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A blockchain-based approach to the challenges of EU's environmental policy compliance in aquaculture: From traceability to fraud prevention

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ABSTRACT

In light of the current global scenario, regulatory requirements, and stakeholder expectations for the aquaculture supply chain are more demanding than ever. The latest EU strategies for aquaculture aim to ensure its economic, environmental, and social long-term sustainability through green, technological, and social transformations. This objective is as ambitious as it is complex, involving not only the enhancement of key sustainability aspects but also the assurance of transparency, trust, and security standards across the entire supply chain. In this context, the present paper proposes a novel blockchain framework, along with the strategic implementation of smart contracts, specifically designed to effectively address the prevalent environmental challenges within the aquaculture supply chain.

1. Introduction

The current global scenario makes environmental regulations and stakeholder expectations for all industries more stringent than ever before, particularly in places such as the European Union (EU). The aquaculture sector is no exception and, following a period of unprecedented growth, it is increasingly concerned about efficiency and long-term sustainability [39].

Guided by a strategic approach, the EU encourages "green transition" aiming to expand the aquaculture sector while upholding economic, environmental, and social sustainability. This way, as detailed in the 'Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021–2030' [14], the green transition objectives are inter-related with those of resilience, technological innovation, and social acceptance. In particular, the EU aims to avoid fraud and ensure full compliance with legislation on environmental control, sustainable feeding practices, circular economy adoption and waste reduction throughout its supply chain.

In addition, EU firms and institutions are also committed with organic and "eco-labelled" aquaculture. The European Green Deal (GD) and its Farm to Fork (F2F) initiative signify a decisive impulse for organic aquaculture as it seeks to transition a quarter of the EU's agricultural area to organic farming by 2030 [18]. Moreover, there is a rising number of voluntary third-party standards that strive to verify to consumers that products have met higher environmental criteria and different indicators of transparency, trust and security across the supply chain [50].

The above implies a strategic and operational change that is as ambitious as it is complex. So far, this has led aquaculture companies to face many challenges in adhering to present regulations without losing competitiveness and has hindered the potential expansion of aquaculture production, placing significant importance on the advancement of improved regulations [63]. Furthermore, the development of a sustainable aquaculture lies in technological innovations, such as vigilant control mechanisms, transparency, and robust data collection. Similarly, there is a need to enhance potential yields as, according to most of the studies, manufacturers will adopt these requirements as long as the balance between additional costs and benefits becomes more favorable [47,64].

In this context, as witnessed in other sectors, blockchain technology, with its decentralized network structure and data immutability, may be the ideal solution to help adopt new policies [33] and, in particular,

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environmental standards [58]. This mainly responds to blockchain's traceability, accountability, transparency, privacy, and security which may establish technology-based trust among supply chain stakeholders. Additionally, it permits real-time data gathering, transparency, accessibility, and visibility, as well as product quality monitoring and management [11]. This technology has the potential to offer the aquaculture supply chains the possibility to adhere to the "green transition", while improving consumer access to information [9]. Nevertheless, several studies find limitations to its widespread use particularly in aquaculture, highlighting the industry's specific needs and the lack of support from technological partners and institutions (Garrard et al., 2020; [28]).

With this in mind, the primary aim of this research is to establish a blockchain architecture that enables producers to align with the requirements of the European Union's primary public policies and voluntary environmental standards, all while upholding their competitiveness. To address this intricate challenge, considering the historical prevalence of technology implementation failures—especially when applied in a non-specialized manner within the aquaculture sector—we adopt an approach involving an initial comprehensive assessment of the manifold regulations, guidelines, and standards. Following this assessment which allows us to identify specific challenges that can be effectively addressed, we concentrate on the seamless integration of blockchain technology, accompanied by the strategic implementation of targeted smart contracts to tackle crucial and well-defined aspects. Our suggestions are beneficial for both businesses and regulatory bodies, demonstrating the efficacy of blockchain-based approaches in facilitating producers' compliance with the most up-to-date environmental policies and standards.

2. EU policies for an environmentally sustainable aquaculture industry: Regulations, guidelines, and voluntary standards

Aquaculture practices are influenced by a wide range of EU legislation, encompassing both overarching and sector-specific regulations, often supplemented by voluntary standards. As a result, the effective implementation of compliance-aiding technologies necessitates a preliminary analysis to identify specific challenges that can be effectively addressed through the implementation of blockchain. In the subsequent sections, this process is delineated, moving progressively from initial and more generic regulations to the most specific aspects.

2.1. Main EU aquaculture regulatory framework

The backbone of the EU fisheries policy is Regulation 1380/20136 on the Common Fisheries Policy (CFP). The CFP explicitly addresses the management and control of fisheries and aquaculture operations within EU seas as well as for EU-registered fishing vessels in external waters. It was first stablished in 1983 through the Council Regulation (EEC) No 170/83 [13]. Its key objectives are to guarantee sustainable exploitation of fisheries resources, to safeguard the marine environment, to encourage responsible fishing practices, and to level the playing field for fishing operations across EU member states [25].

The Common Market Organization (CMO) was the first component of the CFP, created in 1976, which put into place a structural policy for fisheries. The CMO is the EU's strategy for controlling the market for fisheries and aquaculture goods while maintaining their environmental and economic viability. The present rule, Regulation (EU) No 1379/2013 on CMO in fisheries and aquaculture products, is becoming increasingly integrated by tying market concerns with management plans. The current CMO for fisheries and aquaculture establishes a legal framework for producer organizations, marketing standards, consumer information and certification (ecolabels), competition rules, and market intelligence (such as that provided by the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA)). Amongst others, some of its main objectives are to improve the transparency and stability of the markets as well as to offer verifiable and correct information to the consumer about the origin of the product and its way of manufacture, particularly through marking and labeling [24].

The EU has a regulatory system in place to guarantee that the CFP regulations are followed. The systems include Regulation 1224/200910 on Fisheries Control and its implementing rules (404/2011), the Illegal, Unreported, and Unregulated (IUU) Regulation 1005/200811, the European Fisheries Control Agency (EFCA) founding regulation (768/200512), and the Sustainable Management of External Fleet (1006/201713), which is especially important for the CFP's external dimension. Other control mechanisms, such as the transfer of dispositions of Regional Fisheries Management Organizations (RFMOs), multiannual plans, and deep-sea rules, supplement the system.

