chain [67]. Similarly, [68] focused on designing a two-echelon supply chain network for shrimp production, aiming to minimize total costs, including fixed and operational expenses. Their MILP model also determined target markets for producers, optimal input quantities for each company, and the most efficient transportation modes. The MILP base model is defined as follows:

min (or max) cx

$Ax \geq b$

$x \in \mathbb{R}^n, x_j \in \mathbb{Z}$ for $j \in J$

Where c is the coefficient vector of the objective function (e.g., costs), x is the vector of decision variables, A is the constraint matrix, b is the right-hand side values of the constraints, and J is the index set of variables that must take integer values [68].

4.7 Branch and Efficiency (B&E) Algorithm

The B&E algorithm is designed to optimize production and distribution processes, particularly in the food sector, by effectively solving MILP problems through a branching and efficiency-oriented approach. This algorithm aims to reduce production costs, inventory losses, and logistical time delays by decomposing complex optimization problems into smaller subproblems. For example, in a food production line, the B&E algorithm can optimize different fat ratios or flavors of food. In fresh food distribution, it can minimize spoilage losses and reduce the energy consumption of cold chain logistics. The effectiveness of such algorithms in solving large-scale integer opti-

mization problems has been well established in the literature [69]. The B&E algorithm is an approach for solving MILP problems through a combination of strategic branching and efficiency-based node selection.

Nodes with higher efficiency scores are prioritized for branching, enabling faster convergence to optimal or near-optimal solutions [70].

4.8 Simultaneous Data Envelopment Analysis (SDEA) Model

The SDEA model is a methodology developed to concurrently analyze the performance of multiple food production or distribution units. By utilizing input parameters (e.g., raw material cost, labor, energy consumption) and output parameters (e.g., production quantity, product quality, delivery speed), SDEA calculates the relative efficiency of each unit and identifies “best practice” units. In the food sector, this model allows for a comparative analysis of the efficiency of different production lines or distribution networks, thereby optimizing cost-effectiveness and sustainability. For instance, it can evaluate the performance of various yogurt production lines concerning energy consumption and production speed. SDEA’s data-driven approach provides an objective basis for performance evaluation in the food sector [71]. The SDEA model is used to evaluate the efficiencies of multiple Decision-Making Units (DMUs) simultaneously, rather than solving a separate DEA model for each DMU. This model provides a computationally efficient approach for large datasets.

Objective Function:

Minimize the total inefficiency:

$$\text{minimize } \sum d_r \text{ for } r = 1 \text{ to } n$$

Constraints:

The model is subject to the following constraints:

$$\sum v_i * x_{ir} = 1 \text{ for all } r$$

$$\sum u_j * y_{jr} - \sum v_i * x_{ir} = d_r \text{ for all } r$$

$$u_j, v_i \geq \varepsilon > 0 \text{ for all } i, j$$

Definitions:

- x_{ir} : Input i used by DMU r
- y_{jr} : Output j produced by DMU r
- v_i : Weight of input i
- u_j : Weight of output j
- d_r : Inefficiency level of DMU r
- ε : A small positive constant to ensure positive weights [72].

4.9 Bi-Level Model and Single-Level Model Using the Karush-Kuhn-Tucker (KKT) Approach

Bi-level optimization models are well-suited for analyzing hierarchical decision-making processes prevalent in blockchain networks. This model addresses two-stage decision-making processes in any production system. The upper level optimizes system security and transaction fees, while the lower level strives to maximize individual gains [73]. For instance, in a food processing facility, upper-

level management plans overall production and distribution, while lower-level units focus on reducing costs through optimized cutting orders and machine use. Coordinating these levels can improve both unit efficiency and overall factory performance.

The single-level model using the KKT approach simplifies resource allocation in blockchain systems by transforming bi-level optimization problems into a single-level framework. This approach involves analyzing constraints and Lagrange multipliers to balance conflicting objectives, such as energy consumption and network latency in transaction verification processes. The single-level model derived using KKT conditions offers solutions that enhance the operational efficiency of blockchain networks, particularly relevant for hybrid consensus mechanisms [74].