2.2. New strategic rules for a more sustainable and competitive EU aquaculture

In recent years, various EU policies, notably the Green Deal (GD) and its Farm to Fork (F2F) initiative, have set distinct objectives impacting aquaculture production, such as ensuring sustainable food production, promoting sustainable food processing at all levels, stimulating sustainable food consumption, and addressing concerns regarding food loss and waste [59]. Moreover, numerous aspects that require consideration are embedded within a range of EU legislations – including the EU Environmental Impact Directives [22], the Water Framework Directive [20], the EU Regulation on Animal Health and Welfare [17], and the Marine Strategy Framework Directive [21] – and described in studies aiming at creating a sustainable blue economy that is fair and equitable [14].

As a result of the various measures envisioned within those strategies for creating a sustainable food system, the Commission published the 'Strategic Guidelines for a More Sustainable and Competitive EU Aquaculture for the Period 2021–2030' [15]. This communication, in alignment with the CFP Regulation, emphasizes the requirement for a comprehensive EU aquaculture strategy that ensures long-term sustainability across economic, environmental, and social dimensions. In particular, it outlines four interlinked primary objectives, each further divided into specific challenges: (1) enhancing resilience and competitiveness; (2) driving the green transition; (3) ensuring social acceptance and consumer information provision; and (4) promoting knowledge and innovation. These challenges can be summarized within two overarching areas:

On the one hand, the environmental performance of aquaculture needs to be improved by ensuring full compliance with EU environmental legislation and mitigating key impacts. Based on the communication this should include, at least:

2.2.1. Ensuring sustainable feed practices

Firstly, this communication emphasizes the importance of sustainable feeding practices. This involves using feed ingredients that are environmentally friendly, reducing the use of fish meal and oil taken from wild stocks, and promote animal health. Additionally, it also highlights the need to decrease the use of veterinary products and other related substances.

2.2.2. Reducing the impact on the closest environment

The EU guidelines recommend applying a circular-economy approach, emphasizing fish management, food waste, and energy efficiency. It attaches special importance to the closest environment, including waste management systems and risk plans to reduce effects (emissions, marine litter, escapes, etc.), especially considering their potential harm to local species and ecosystems.

2.2.3. Ensuring Animal Welfare

Further action is needed to improve fish welfare in aquaculture, not only following good practices on fish welfare during farming, transport and killing, but also developing species-specific guidelines and indicators, research on welfare parameters, and providing training on fish welfare to producers.

2.2.4. *Monitoring*

Lastly, it underscored the necessity of guaranteeing effective monitoring of the environmental conditions of aquaculture locations, including aspects like water quality, releases, and the emission of various substances.

On the other hand, it also emphasizes that, while aquaculture already has a significant potential for low environmental impact food production, realizing this potential necessitates multifaceted action and, notably, the support from technological innovation in certain ways:

2.2.5. *Control*

Ensuring long-term sustainability of EU aquaculture relies on effectively controlling products across the entire supply chain, spanning from their harvest to retail transactions, in alignment with the guidelines outlined in the EU Fisheries Control Regulation:

i. Traceability: Traceability requirements are in place to identify the source of aquaculture products. EU regulation aims to expand the scope of traceability obligations, encompassing all aquaculture products including processed items and imports.
ii. Fraud prevention: More precisely, environmental regulation stresses the need to counteract fraudulent activities, such as product replacement, manipulation, stolen items, and redirecting product sales to gray markets.

2.2.6. *Data Collection*

Accurate data collection is crucial for informed aquaculture planning, as well as building stakeholder trust. While current reporting covers socio-economic and animal health aspects, enhanced coordination, structured guidance is needed for data collection and reporting, encompassing environmental indicators and broader aquaculture production. Ensuring data quality and storage can be achieved via traceability technologies and on-farm sensors. Regulation 2017/10048 governs fishing and aquaculture data collection, establishing an EU framework for using fisheries data in scientific processes [23].

2.2.7. *Knowledge, transparency and social perception*

A shift in societal attitudes and market demands towards environmentally sustainable aquaculture is pivotal. Transparency, product information, certification schemes, and consumer campaigns empower the public to make informed choices. This aligns with the promotion of organic aquaculture.

2.3. *Additional rules for organic and "eco-labelled" aquaculture products*

The EU institutions, as well as an increasing number of companies, are opting for organic aquaculture or adopting specific standards that extend (and certify) their environmentally responsible behavior.

2.3.1. *Organic aquaculture regulation*

Regarding the regulation for organic sectors, all aquaculture products marketed as "organic" in the EU must adhere to the regulation (EU) 2018/848 of the European Parliament and of the Council [19]. As reviewed by Busacca and Lembo [8], the specific requirements for organic aquaculture can be summarized as follows: sustainable fisheries utilization, animal health via natural defenses, high animal welfare standards, selection of resilient breeds, prohibition of polypoid animals, preservation of biodiversity and aquatic environments, and sustainable feeding practices. These requirements emphasize responsible resource use, animal well-being, breed selection, environmental conservation, and the use of sustainable feeds in organic aquaculture operations.

In addition to these specific principles, the EU has established a control system for organic food and feed production. This system ensures that operators in the supply chain (such as farmers, processors, traders, and importers) adhere to organic production rules. The control authority/body is responsible for conducting physical inspections of organic operators, with at least one inspection per year. The frequency of inspections can be increased based on risk assessments. Following this regulation, controls should be made to ensure traceability at all stages, such as: (i) checks of documentary accounts and (ii) controls performed on specific categories of operators.

For instance, any product placed on the market as an organic product after being imported into the EU under any of the import procedures provided for in the Regulation shall be subject to the availability of the information required to guarantee the product's traceability along the food chain (article 98, Regulation 2018/848).

2.3.2. *Third-party standards*

Regarding third-party standards, they can potentially cover both, on-farm and off-farm processes, encompassing aquaculture performance metrics and supply chain member adherence.

2.3.2.1. Standards addressing both processes. Some certifying bodies manage both on-farm and off-farm agent certification, offering either two standards or distinct standards for each stage of the supply chain. A well-known example is the Aquaculture Stewardship Council (ASC), a certification scheme and a label that appears on fish products from farms and intermediaries that have been independently evaluated by an impartial organization. The ASC defines two different types of certification standards depending on the stage of the supply chain: (i) the production or farm standards, which presents several separate farm standards with robust environmental and social requirements, covering different species; and (ii) the CoC standard, which is a traceability and segregation standard that is applicable to the full supply chain from a certified farm to the product carrying the ASC logo [3]. This way they not only ensure that certified products come from an ASC-certified farm but also fish volumes are distinguishable and adequately managed [39].

Conversely, the Best Aquaculture Practices (BAP) [5] ensures a responsible behavior in all the various stages of the production chain with different standards. It identifies different components as the pillars for responsible aquaculture, including environmental responsibility, social responsibility, food safety, animal welfare, and traceability, for production on farms and hatcheries alike [51]. This way, BAP gives an emblem to several farmed seafood items across the world to disseminate the accomplishment of their requirements and offers a series of marketing tools for certified products.

2.3.2.2. Standards oriented to specific stages of the supply chain. Other certification bodies have developed more precise standards for the various stages of the manufacturing process, specializing on certain processes such as organic feeding or healthy production.

One of the most relevant organizations is the Global Good Agricultural Practice (GAP), an attempt to establish a generic standard capable of fitting to the whole range of global conventional agricultural products, offering 16 standards in three different categories: crops, livestock, and aquaculture [29]. Similarly, other important organizations are Friend of the Sea (FoS), a prominent international certification scheme for sustainable fisheries and aquaculture goods, and Naturland, designed to serve as a consumer guide for several species and production techniques.

Finally, in terms of health-specific criteria, some organizations might be highlighted based on their primary goals, such as antibiotic-free production -i.e. Antibiotic-free certification [4], non-genetically modified production (Non-GMO) [30], or cold chain safety (ISO 23412, JSA-S1004).

3. Blockchain Methodology

Due to its complexity and failure rate, the correct implementation of new technologies has been extensively researched, with the conclusion that efficient deployment requires commencing with building the conceptual framework and understanding the technical aspects of implementation [44]. Publications, such as Labazova [37] or Koteska et al. [36], emphasized how blockchain technology application in any industry necessitates starting with a proper study of the most appropriate architecture and implementation processes, to further test it on specific use cases. Other studies have reviewed its deployment in the food supply chain, emphasizing the creation of such procedures [57].

3.1. Distributed shared ledger

Blockchain follows a distributed ledger data structure that is duplicated and shared amongst network users. Nakamoto [42] first developed this technology to overcome the problem of double spending when using the cryptocurrency Bitcoin. The blockchain keeps the official record of transactions that reveals who owns what as a result of how nodes on the network (miners) add confirmed, universally agreed-upon transactions to the system [2]. Each block within the chain is uniquely identified through a cryptographic hash.[3] It also contains a reference to the hash of the block immediately preceding it, creating a link between all blocks of the chain. Every node having access to this organized, back-linked list of blocks may read it and determine the current global state of the data being transmitted on the network. This is done through the use of public or private keys.[4]

There are two main types of blockchain, private (permissioned) and public (permissionless). The former requires certain permissions to access the ledger. They are tightly controlled by their owners, which may be advantageous in some cases. The latter requires no need for authorization to view the ledger. Any user can connect to the network, having access to all transactions, which are visible and available to all blockchain participants [27].

This system promotes technology-based trust among partners, supply chain openness, and visibility, allowing for easier execution of government regulations and policies. Thus, the blockchain should capture all transactional data and provide tailored access to supply chain participants while being auditable and verifiable [10]. Blockchain also contributes to improving traceability by providing a data trail along the whole supply chain while preserving and protecting data. It also enables product quality monitoring and management, as well as the collection of real-time data and the promotion of transparency, accessibility, and visibility [38,43].

In this way, it is essential to firstly examine blockchain operationalization and establish the most appropriate design for the situation at hand to construct the blockchain-based architecture. In addition, data confidentiality is an important consideration that should be addressed prior to adoption. A blockchain system must allow both internal corporate transactions and cross-enterprise transactions in order to deploy distributed applications across varied collaborating groups, and each partner must collaborate to manage its flow and safeguard proprietary information [32]. In this regard, it is critical to collect and share only necessary data to fulfill the requirements of local regulations and certifying agencies. Afterwards, technology can be applied to specific use cases in order to solve the most crucial challenges.

3.2. Smart Contracts

Within the blockchain, smart contracts are often used to establish commitments and trust limits between contributing parties. A smart contract (Fig. 1), in its most basic form, is a program within a blockchain network that can run automatically when specific circumstances are satisfied without the need for an authorized third party to interfere [52]. Traditional supply chains depend on centralized systems, which results in data loss, data manipulation, and security threats. Unlike conventional contracts which rely on human procedures, blockchain-based smart contracts have multiple advantages. Their automated nature saves money, time, labor as well as improving speed, traceability and transparency while reducing the potential of mistakes or fraud. This built-in automation also improves security by reducing possible breaches [56,61]. In addition, these contracts establish accountability for each person participating in the transaction, guaranteeing that their duties are met and, as a result, that the contract is executed [45].

Smart contracts might also be used to accelerate document processing and free up trade finance on the basis of preconditions [34]. This structure enables each party in the supply chain to fulfill their separate responsibilities for assuring the legality and traceability of, for instance, seafood. The system built on blockchain would be "owned" by all participants, not just one. From a technological standpoint, this means that each agent will be able to establish a node to this system in their territory (i.e. country) and operate as a validator. Each participant will be granted appropriate rights in the system, and the data will be protected by the inherent security of blockchains [32,53]. To guarantee that all information is captured on the blockchain, such a system may interface with any national seafood traceability system. By establishing a uniform digital platform for regulatory bodies to evaluate the data about the seafood and verify any legal papers accompanying it, this paperless procedure would save costs and speed up trade operations [6].

An initial review of the common challenges in aquaculture supply chains that could be addressed by blockchain technology indicates a number of unique characteristics [33], among which stand out transparency, trust, information associated to product origin, and food safety assurance [49,7], which could be all addressed by the introduction of smart contracts.

4. Blockchain-based framework for the aquaculture supply chain

As emphasized by the frequently referenced EU communication [14], technological innovation emerges as a pivotal factor in attaining the sought-after environmental transformation. The objective of this section is to implement a blockchain-based framework for the aquaculture supply chain, culminating in a substantial contribution to the transformative process of this chain.