Bi-level Optimization Model:

The general form of a bi-level optimization problem is given as follows:

Upper-level (Leader) Problem:

$$\min_x F(x, y)$$

$$\text{s.t. } G(x, y) \leq 0$$

$$y \in \operatorname{argmin}_y \{ f(x, y) \mid g(x, y) \leq 0 \}$$

Here, the decision variable y is implicitly defined through the solution to a lower-level optimization problem. To reformulate this into a single-level problem, the KKT conditions are applied to the lower-level problem.

Single-level Reformulation using KKT Conditions:

Assuming the lower-level problem is convex, we write its KKT conditions:

Lower-level (Follower) Problem:

$$\min_y f(x, y)$$

$$\text{s.t. } g(x, y) \leq 0$$

KKT Conditions:

$$\nabla_y f(x, y) + \sum \lambda_i \nabla_y g_i(x, y) = 0 \text{ (Stationarity)}$$

$$g_i(x, y) \leq 0 \text{ (Primal feasibility)}$$

$$\lambda_i \geq 0 \text{ (Dual feasibility)}$$

$$\lambda_i * g_i(x, y) = 0 \text{ (Complementary slackness)}$$

Definitions:

- x : Upper-level decision variable
- y : Lower-level decision variable
- $F(x, y)$: Objective function of the upper-level
- $f(x, y)$: Objective function of the lower-level
- $G(x, y), g(x, y)$: Constraint functions
- λ_i : Lagrange multipliers for lower-level constraints

4.10 Fuzzy DEMATEL Technique

The Fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) technique analyzes the cause-and-effect relationships of risk factors (e.g., network security threats, transaction failures) under conditions of uncertainty within blockchain systems. This method, integrated with fuzzy logic, converts complex interactions into a numerical impact matrix, enabling the prioritization of risks. In the context of blockchain, the Fuzzy DEMATEL technique

provides strategic insights for network design and operational decision-making processes [75].

Mamdani, Larsen, and Tsukamoto are the most widely used fuzzy implication functions [76]. Accordingly, in summary:

- Mamdani’s method uses the minimum operator to link input membership levels with the output membership function.
- Larsen’s method employs the algebraic product operator for the same purpose.
- Tsukamoto’s method relates input membership levels to the inverse of the output membership function.

These fuzzy relation operators are detailed in equations, respectively [77,78].

$$Z_i = (\mu_{x_i}(u) \cap \mu_{y_i}(v)) \cap \mu_{z_i}(w) \quad (1)$$

$$Z_i = (\mu_{x_i}(u) \cap \mu_{y_i}(v)) \times \mu_{z_i}(w) \quad (2)$$

$$Z_i = f^{-1} \mu_{z_i}(\alpha_i) = f^{-1} \mu_{z_i}(\mu_{x_i}(u) \cap \mu_{y_i}(v)) \quad (3)$$

Here, μ_X and μ_Y are the input membership functions, μ_Z is the output membership functions, Z is the inference result, and i is the rule order.

Table 1 (Ref. [13,44–47,50,52,54,56,59,60,62–65,67,69,71,73–78]) summarizes the key mathematical and analytical models developed to optimize the integration of IoT technologies with blockchain systems, highlighting their applications in enhancing security, traceability, and operational efficiency.

5. Industrial Use Cases in the Seafood Supply Chain

Seafood is highly perishable, with freshness deteriorating rapidly, which poses significant risks of spoilage and potential health hazards if appropriate protective measures are not implemented [79]. To address these challenges, a variety of innovative packaging and preservation technologies have been developed. Maintaining seafood quality is essential for ensuring food safety and protecting public health [10,11]. The global seafood industry represents a critical and rapidly expanding source of dietary protein. Seafood traceability systems (STS) play a central role in mitigating risks, enhancing brand reputation, building consumer trust, and safeguarding food safety [11]. As a globally traded commodity, seafood supply chains are often complex and involve multiple stakeholders, each with varying levels of traceability. Robust traceability systems capture and transmit essential information regarding catch origins, which is vital for verifying legality and promoting sustainability. End-to-end traceability is increasingly demanded by retailers and consumers alike [10], particularly

in major markets such as Europe and North America, where it is necessary to ensure quality control and seafood safety.