While it's evident that a comprehensive shift to sustainable aquaculture hinges on numerous factors beyond the scope of blockchain technology, as demonstrated below, several crucial aspects, from *Section 2* , have been effectively tackled. The presented blockchain-based framework consists, in the first place, in a technological transformation at the organizational level. This way, blockchain technology would allow aquaculture firms to potentially handle almost every issue relating to the traceability of aquaculture products and, in conjunction with other technologies, to control the right adherence to ecological norms [62]. Secondly, the consequent implementation of controls at an operational level, based on the ability to write and execute smart contracts on an ad hoc and task-specific basis, allows to go beyond these criteria and integrate additional controls, such as fraud protection steps [2].

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[3] A cryptographic hash function is an equation that is used to validate data. It has several uses, most notably in information security (for example, user authentication). It converts variable-length data (the message) into a fixed-length numerical string (the hash).

[4] Two users can utilize public key systems to establish a secure connection and exchange information securely across a public network using public procedures. The sender would send a message that was encrypted using the receiver's public enciphering key (public key). The recipient would use its own secret decoding key (private key) to decipher the message (Diffie et al., 1976).

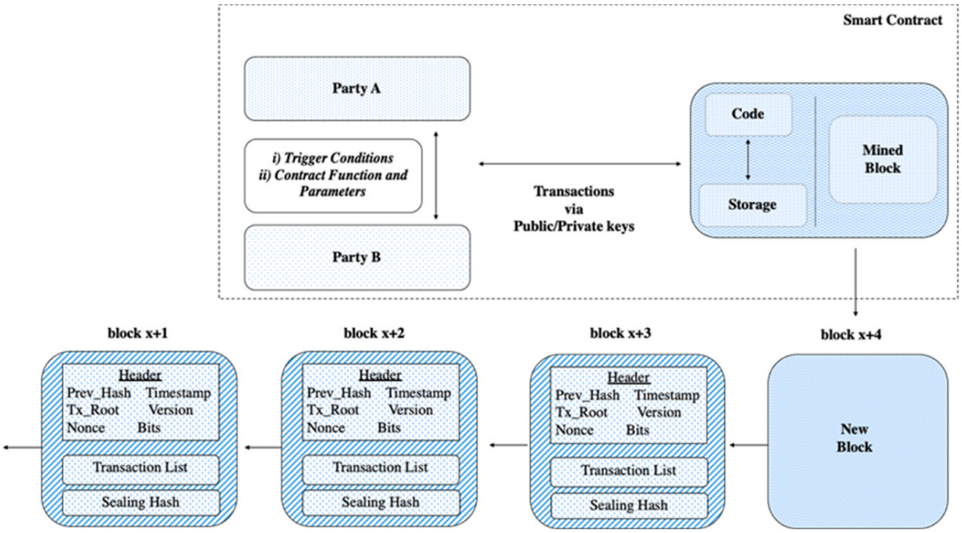

Fig. 1. Steps involved in the creation of a new block using smart contracts.

4.1. *Organizational level*

This section addresses the implementation of a blockchain network for the aquaculture supply chain through the use of layers, which create customized accessibility of transactional data, and ways of accessing the blockchain network through the use of an interface.

From the perspective of the interrelation between the technology and the green transformation objectives mentioned in section two, this technology enables the control and traceability of specific aspects, ranging from feeding practices or environmental monitoring on the farms, to animal welfare throughout the supply chain. Furthermore, since blockchain provides secure, reliable, and transparent access to this information, it would also contribute to enhancing the aspect of social perception, bolstering the society's confidence in sustainable aquaculture practices.

4.1.1. *Layer system*

The aquaculture supply chain is frequently a global network with several levels and operations. Supply chain partners are frequently located on a worldwide scale, and the path from the breeding stages to the ultimate customer can be lengthy. Due to the supply chain's complex structure and extensive geographical distribution, firms usually struggle to manage the supply chain's sustainability risk, having difficulties to maintain track of all related suppliers, contractors and sub-suppliers [46].

The aquaculture food supply chain system is comprised of numerous layers of transactions, each with its own set of rules and regulations. Food production, distribution, preservation, and wholesalers all operate within a supply chain with distinct characteristics and functions (Fig. 2). All these layers track all things from manufacture to packaging, shipping to warehousing, and delivery, which are all time-consuming and difficult processes. Smart contracts can aid in streamlining the process and increasing transparency across the supply chain [6]. Combining blockchain-based smart contracts, for instance, with Internet of Things (IoT) devices enables commodity monitoring, inventory management, and changes in ownership rights across the supply chain. Businesses can then be completely prepared for any disruptions or mishaps. Furthermore, smart contracts enable companies and customers to assess food quality by tracing all data (Kamble et al., 2020).

The proposed approach is based on a multilayer system (Fig. 2) to trace the eco-certified products throughout the entire supply chain.

i. Physical layer: Comprises products from the different agents throughout the entire supply chain.
ii. Digital layer: Any data linked with a physical item that is important to the traceability process is included. Data might be simple (i.e. location) or complex (i.e. documents). They can be recorded by both human and non-human actors, such as sensors.
iii. Blockchain layer: It is the blockchain platform that is utilized to preserve each digital traceable data.

4.1.2. *Access Control List*

Access to the system must be evaluated to guarantee compliance with certifying bodies' policies and actions. To prevent a centralized decision-making authority from gaining control, a group of trustworthy and independent external entities form a consortium that allows the formulation of an agreement that includes information about valid players as well as rules to be followed internally along the supply chain. An access control list (ACL) will be extracted from this manual and delivered to an entity recognized as trustworthy by the entire consortium, granting write access privileges to the system that relies on ACL and limiting a single involved entity's dominant position in the decision-making procedure.

The Ethereum blockchain network has been used for this purpose, as it is the biggest network allowing the use of smart contracts. In this network, there is a gas fee for every type of transaction. The key constraint of our present study is that the cost of the traceability system will drastically increase if the price of Ethereum rises to very high levels. Based on these factors, this proposed traceability system may be combined with emerging technology, such Radio-frequency identification (RFID), IoT, Wireless Sensor Networks (WSN), Global Positioning System (GPS) or Artificial Intelligence (AI), to increase its thoroughness and effectiveness. These technologies combined together would improve certification and control procedures for all standards.

4.1.3. *Software interface*

Ultimately, this architecture enables the creation of a user-friendly software interface, such as a dApp[5] (decentralized application), to send requests to the blockchain. Whereas the smart contract is written in a specific programming language (i.e. Solidity) and sent to the blockchain, the dApp with which the user interacts may be developed in any number of current web programming languages (i.e. React) and distributed via conventional web servers. Each partner may also develop blockchain applications on multiple devices with varying access

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[5] Digital applications (dApps) are applications or programs that operate on a network rather than a single computer or server.

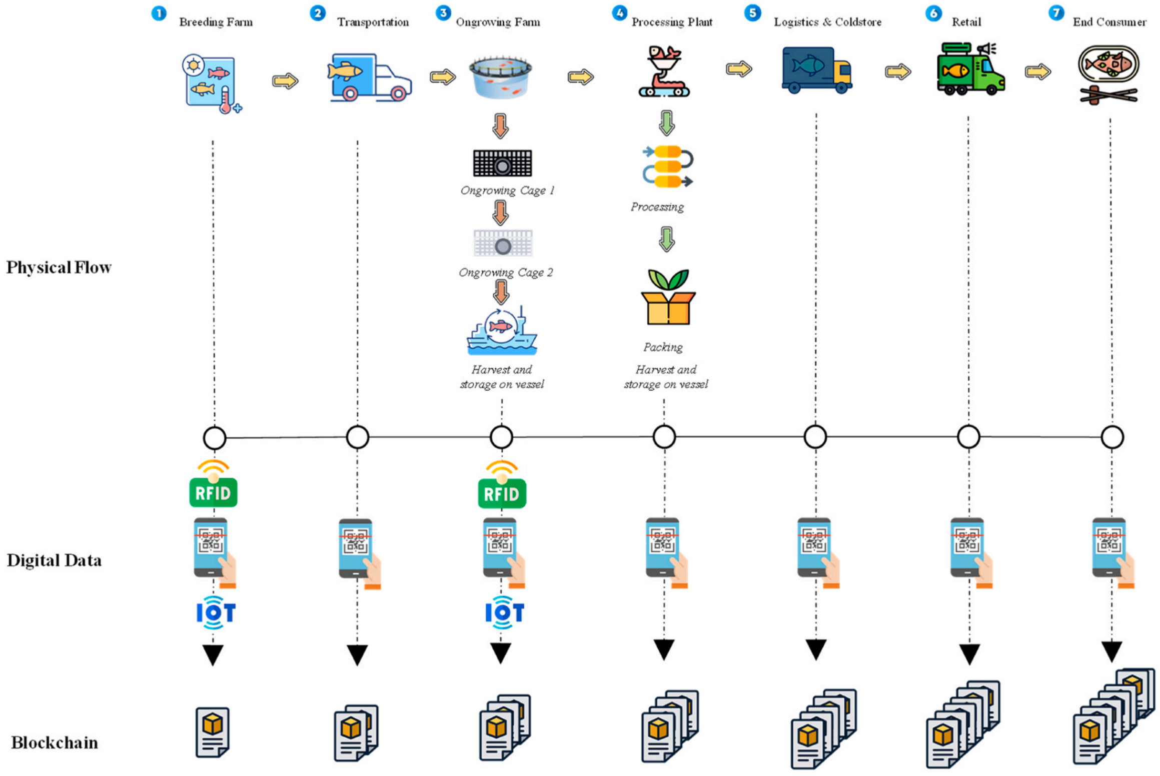


Fig. 2. Proposed approach for the integration of blockchain technology in the aquaculture supply chain, from breeding farms to final consumers, through the use of digital technologies.

limitations. A channel, for example, can be directly linked to a QR-code reader in order to post, tag, and scan timestamps and locations. Customers can also obtain limited amounts of data on product trade using a different application connected to the same blockchain. A snapshot from the web interface is shown in Fig. 3. It shows all the transactions that occurred in the example scenario along with the timestamp.

4.2. Operational Controls

This section describes the utilization of smart contracts and blockchain transaction validation mechanisms, implemented for detailed aspects of the supply chain traceability applications. Specifically, the use of smart contracts allows for specific controls, either by involving routine or exceptional aspects. In this case, the primary focus addressed is food fraud, defined as the substitution or manipulation of sustainably produced goods with lower-priced alternatives. Similarly, it could be employed for other purposes, such as setting up automatic alerts for violations of animal welfare or environmental standards. This approach thus tackles the EU's concern of ensuring full and genuine compliance with EU legislation.

4.2.1. Smart Contracts

One of the main concerns expressed on EU communications is to ensure full and real compliance with EU legislation which is also important for third-party standards and the society as a whole. In particular, environmentally sustainable and “eco-labelled” aquaculture products should guarantee that has not been fraud in any step of the supply chain.

In the present case, aiming at preventing fraud, a focus has been placed on minimizing the entrance of non-certified commodities into the supply chain. Other additional indicators, such as the usage of antibiotics or different aspects of human health, can also, be tracked.

As a result, a smart contract has been created to verify and audit each transaction involving a certified product before it is carried out. The representation of this smart contract in pseudo-code may be divided into three modules (Fig. 4):

1. The first module, which is equivalent to the function "add company," restricts the ability to declare blockchain addresses as certified firms to the certifying company (in this case, the owner of the smart contract). This keeps the smart contract secure and allows to introduce a requirement in the following functions to guarantee that the products come from a certified company. This constraint is only applicable in this example to the batch formation and batch weight addition operations, which are covered in the next module.
2. The second module consists of the "create batch" and "add weight" methods. It is created to prevent fraud using the certified product. In order accomplish this, the concept of mass balance is presented. Only certified farms are granted access, limiting the introduction of new batches and, consequently, new product amounts. This follows a methodology proposed in several articles, such as Agrawal et al. [2], and widely used in practice, which assumes that mass cannot appear in the intermediate stages of the system, only in the production process. Thus, the total weight of fish that has left the certified farm is recorded and plotted to track the mass transferred along the supply chain. The fish mass entering and leaving is accounted for along with the current mass accumulated in the system (Input = Output + Accumulation), tracking or invalidating any transaction that recodes the mass flow allowing to identify any duplicate transfer of the same quantity [60].
3. Lastly, to guarantee batch traceability, the function "transfer" monitors the verification of correct compliance with all of the above-mentioned elements and documents all transaction information. It works in a simple manner, having each batch a range of blockchain addresses. This array displays each batch's ownership history for each business that had custody of a certain batch. When a batch is transferred from one person to another, its owner specifies with this transaction which business will handle it, saving it in the array. The