Blockchain technology has been applied in several countries to manage shrimp supply chain quality, covering production and processing stages [80]. These blockchain-based systems allow both consumers and authorities to verify that seafood products are legal, ethical, hygienic, and economically traceable by providing secure access to product histories [81]. Blockchain platforms also facilitate safe digital collaboration among supply chain actors by removing intermediaries, ensuring the integrity of information sharing. For instance, the Tracy project developed a smartphone application that enables fishermen to record and view the history of their catch, including details such as fish species, weight, length, date of capture, and vessel name. The application also allows updates to transaction histories, fishermen’s identities, and quantities of fish to be sold, further enhancing traceability [15]. Some studies propose integrating blockchain with AI to transform future fisheries, emphasizing sustainability, biodiversity preservation, and improved transparency [6]. These approaches aim to create robust, verifiable systems that tackle key challenges in the global fishing industry, supporting responsible resource management and ecological balance. Similarly, [82] presents a conceptual framework for an intelligent blockchain- and IoT-enabled fish supply chain. Their model highlights how IoT devices can collect real-time data on fish condition, location, and handling, while blockchain ensures secure recording and sharing across the supply chain. This integrated approach improves food safety, prevents fraud, and promotes sustainable fishing practices. Further, [15] demonstrates how blockchain can underpin traceability systems to enhance food safety and sustainability throughout the seafood supply chain. By providing immutable records from catch to consumption, blockchain helps prevent food fraud, combats illegal fishing, and enables consumers to make informed decisions based on verified product origins and handling practices. Such verifiable data reinforce consumer trust and safeguard the integrity of seafood supply chains. The cumulative findings emphasize the urgent need for more integrated and advanced traceability solutions to enhance marine resource sustainability and ensure the long-term viability of the seafood industry [83]. Table 2 (Ref. [6,10,11,15,80–83]) summarizes key industrial applications of blockchain technology within the seafood supply chain.

6. Advancing Food Quality and Safety Through Blockchain Technologies

The global seafood industry faces increasing challenges, including contamination, foodborne illnesses, fraud, and climate-related disruptions, which threaten both public health and supply chain security [28]. Traditional traceability systems, often reliant on barcodes and manual documentation, are no longer sufficient to manage the com-

Table 1. Mathematical and analytical models for IoT-integrated blockchain technologies.

| Model/Technique | Application area | Description | References |
|---|---|---|------------|
| Hybrid Blockchain Model | Enterprise systems, supply chains | Combines private and public blockchains; offers flexibility, transparency, and enhanced control. | [44–47] |
| Access Control (AC) Mechanism | IoT, cross-chain networks | Uses smart contracts, cryptography, and decentralization to secure user/device access. | [13,50,52] |
| Role-Based Access Control (RBAC) | Blockchain systems | Assigns permissions based on user roles for secure access. | [54,56] |
| Attribute-Based Encryption (ABE) | Cloud systems, EHR, blockchain | Fine-grained access control with encryption; suitable for sensitive data protection. | [59,60] |
| Physical Node (NoE) & Consumer Node (NoC) | IoT-Blockchain Systems | NoE collects/processes data; NoC verifies and queries transactions, particularly in food traceability. | [62–65] |
| Mixed Integer Linear Programming (MILP) Models (4 types) | Food production, logistics, and menu planning | Mathematical optimization for production sequencing, supply chain, inventory, and nutritional planning. | [67] |
| Branch & Efficiency (B&E) | Food logistics, cold chain optimization | MILP-based subproblem-solving method to minimize costs and losses in food distribution. | [69] |
| Simultaneous DEA (SDEA) | Food unit performance analysis | Efficiency comparison of production/distribution units based on input-output analysis. | [71] |
| Bi-Level Model | Hierarchical decision-making in blockchain networks | Two-tier optimization: top-level (system), bottom-level (individual units), e.g., factory-wide vs. production-line level. | [73] |
| Single-Level Karush-Kuhn-Tucker (KKT) Model | Blockchain resource optimization | Reduces bi-level problems using Lagrangian multipliers to optimize energy, latency, and network parameters. | [74] |
| Fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) Technique | Risk analysis in blockchain networks | Evaluates cause-and-effect relationships of risk factors under uncertainty using fuzzy logic matrices. | [75–78] |