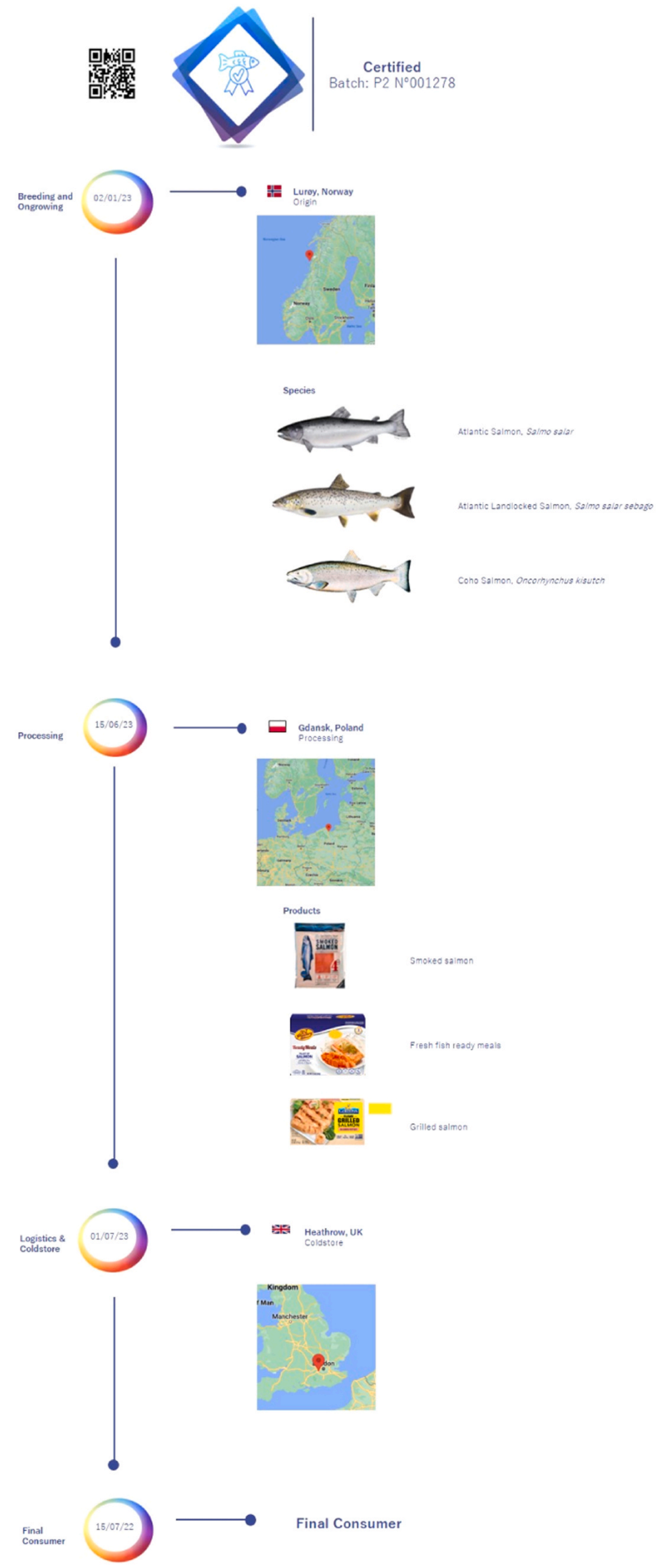
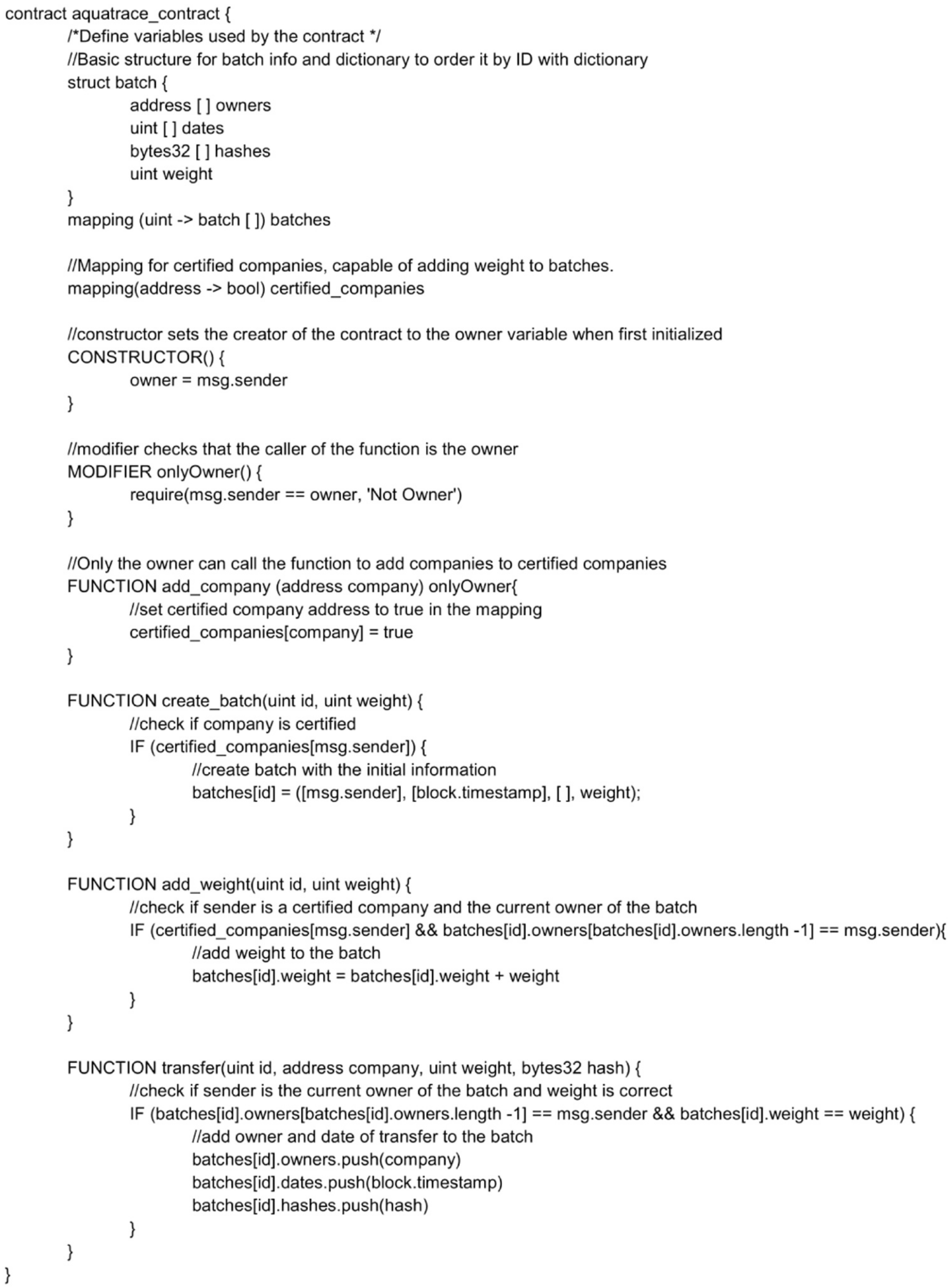


Fig. 3. Mockup of a web-based interface displayed to final customer using a QR code.



```
contract aquatrace_contract {
    /*Define variables used by the contract */
    //Basic structure for batch info and dictionary to order it by ID with dictionary
    struct batch {
        address [ ] owners
        uint [ ] dates
        bytes32 [ ] hashes
        uint weight
    }
    mapping (uint -> batch [ ]) batches

    //Mapping for certified companies, capable of adding weight to batches.
    mapping(address -> bool) certified_companies

    //constructor sets the creator of the contract to the owner variable when first initialized
    CONSTRUCTOR() {
        owner = msg.sender
    }

    //modifier checks that the caller of the function is the owner
    MODIFIER onlyOwner() {
        require(msg.sender == owner, 'Not Owner')
    }

    //Only the owner can call the function to add companies to certified companies
    FUNCTION add_company (address company) onlyOwner{
        //set certified company address to true in the mapping
        certified_companies[company] = true
    }

    FUNCTION create_batch(uint id, uint weight) {
        //check if company is certified
        IF (certified_companies[msg.sender]) {
            //create batch with the initial information
            batches[id] = ([msg.sender], [block.timestamp], [ ], weight);
        }
    }

    FUNCTION add_weight(uint id, uint weight) {
        //check if sender is a certified company and the current owner of the batch
        IF (certified_companies[msg.sender] && batches[id].owners[batches[id].owners.length -1] == msg.sender){
            //add weight to the batch
            batches[id].weight = batches[id].weight + weight
        }
    }

    FUNCTION transfer(uint id, address company, uint weight, bytes32 hash) {
        //check if sender is the current owner of the batch and weight is correct
        IF (batches[id].owners[batches[id].owners.length -1] == msg.sender && batches[id].weight == weight) {
            //add owner and date of transfer to the batch
            batches[id].owners.push(company)
            batches[id].dates.push(block.timestamp)
            batches[id].hashes.push(hash)
        }
    }
}
```

Fig. 4. This figure illustrates the pseudo-code used to implement the proposed smart contract.

ownership exchange times used to create the batch's "timeline" are represented as a parallel array of timestamps. Additionally, the owner must indicate the batch's weight to ensure that it hasn't changed since the time of the transaction. Finally, the presence of a hash shows that a company has the choice to transmit a document to the entity that certifies documents. This document could include information on antibiotic usage or a health analysis. The user application can display this document—or a condensed version of its information—while maintaining its authenticity by keeping the document's hash.

Every time one of the previous operations are carried out, a new block is created on the blockchain to record the transaction. This updates the batch's information by modifying the data that is contained in the smart contract's state. A rise in reported mass may only be seen in the early stages, during the raising and fattening periods. Further down the supply chain, the merchant or customer may access the smart contract's state to follow all previous blockchain operations that confirm the legitimacy of the eco-certified items purchased. This would enable secure supply chain tracking through technology-based trust.

The costs at the operational level within the Ethereum network can be broken down into two main parts. On the one hand, the deployment costs of the contract/contract must be considered and, on the other hand, the operations within the smart contract that require an alteration in the state of the blockchain. According to the estimated number of functions, the contract will cost around 700k units of gas, which, depending on the price at the time of deployment and other factors like network congestion and the conversion from ether to traditional

Table 1
Gas and euro amount per function in Ethereum.

Function	Gas amount	Amount in Euros[a]
AddCompany	55,000	€1.54
CreateBatch	160,000	€4.48
AddWeight	40,000	€1.12
Transfer	40,000	€1.12
Contract deployment	700,000	€19.60

[a] Prices as of 7th December 2022.

currency, may mean a higher or lower cost in traditional monetary units (Table 1).

In today's prices, the high price of Ether[6] makes Ethereum transactions exceedingly expensive. It should be stressed for this reason that after switching to a Proof of Stake (PoS) method, Ethereum will have lower transaction costs, with sharing technology deployment bringing more gains in the future. Currently, it is encouraged to operate these traceability applications either in combination with backup storage or in less expensive networks, such as those based on the EOS.IO protocol. With an approximate cost of 0.5€ for contract storage and less than 0.01 € for all the information in a batch, this third-generation network can run a traceability application like the one described in this paper.

5. Discussion

The successful blockchain implementation offers numerous benefits for aquaculture firms, consumers, and society. However, challenges arise, primarily due to its technological nature. After analyzing industry regulations, needs, and blockchain's potential to address key challenges, a critical consideration involves weighing potential benefits against associated costs, as well as assessing the industry's capacity to implement these solutions.

On the positive side, blockchain allows aquaculture companies in the EU to better meet the mandatory and voluntary environmental requirements, without losing efficiency, profitability, and global competitiveness. This is one of the main concerns expressed by the EU institutions in the latest communications [14]. Objectively quantifying the benefits of each of the two levels of the proposed blockchain framework is particularly difficult, but some of them can be listed and assessed based on external sources:

1. At the organizational level, the framework outlines the establishment of a blockchain network for supply chains, focusing on traceability, data accessibility and network interaction. It facilitates *control and traceability* across various aspects, ranging from feeding practices or environmental monitoring on the farms, to animal welfare throughout the supply chain, improving compliance and social trust in sustainable aquaculture practices.