Table 2. Industrial applications of blockchain technology for seafood supply chain.

| Application area | Description | Key benefits/Outcomes | Level of impact/Focus | References |
|-----------------------------------|--|--|-----------------------------|------------|
| Traceability & Origin | Enables transparent tracking of seafood products from their origin (fishing or aquaculture) to the consumer, providing verifiable information about catch methods, processing, and handling. | Increased transparency, enhanced consumer trust, improved supply chain visibility. | End-to-End | [10,11,15] |
| Combating Fraud & Illegal Fishing | Provides immutable records of seafood origin and journey, helping to prevent mislabeling, illegal, unreported, and unregulated (IUU) fishing, and ensuring the legality and sustainability of seafood products. | Reduced instances of fraud, contributed to sustainable fishing practices, and ensured the legality of seafood products. | End-to-End | [6,15,83] |
| Quality Management | Facilitates the monitoring of critical parameters like temperature and handling conditions throughout the supply chain, helping to maintain seafood freshness and quality, and ensuring hygienic practices. | Improved food safety, reduced spoilage, and maintenance of product quality throughout the supply chain. | Specific Stages | [80] |
| Consumer Empowerment | Provides consumers with access to detailed information about the seafood they purchase, including origin, processing methods, sustainability certifications, and potentially even the history of the fishing vessel or aquaculture farm. | Enables informed consumer choices, builds brand loyalty through transparency, and increases consumer confidence. | End-to-End (Consumer Focus) | [10,15] |
| Supply Chain Collaboration | Promotes secure digital collaboration among actors in the seafood supply chain by eliminating intermediaries and providing a shared, trusted platform for data exchange and transactions. | Streamlined processes, reduced reliance on intermediaries, enhanced efficiency, improved trust among stakeholders. | Cross-Chain | [81] |
| Fisher/Aquaculture Empowerment | Applications like the Tracy project allow fishermen to view the history of their catch and exchange information, potentially leading to fairer pricing and increased transparency in their transactions. | Increased transparency for producers, potential for better pricing, improved record-keeping for fishers and aquaculture farmers. | Production/Harvest | [15] |
| Sustainability & Biodiversity | Supports efforts towards sustainable fishing practices and biodiversity preservation by providing a verifiable system for tracking the origin and legality of seafood, as well as potentially monitoring environmental impacts. | Contribution to the long-term viability of marine resources, promotion of responsible resource management, and potential for tracking environmental impact. | End-to-End (Impact Focus) | [6,83] |
| Conceptual Frameworks | Research proposes intelligent blockchain and IoT-enabled frameworks for fish supply chains to enhance overall traceability, transparency, and efficiency, focusing on real-time data collection and secure information sharing. | Provides blueprints for future integrated systems, highlights potential for significant improvements in the seafood supply chain through technology convergence. | End-to-End (Conceptual) | [82] |

plexity of modern seafood supply chains [28]. To address these critical issues, advanced technologies such as AI, ML, IoT, and blockchain are being integrated to transform seafood quality and safety management. AI and ML algorithms analyze large datasets to detect patterns indicative of seafood fraud, while IoT devices monitor the supply chain in real time, ensuring compliance with quality standards. Blockchain provides secure, transparent, and immutable record-keeping, enabling farm-to-table traceability and guaranteeing the authenticity and safety of seafood products [27].

Seafood safety represents a significant public health concern. Blockchain enables precise recording of product origins and movement, helping to prevent fraudulent practices. Consumers benefit from accurate, verifiable information regarding product provenance and delivery routes [84]. Contamination not only endangers public health but also results in financial losses; thus, blockchain's role in preventing contamination is critical for retailers [32].

Product traceability is essential for ensuring safety, quality, and transparency within modern seafood supply chains [85]. Blockchain, as a forward-looking distributed ledger technology, enhances supply chain efficiency by reducing transaction time and cost, increasing traceability, and fostering stakeholder trust [23]. Operating as a decentralized ledger across peer-to-peer devices without a central authority, blockchain securely manages transaction data, provides immutable records, and allows stakeholders to track seafood from catch to consumption, thereby enhancing accountability and combating fraud. However, challenges such as scalability, interoperability, and data accuracy must be addressed to fully leverage the technology [39].

AI further augments fisheries management through predictive analytics, fish stock assessments, intelligent monitoring systems, and ecosystem modeling, enhancing decision-making, resource allocation, and sustainability [26]. Despite hurdles such as data privacy and integration issues, the combination of blockchain and AI promises a transformative impact on seafood supply chain management [26]. Additional challenges include managing comprehensive datasets for traceability and addressing blockchain storage limitations in complex supply chains [25]. Regulatory compliance, standardization, and infrastructure development are also crucial for successful technology adoption [7]. Collaboration among governments, industry actors, and technology providers is essential to realize the full potential of blockchain and IoT in improving seafood safety and supply chain efficiency [86].

Several studies illustrate the application of blockchain in seafood safety and traceability. For instance, [87] examines blockchain's role in enhancing transparency and safety, while [33] highlights its potential to revolutionize supply chain traceability and quality management, addressing shortcomings of traditional methods. IoT-blockchain inte-

grated techniques have been proposed to further strengthen seafood safety [88], and methods leveraging blockchain for enhanced traceability have also been explored [89]. Additional research [35,81] investigates integrated systems combining HACCP, blockchain, and IoT to ensure comprehensive food safety in seafood supply chains. The combination of AI, blockchain, and data analytics enables predictive modeling, anomaly detection, and optimized operations, improving efficiency, risk management, and sustainability across the seafood industry [90]. Overall, the integration of AI, ML, IoT, and blockchain seeks to enhance transparency, safety, and sustainability in seafood supply chains, ultimately delivering high-quality and reliable products to consumers.

7. Conclusion

In summary, the convergence of AI, blockchain, and IoT technologies represents a transformative paradigm for the seafood industry, offering robust solutions to persistent challenges in traceability, food safety, fraud prevention, and sustainability. Blockchain's immutable and transparent ledger provides a foundational framework for trust and verifiable provenance, while IoT delivers real-time, granular data crucial for monitoring environmental conditions and product handling. The strategic integration of AI acts as a catalyst, enabling advanced data analysis, predictive insights, and optimized decision-making across complex supply networks. Despite existing challenges—such as high implementation costs, regulatory uncertainties, and the need for seamless interoperability—the potential benefits are substantial. These include enhanced operational efficiency, strengthened consumer confidence, support for green technologies, reduced energy and analytical costs, minimized human error, and the promotion of sustainable marine ecosystem management. Future research and collaborative initiatives will be essential for realizing the full potential of this integrated technological framework. Key focus areas include the development of standardization protocols, practical pilot implementations, and proactive mitigation of adoption barriers. Real-time monitoring applications accessible via mobile devices, coupled with traceability systems dependent on immediate data, as well as the integration of computer vision and machine learning for instantaneous quality and safety assessment, represent critical avenues for future advancement. Moreover, exploring genomic technologies, smart contracts for automated compliance, predictive analytics for supply chain optimization, improved ecosystem and supply chain management, and decentralized finance solutions offer promising opportunities to enhance resilience, transparency, and value creation within the seafood industry. Collectively, these approaches have the potential to foster a safer, more efficient, and ecologically responsible seafood sector, establishing a future where AI-driven, blockchain-enabled, and IoT-connected systems are standard practice.

Author Contributions

İK: Conceptualization, study design, development of research hypotheses, supervision, review, and editing. BK: Conceptualization, study design, supervision, review, and editing. YG: Conceptualization, study design, supervision, review, and editing. ÇT: Conceptualization, study design, supervision, review, and editing. All authors have contributed to the editorial changes made to the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

AI and AI-Assisted Technologies were also utilized for the editing.

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