   According to the World Health Organization (WHO), each year about 600 million people fall ill due to contaminated food, causing 420,000 deaths and a loss of 33 million healthy life years. In this line, several publications have shown that blockchain technology can trace, identify, and categorize products in supply chains, and immediately identify food contamination risks to aid in product recalls [54]. A secure food supply not only contributes to food and nutrition security, but it also promotes national economies, trade, and tourism, therefore supporting sustainable development. Furthermore, the European Parliament [26], has consistently highlight the need for the required due diligence steps to guarantee that the whole seafood sector supply chain is fair and completely traceable.

   In relation to food loss and waste, Food and Agriculture Organization's [7] show that 14% of the world's food is lost after harvesting and before reaching the stores, while the United Nation, in UNEP (2021), shows that an additional 17% is wasted in retail and by consumers. Blockchain could help tackle this issue through an increase real-time communication, control and data visibility along the supply chain [33].
2. On the operational front, the utilization of smart contracts and blockchain validation mechanisms enables specific controls and improved traceability. In this case, smart contracts are used to address fraud prevention, and could be extended to automated alerts for animal welfare and environmental violations, aligning with the EU's regulatory objectives.

As Manogaran et al. [40] states, blockchain technology can help to avoid food fraud by securely documenting transactions between participants in a verifiable and permanent manner, making it extremely difficult to hack the system (Manogaran el al., 2021). In aquaculture, the EU highlight specific frauds, such as product replacement or manipulation, that can reduce confidence in sustainable aquaculture and "eco-labels". This could tackle this problem as address the need for reducing the information gap between consumers and producers [41] as the labels will be effective only if they are believable [12].

On the contrary, there are still hurdles and limitations that prevent blockchain widespread use in aquaculture. Technological development of the industry in each geography has proven to be a constraint, since some companies are highly digitalized, whereas others still use paper records (Garrard et al., 2020). Also, some firms have a low understanding of how traceability systems can improve farm management processes and might be reluctant to invest in blockchain [28]. In this regard, Abderahman [1] suggest that the high need for technological infrastructures and understanding in the aquaculture farms applying blockchain requires the participation of technological partners and institutions supporting farm in this process. In addition, the expense of constructing and maintaining blockchains is another big concern, but transaction or maintenance fees, or other forms of payment like as tokens (i.e., FarmShare), might be used to fund these blockchains [35].

6. Conclusions

The development of a sustainable aquaculture has been a key objective of the European union through the last decades. As early as the CFP was developed, the sustainability of the aquaculture industry was already considered critical in the short and long term. From then on, both the EU and the member states have developed several aquaculture regulations and guidelines aimed at promoting sustainable practices, ensuring environmental protection, and increasing the competitiveness of the aquaculture business. Building on this foundation and in alignment with the GD and F2F strategy, the European Commission released a communication [14] that emphasizes the requirement for a coordinated EU strategy, outlining specific inter-related objectives between the green transition and the technological innovation and competitiveness.

In this context, the future of aquaculture supply chain depends not only on the compliance of the environmentally sustainable production requirements, but also in ensuring that minimum transparency, trust, and security standards are met throughout the whole supply chain. All those lead to the conclusion that blockchain should play a significant role [48]. Not only studies, but also certifying companies [3,29] and FAO have already expressed interest in blockchain's potential application for fulfilling CoC requirements, preventing the mixing of certified and uncertified fish [7].

This study provides a blockchain architecture that, through the use of specific smart contracts, allows producers to improve their compliance with the aforementioned requirements while maintaining efficiency, profitability and global competitiveness. Furthermore, this study builds on the usage of blockchain technology beyond its most well-known use

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[6] The cryptocurrency known as Ether (ETH) was created in line with the Ethereum protocol as a payment to miners for adding blocks to the network.

in the supply chain, addressing other existing problems in organic aquaculture, using fraud prevention as an example. Lastly, this study demonstrates how the capability to trace a product throughout the entire supply chain and present such information reliably and securely to stakeholders is another advantage of this technology that aligns with the EU's "social perception" objectives.

6.1. Policy implications and future research

The present study contributes to the body of knowledge on blockchain technology in the field of environmental policy compliance not only from a theoretical perspective, but also from a practical angle. The depth of blockchain applications covered in this study is mostly focused on their use in industrialized countries and within the domain of large-scale organizations. This emphasis is largely due to the high implementation costs and technological readiness required by the players involved.

One of the main conclusions drawn from this paper is the need for regulators, technologists, scientists, and industry professionals to work together to achieve real progress in terms of efficiency and sustainability. To build efficient regulatory frameworks, the complicated structure of international supply chains needs a rigorous demarcation of duties between national governments and multinational businesses (Khanna, 2020). By doing so, the whole aquaculture supply chain will benefit from the characteristics of blockchain technology in making it a more secure, transparent and efficient chain as previously discussed.

Regarding the aquaculture supply chain in the green transition, the development of increasingly advanced policies for the aquaculture industry must go hand in hand with technological development, otherwise they will be limited both in their design and implementation (Garrard et al., 2020). By enabling policy development and the setting of more defined objectives, information and communication technologies have the potential to improve policy efficiency and efficacy [55]. As a result, working on the creation and analysis of digital agricultural policies should concentrate on dissecting policy into its individual specifications and demonstrating how digital technology may assist each of them [16]. Legislative strategies should prioritize consumer safeguards while educating the public about blockchain's potential, paralleling the approach taken in the United States [31].

Government involvement, exemplified by the EU, has the ability to drive blockchain education for food safety enhancements, as institutions hold influence through policy advocacy and public engagement, particularly pertinent for products like organic products. The EU institutions play an important role in policy education by modeling policy awareness and political advocacy for certain products, such as organic aquaculture. By highlighting how policies connect with the lives of end consumers and emphasizing the necessity of active engagement in policymaking processes, these consumers can be empowered to critically assess the importance, in this case, of the organic supply chain.

The consequences of the international nature of agri-food supply chain links to the prospective uses of blockchain technology are also significant. While this research focuses on the aquaculture regulatory environment in the EU, there are numerous unaddressed and emerging concerns about the relative responsibilities of national governments and transnational entities in coordinating, enforcing, and overseeing legislation pertaining to this technology. With respect to the potential drawbacks of blockchain technology, regulations that currently exist do not pose substantial challenges to blockchain use cases other than cryptocurrency. If these applications show to be sustainable and profitable, EU regulators will need to strike a constant balance between permitting blockchain applications and ensuring appropriate user safeguards.

Declaration of Competing Interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report.

Data Availability

No data was used for the research described in the article.

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